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W.P.

SHORE EROSION STUDY

TECHNICAL REPORT

SHORELINE EROSION AND BLUFF STABILITY

ALONG LAKE MICHIGAN AND LAKE SUPERIOR

SHORELINES OF WISCONSIN

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Wisconsin Coastal Management Program

WISCONSIN
COASTAL MANAGEMENT

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INTRODUCTION

The Erosion Problem

Shoreline erosion is a critical problem along Wisconsin's Lake Michigan and Lake Superior Coasts. In recent years Wisconsin has suffered millions of dollars in property losses as a result of erosion damage to homes, commercial and industrial buildings and public facilities. These damages have increased from $4,591,000 in 1951-2 to an estimated $15,000,000 in 1973. Public concern has also intensified with the increasing destruction to private and public property as repeatedly reflected in telephone surveys, questionaires, public meetings and the news media. The Coastal Management Program is a joint state/local effort formed to deal with the many issues confronting Wisconsin's coastal areas, including shoreline erosion as one of the highest ranking problems. The Shore Erosion Study forms an integral part of the Coastal Management Development Program with a primary goal of developing alternative plans for the prevention and abatement of shore damage to private and public coastal property.

The foundations of the study were developed during the first year effort of the Coastal Management Development Program with the initiation of basic data inventories by state agencies, institutions, and, in the second year effort, the Regional Planning Commissions. A Shore Erosion Study Plan was developed following a series of technical meetings that defined informational needs and delineated the technical studies required for the formulation of alternative plans related to shore erosion (Fig. 1).

The Shore Erosion Study may be divided into three major elements: (1) the analysis of protective structural alternatives, (2) the analysis of non-structural alternatives, (3) the field survey of erosion problem areas. This report represents the field survey effort and is based directly on many of the preceding work elements of the study, and forms the essential basis for the analyses of structural and non-structural alternatives.

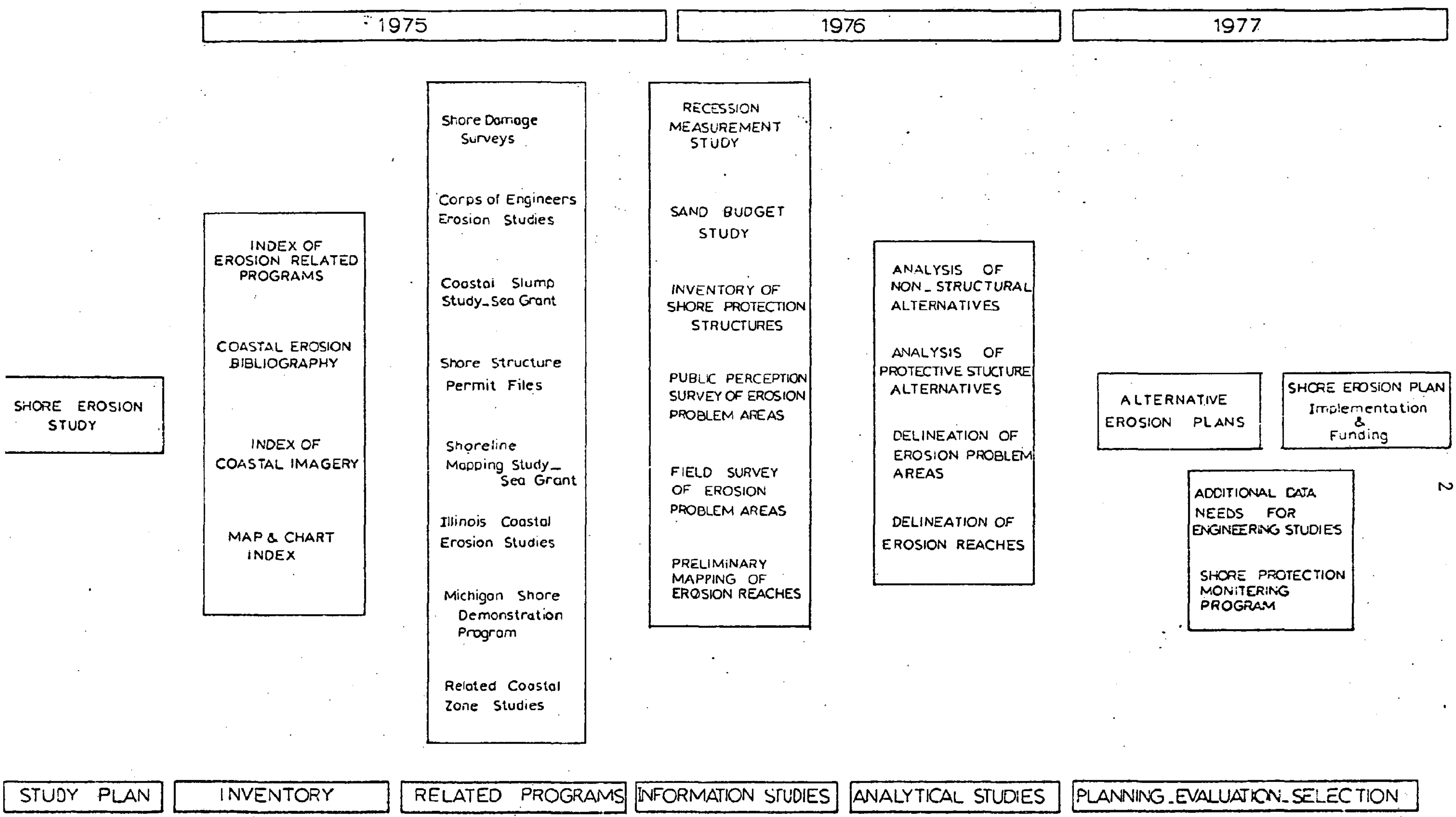

Figure 1. Flow chart of shore erosion study.

Determination of Critical Areas

Critical erosion areas are defined as areas in which property of unusual cultural, economic or scientific value is in danger of being damaged or destroyed through the processes of coastal erosion. For the purposes of this study a quantitative working definition of erosion problem areas was developed so that the resources of the study could be directed toward the most serious erosion problem areas. The criteria of this definition included; (1) public perception, (2) shore recession rates, (3) shore damages, (4) protective structures, (5) bluff height and (6) shore development.

The public perception of erosion hazard areas was obtained through regional workshops where the regional technical and citizen committees mapped known areas where erosion threatened public safety, private or public property, historic or scientific landmarks or environmental values. These maps were further detailed through a canvas of Wisconsin Department of Natural Resources and Department of Transportation field personnel. Shore recession rates were calculated from measurements of changes in the shoreline on sequential aerial photographs. These measurements were supplemented by historic recession rates as reported by previous investigators. The dollar value of shore damages was obtained from the 1952 Shore Damage Survey by the U.S. Army Corps of Engineers. This was the only year for which damages could be obtained for all of Wisconsin's Great Lakes Shoreline. Shore protection structures were interpreted from aerial photographs and supplemented by field checks where available. Bluff heights and shore development were estimated from U.S. Geological Survey topographic maps. All of this information was quantified by reach in the Lake Michigan basin (Fig. 2) and mapped on a series of shoreline base maps (reproduced by reach in the Appendices). The mapped values were then summed for each mile of shoreline and averaged for reaches of the shore. The resulting values are shown in Table 1 and form a priority list of serious erosion problem areas. Field work was concentrated in areas with a high priority ranking.

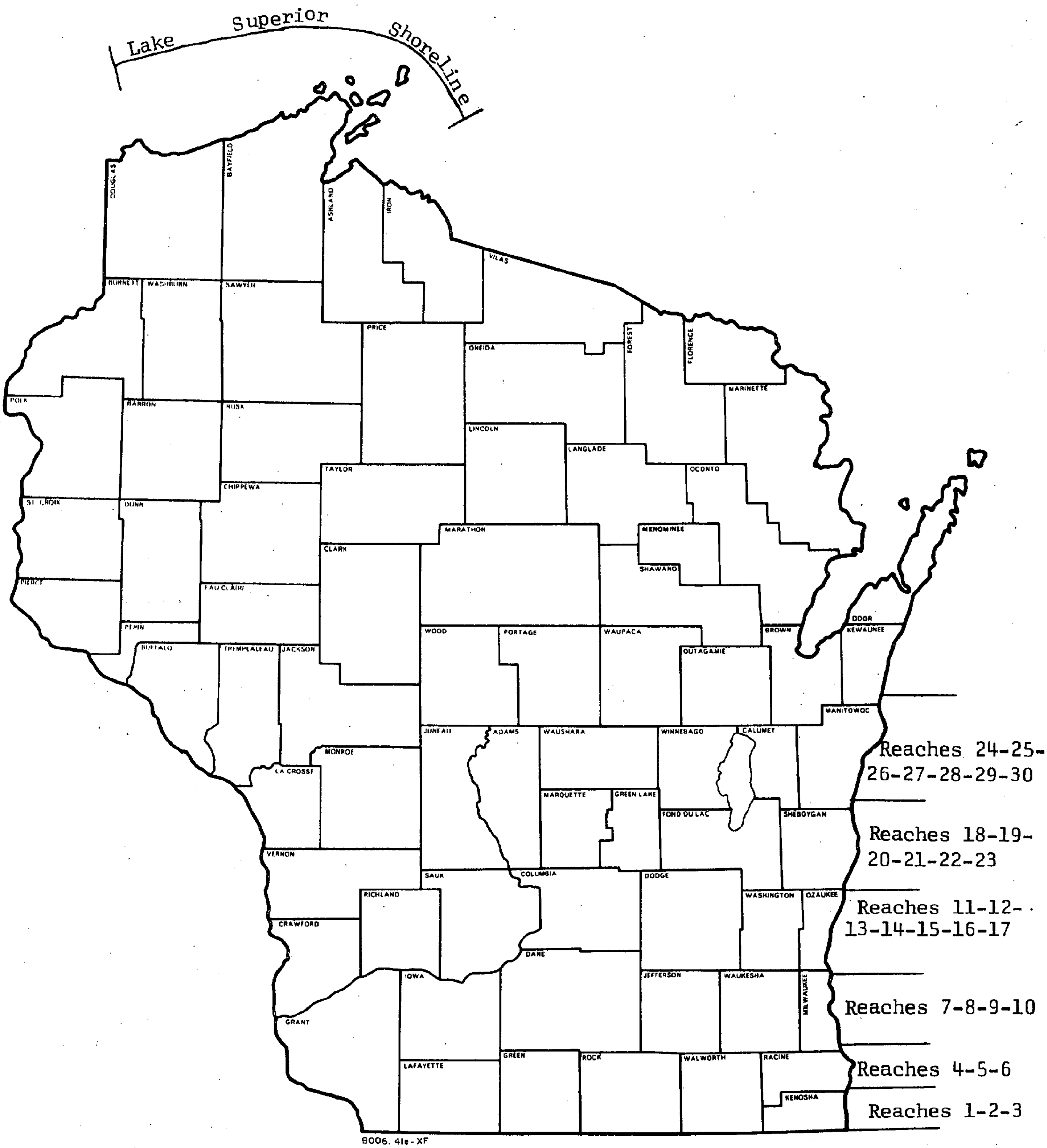

Figure 2 Outline map of Wisconsin showing location of reaches along the Lake Michigan shoreline and the extent of the study area on Lake Superior. For more detailed location of the reaches consult the individual reach descriptions under General Shoreline Conditions.

Table 1. List of reaches by priority and value/mile

					GRID MILES N-S		
PRIORITY	REACH	VALUE/MILE	COUNTY	TOWNSHIP	LENGTH	LOCATION	TOTAL
1	1	32	KEN	1	4.5	0-4.5	4.5
2	12	27	OZA	9-10	6.6	49.2-55.8	11.1
3	6	25	RAC-MIL	4-5	4.6	19.8-24.4	15.7
4	7	23	MIL	5	2.8	24.4-27.2	18.5
5	11	23	MIL-OZA	8-9	2.6	46.6-49.2	21.1
6	10	20	MIL	7-8	6.6	40.0-46.6	27.7
7	13	18	OZA	10-11	5.2	55.8-61.0	32.9
8	18B	17	SHE	13-14	5.0	74.0-74.9	37.9
9	3	13	KEN-RAC	2-3	6.0	7.5-13.5	43.9
10	5	13	RAC	3-4	3.0	16.8-19.8	46.9
11	8	12	MIL	5-6	5.8	27.2-33.0	52.7
12	16	12	OZA	11-12	3.0	65.5-68.5	55.7
13	17	11	OZA	12	3.5	68.5-72.0	59.2
14	14	10	OZA	11	1.0	61.0-62.0	60.2
15	15	10	OZA	11	3.5	62.0-65.5	63.7
16	27	10	MAN	19	3.5	110.0-113.5	67.2
17	24	9	MAN	17	3.5	97.6-101.1	70.7
18	18A	7	SHE	13	2.0	72.0-74.0	72.7
19	19	7	SHE	14-15	2.2	82.0-84.2	74.9
20	25	7	MAN	17-18	5.9	101.1-107.0	80.8
21	29	7	MAN	20-21	2.3	119.1-121.4	83.1
22	22	6	SHE	16	2.4	90.7-93.1	85.5
23	23	6	SHE-MAN	16-17	4.5	93.1-97.6	90.0
24	18C	5	SHE	14	3.0	79.0-82.0	93.0
25	21	5	SHE	15-16	3.5	87.2-90.7	96.5
26	26	5	MAN	18-19	3.0	107.0-110.0	99.5
27	30	5	MAN	21	4.6	121.4-126.0	104.1
28	2	4	KEN	1-2	3.0	4.5-7.5	107.1
29	4	3	RAC	3	3.3	13.5-16.8	110.4
30	28	3	MAN	19-20	5.6	113.5-119.1	116.0
31	20	2	SHE	15	3.0	84.2-87.2	119.0
32	9	0	MIL	6-7	7.0	33.0-40.0	126.0

Components of Project and Methods Used

The project was designed to provide information at two levels of detail for a variety of users. This report on general shoreline conditions and types of bluff failure is for use by homeowners living on the Great Lakes, persons concerned with the non-technical aspects of planning coastal areas, and other interested citizens. More detailed information on critical areas in each county is provided in the Appendices. This information will most likely be used by engineers and planners in municipalities directly concerned with the erosion problem and also will be used in the preparation of the final shore erosion plan for the State of Wisconsin. The information in the Appendices does not provide site specific information for all locations within the critical areas. It does, however, provide a framework with a sufficient amount of information so that relatively detailed planning of structures and slope stabilization projects can be done before on-site field investigations are undertaken. For most projects this site specific information will also have to be collected.

After bluff recession rates and critical erosion areas were determined, field work was undertaken. Since beach erosion and slope failure on the adjacent bluffs are intimately related, both aspects of the erosion problem were examined. Field parties of geologists walked all of the shoreline in the most critical areas, measuring topographic profiles and mapping in as much detail as possible the stratigraphy of materials in the bluff. The mapping also included a description of the kind of slope failure that was taking place. All of these profiles and maps are given in the Appendices by county and reach. Samples of many of the materials were collected for laboratory analysis.

Another aspect of the project involved description of beach conditions including nature of beach material and beach slope angle, beach width, and the distance from shore to the five-foot water depth. Since structures along the shoreline play an important role in determining the width of the beach, all structures were described, located, and evaluated for their effectiveness. This information is also tabulated in the Appendices for the critical areas.

A fourth phase of the project involved the placement of engineering borings at 20 locations along the Lake Michigan shoreline. Samples were collected with shelby tube and split spoon samplers and were returned to the engineering laboratory for analysis. The engineering data and drill-hole stratigraphy provided by this phase of the study are also given in the Appendices. In the next phase of the study engineering data from the test holes was extrapolated to include all of the critical areas by using the geologic information derived from bluff descriptions. This provides the basis for the mapping of factor of safety and stable slope angles which are given in the Appendices.

The following methods were used in the collection and analysis of data.

Computation of Erosion Rates

Before a mapping of critical areas was undertaken, erosion rates were measured for the Lake Michigan shoreline from Kenosha County north to Bailey's Harbor in Door County. Additional measurements were made in all of Douglas County, most of Ashland County, and parts of Bayfield County along the Lake Superior shoreline. All of the shoreline recession measurements were done under the direction of Mr. Charles Hess as the Department of Natural Resources' contribution to the Coastal Management Program. Two types of shoreline recession information were used in the determination of critical areas.

The first is the long-term rate of recession which integrates periods of time when there was little or no erosion with those periods of time that have had fairly high erosion rates. The long-term erosion rates were developed from a variety of sources of data including the U.S. Army Corps of Engineers and other specific studies along the Lake Michigan shoreline. Along the shoreline of Lake Superior old maps from original surveys are available which accurately portray the shoreline position at that time. These were used as the base line data for long-term recession rates where they were available.

The second type of information is recession rate over the last 10 years. In many cases these values are considerably higher but in some they are lower because of the sporadic nature of some types of slope failure along the bluff. These recession rates were measured from vertical aerial photographs at scales 1:12,000 to 1:20,000 that were taken during the last 10 to 15 years. The measurements were made by plotting shoreline positions from the older photograph onto the most recent photograph and measuring the distance of recession with a Bausch and Lomb Microline Supergauge. Distances were measured to 5/10,000 of an inch. These were then converted to distance on the ground by determining photo scale in comparison with U.S. Geological Survey topographic maps. The amounts of recession were then divided by the number of years of record to produce a recession rate in feet per year. Recession rates are shown on each reach map in the Appendices.

Profile Measurements and Geologic Observation

In the areas which were determined to have high priority in terms of this erosion study, field parties did detailed observation and profile measurements during the summer of 1976. One field party, under the direction of Dr. Alan F. Schneider, concentrated on Kenosha (Appendix 1) and Racine (Appendix 2) Counties. Another field party, under the direction of Dr. David M. Mickelson, concentrated on Milwaukee (Appendix 3) and Ozaukee (Appendix4) Counties, and a third field party, under the direction of Dr. David Hadley, concentrated on Sheboygan (Appendix 5) and Manitowoc (Appendix 6) Counties. Some measurements were also done in Kewaunee and Door Counties on Lake Michigan. For the Lake Superior counties (Appendix 7) some detailed profiling and stratigraphic description was available from previous investigations. Mr. Charles Hess collated this information and also did detailed bluff descriptions in high priority areas.

All of field work along Lake Michigan was done on a section-(one mile) by-section basis. In each section where a bluff was present, 2 - 6 profiles were measured. The topographic profiles were determined by measuring slope angle with a hand-held Brunton compass and measuring distances with a tape. All significant slope breaks were recorded and are shown on the profiles. As the topographic profile was measured, materials in the bluff were also described where exposure of the materials was available, and the thicknesses of the units were noted on the profiles. Samples were collected for laboratory analysis from all of the till units and some of the intervening lake sediment. The amount of vegetation on the bluff was noted and the type of slope failure that was taking place was described for future incorporation with engineering data.

Because all of the shoreline between the profiles was walked by the field parties, additional information in the areas between the profiles was accumulated. This information includes types of slope failure taking place, position of ground-water discharge along the slope, changes in thickness of types of material in the bluff, types of toe material, and any other features of significance. All of this information is provided either in narrative form or on maps in the Appendices.

In addition to description and measurement along the bluffs, beach widths were taped or paced and the distance from the shoreline to a water depth of 5 feet was measured with tape or optical range finder at each profile. Beach width and material making up the beach (sand, pebbles, cobbles) was also described in the areas between the profiles. Because the nature and width of the beach changes with climatic conditions, season of the year, and lake level, this information only provides some basis for preliminary planning of structures. Information on changes in beach conditions with time, an important factor in planning some structures, is not provided by this study. A generalized description of the beach is also shown in each Appendix.

All of the information accumulated was plotted either directly on vertical aerial photographs at a scale 1:12,000 (about 5-$\frac{1}{4}$ inches per mile), or on oblique aerial photographs of the bluff and transfered to vertical photos. These were also used for location, description of types of slope failure, and for the correlation of stratigraphic materials in the bluffs. All of the information from the photographs was then converted to maps at a scale of 1:12,000, and these maps are provided in the Appendices.

Structure Mapping and Evaluation

For each erosion control or bluff stabilization structure visible along the shoreline a descriptive form was filled out (Fig. 3). Information given on the forms is tabulated in the Appendices, and structure forms are on file at the Department of Natural Resources. All structures were photographed to provide additional description of the structures. The location of the structures is shown by county, township, and range, section, and fraction of a mile north of the south section line along the shoreline. The location of the structures is also shown on maps in the Appendices.

Measurements of structure heights and widths were measured where possible either by taping or pacing the distances. In some cases measurements were difficult or impossible to obtain, and so estimates are provided. Definitions of the structure types are given in the Glossary at the end of this report. Structure condition was based on whether or not the structure was trapping sand and building out a beach at the base of the bluff. Adverse effects were usually erosion on the down-drift side (usually south) of the structure. In some cases, especially with large structures, the beach has actually been removed by waves and currents on one side of the structure and considerable bluff erosion is taking place. The type of material used in the structure was given as the two major materials, and the amount of maintenance needed was a subjective observation related to the way in which the structure was being maintained. Shore parallel structures, such as revetments and bulkheads, commonly fail by being over topped by large waves or by being eroded at the toe; the latter failure usually results in collapse of the structure. In some cases, breakwaters (shore parallel structures away from

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SHORE EROSION STUDY
SHORE PROTECTION
EVALUATION

Report No. ________ Observer ________

LOCATION

County [| |] T[|]N, R[| |][ ], Sec[|].[ ] Mile[| | |]

DATE

Day [|] Month[|] Year[|] Hour[| | |]

PHOTO

Roll ______ Exp ________

PHYSICAL SETTING

Bluff: Height [| |]ft Slope [|]° Vegetation [|]%

Beach: Width [| |]ft Slope [|]° Orientation [| |]°

Nearshore: Distance to 6 ft depth[| |] Depth 50 ft offshore [| |]

Wave height [ ].[ ]ft Wave type [ ]
1. Spilling, 2. Spilling/Plunging
3. Plunging, 4. Surging, 5. Calm

Lake level [| | |]ft

STRUCTURE

Owner [| | | | | | | | | |] Permit [| | | | | | | | | |]

Type [ ]
1. Revetment
2. Bulkhead
3. Groin
4. Breakwater
5. Pier
6. Other ________

Number [ ]

Length [| |]ft

Height [|] ft

Maintenance [ ]
1. None required
2. Minor required
3. Major required
4. Rebuild

Material [|],[|]
1. Stone
2. Broken concrete
3. Steel
4. Timber
5. Poured concrete
6. Asphalt
7. Precast concrete
8. Wire
9. Cloth bags
10. Tires
11. Other ________

Condition [ ]
1. Functional
2. Non-functional
3. Failing

Failures [ ],[ ],[ ]
1. Toe undermined
2. Overtopped
3. Flanked
4. Collapsed
5. Faulty material
6. Vandalism
7. None
8. Other ________

Adverse Effects [ ],[ ],[ ]
1. None
2. Bluff erosion
3. Beach erosion
4. Navigation hazard
5. Other ________

Remarks ____

Figure 3. Example of form used for the description and evaluation of structures. Completed forms are on file with the Department of Natural Resources.

the base of the bluff) also fail in the above-mentioned fashions. Shore perpendicular structures, such as piers, occasionally collapse because of wave or ice damage, but sometimes are so successful in trapping sediments that they become buried in beach material and are not presently acting as sediment traps. In these cases, the accumulation of beach material does protect the toe of the bluff however, and the structures were rated as functioning and requiring none or minor maintenance.

Geotechnical Subsurface Exploration, Sampling, and Field Tests.

Sites for engineering borings were chosen because they represent fairly typical bluff composition, important stratigraphic units from an engineering standpoint, and to some extent because they were accessible to the truck mounted drilling equipment. Locations of the drill holes were monumented and detailed slope profiles on the adjacent bluff were measured. This will enable more detailed studies on slope stability to be undertaken in the future. Locations of all the drill holes are shown on Figure 4, in more detail in maps showing reaches, and in the Appendices.

Two separate drill rig units were used in the sampling of subsurface materials each with a capacity of 120 to 135 feet of auger boring. Solid stem auger flights five feet in length and four and one half inches in diameter were used to open the hole and to determine general stratigraphy. Standard Penetration Resistance was recorded at five foot intervals in Accordance with ASTM d 1586-67, by using either a cathead and blocks system, or a Sate-T-Driver Hoist on the Mobile Drill Unit. The number of blows necessary for a 140-pound hammer dropping 30" to penetrate a split barrel sampler (2 in. O.D., $1\frac{1}{4}$ in. I.D.) into the soil six inches was recorded in three sets, the sum of the last two being the Standard Penetration. Pocket Penetrometer readings were taken on the surface of the split spoon samples thus obtained and averaged to give an estimate of the unconfined compressive strength of cohesive soils. Three-inch Shelby tube samples in lengths of $2\frac{1}{2}$ and 3 feet were pushed hydraulically into the soil approximately

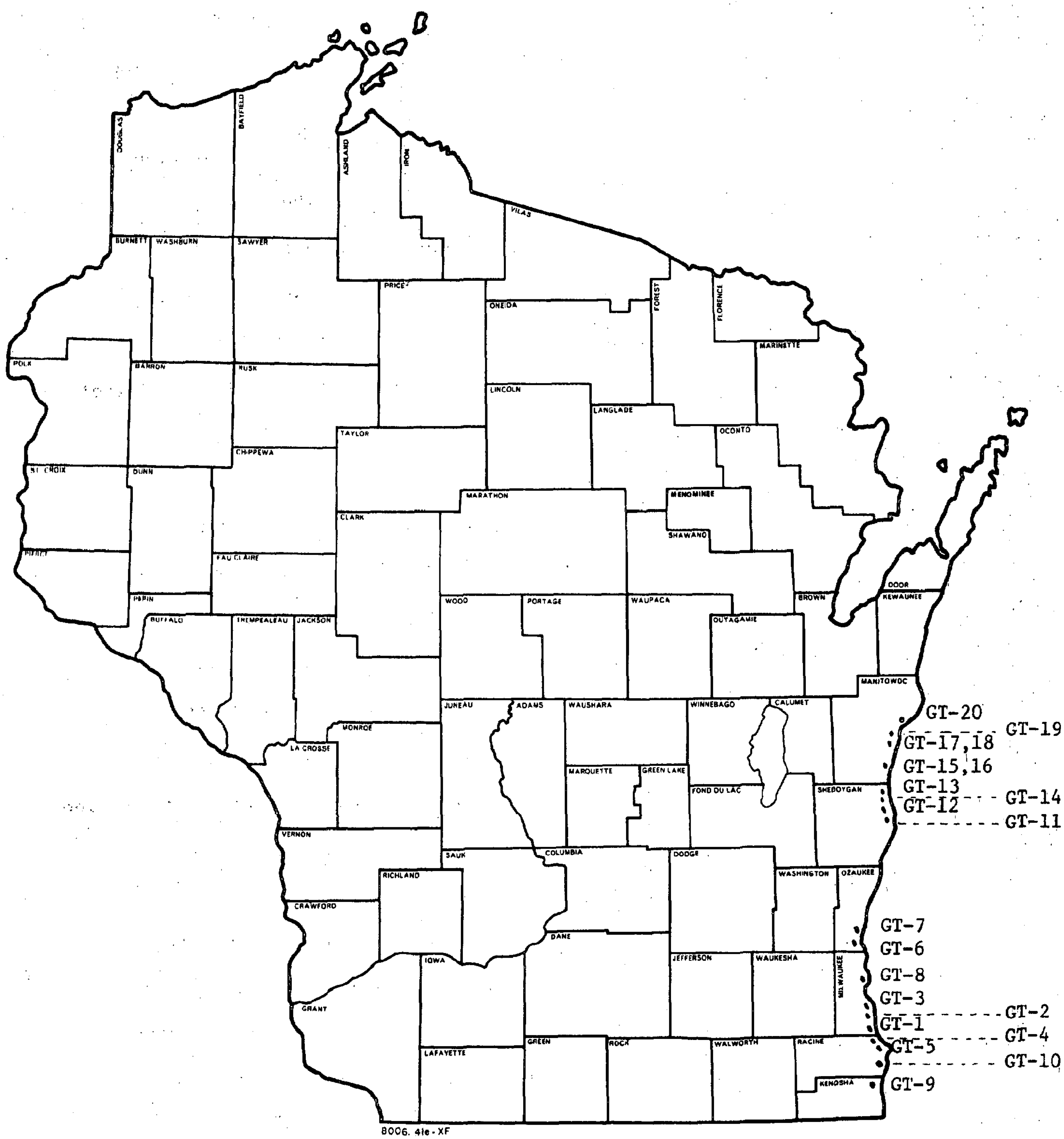


Figure 4. Outline map of Wisconsin showing the location of geotechnical drill holes used in this study. For more detailed locations consult the county maps under General Shoreline Conditions.

every 20 feet, or when a new recognizable layer was reached, as per ASTM D 1587. The ends of the Shelby tubes were stopped with plastic caps, then covered with cloth and sealed in paraffin, then stored horizontally in a moisture room in the laboratory.

Piezometers were prepared in the lab consisting of a 3/8" I.D. perforated plastic core and a 1½" shell of an epoxy/Ottawa Sand matrix. The piezometers were installed in each borehole at the estimated water table levels, or in pervious strata, and connected to the surface by a 3/8" O.D. plastic tubing. Bentonite "plugs" were used where appropriate to isolate the piezometer tip, and sand filled in around the tip. Groundwater levels were determined approximately one month after the installation of the piezometers by registering the voltage through a coaxial wire.

All boreholes were backfilled with soil refuse, capped with a 2½-inch plastic pipe and pipe cap fitting, monumented, and sealed in cement. The borehole location was roughly determined from nearby reference points.

Hollow-stem augers, casing, wash borings and slurry methods were not used in the subsurface investigations. Due to the occurrence of high groundwater tables, or saturated sand layers, it was often necessary to resort to obtaining only "bag" samples from auger flights. These bag samples were used in classification tests only.

Geotechnical Engineering Laboratory Testing

Standard Classification and shear strength tests were conducted on split spoon, bag, and shelby tube samples obtained by the drilling crew. Atterberg Limits (Liquid Limit and Plastic Limit) were determined by the procedure outlined in W.T. Lambe's Soil Testing for Engineers as per ASTM D 423 and D 424. The Liquid Limit was calculated by straight line least squares analysis of the water content vs. the log of the number of blows of the liquid limit dish. The grain size distribution of each sample was determined by wet sieving on standard sieve sizes #10, #40, and #200, and the percentage finer than a particular grain size determined by consecutive subtaction. Standard Hydrometer analysis as described by W.T. Lambe was performed using 50 cc of .4N Calgon solution (Sodium Hexametaphosphate + Na_2CO_3 Buffer) with approximately 50 g of soil passing #200 sieve in one liter of distilled water. A desk calculator (Monroe, Model 1880) was programmed to determine the equivalent corrected grain diameter and the percentage finer for the particular hydrometer used, and the results were interpolated to obtain the percentage finer than .005 and .002 mm. Pipette analysis was also used to determine the percentage of clay. Samples were prepared as described above, then an appropriate volume of suspended material was removed at specified depths and times as described by Tanner and Jackson (1947). The results were corrected for the concentration of Calgon, and the percentage of grain sizes smaller than 0..5 and .002 mm were recorded.

The Unified Soil Classification System was employed as per ASTM D 2487-69 and ASTM D 2488-69 using the following basis for grain sizes:

Gravel	2.0 mm
Coarse Sand -	0.42 to 2.0 mm
Fine Sand -	0.074 to 0.42 mm
Silt -	0.002 to 0.074 mm
Clay	0.002 mm

Natural water content, w, and natural unit weight, y, were determined for all Shelby tube samples, and many split spoon samples. Dry density was then calculated as $\gamma_d = \gamma$ (1+w) as a measure of the concentration of solid matter in a unit volume of soil.

Shear strength tests were conducted on all shelby tube samples. Sand samples were tested at natural densities determined either by Standard Penetration results, or direct density measurements. The specimens (1.4 in. diameter, 3.0 in.high) were placed in triaxial compression test cells, an initial all-around cell pressure applied, and the axial load increased until failure at a shearing rate of .03 to .06 inches/min (strain rate= .01 to .02 per inch). Drainage was allowed, and dilatancy, or volume changes during shearing were used in determining the shear strength. Compilation of the triaxial data and least squares determination of the effective angle of internal friction was performed by a calculator program, assuming cohesion zero and taking failure at the maximum principal stress difference.

Clay sample were extruded from the shelby tubes, trimmed manually to a speciman size approximately 3.6 cm in diameter and 7.8 cm in length. After being enclosed in a rubber membrane, and placed in a triaxial testing cell, the specimens were subjected to a confining pressure of 0.5 ksc and allowed to consolidate. After equilibrium was obtained, B-checks were made wherby the cell pressure was increased, and the subsequent increase in the internal porepressure of the specimens noted. The backpressure, or applied porepressure, was then increased to maintain a constant effective pressure of 0.5 ksc on the specimens. This procedure was continued until saturation was achieved, i.e., the porepressure increase was at least 90% of the increase in cell pressure. Backpressures of 3 to 5 ksc were generally required to achieve saturation. Cell pressure was then increased and specimens allowed to consolidate in order to provide the desired effective normal stress before shearing. All drainage due to consolidation was recorded and the change in specimen height measured. Shearing was done at a rate of about .004 inches per minute, (or a strain rate of .0013 per minute), and the porewater pressure measured (drainage was not allowed during shearing). The effective stress parameters were computed by calculator programs, based on a least squres fit of points of maximum deviator stress. Effective stress paths were plotted, and the corresponding failure envelope indicated for each set of specimens (Fig. 5).

A Farnell automatic shear vane testing apparatus was used to estimate the unconfined compressive strength of several shelby tube samples. The vane had a diameter of 1.27 cm and a length also of 1.27 cm, and sheared at a rate of about 8.5° per minute (or about 40 minutes per rotation).

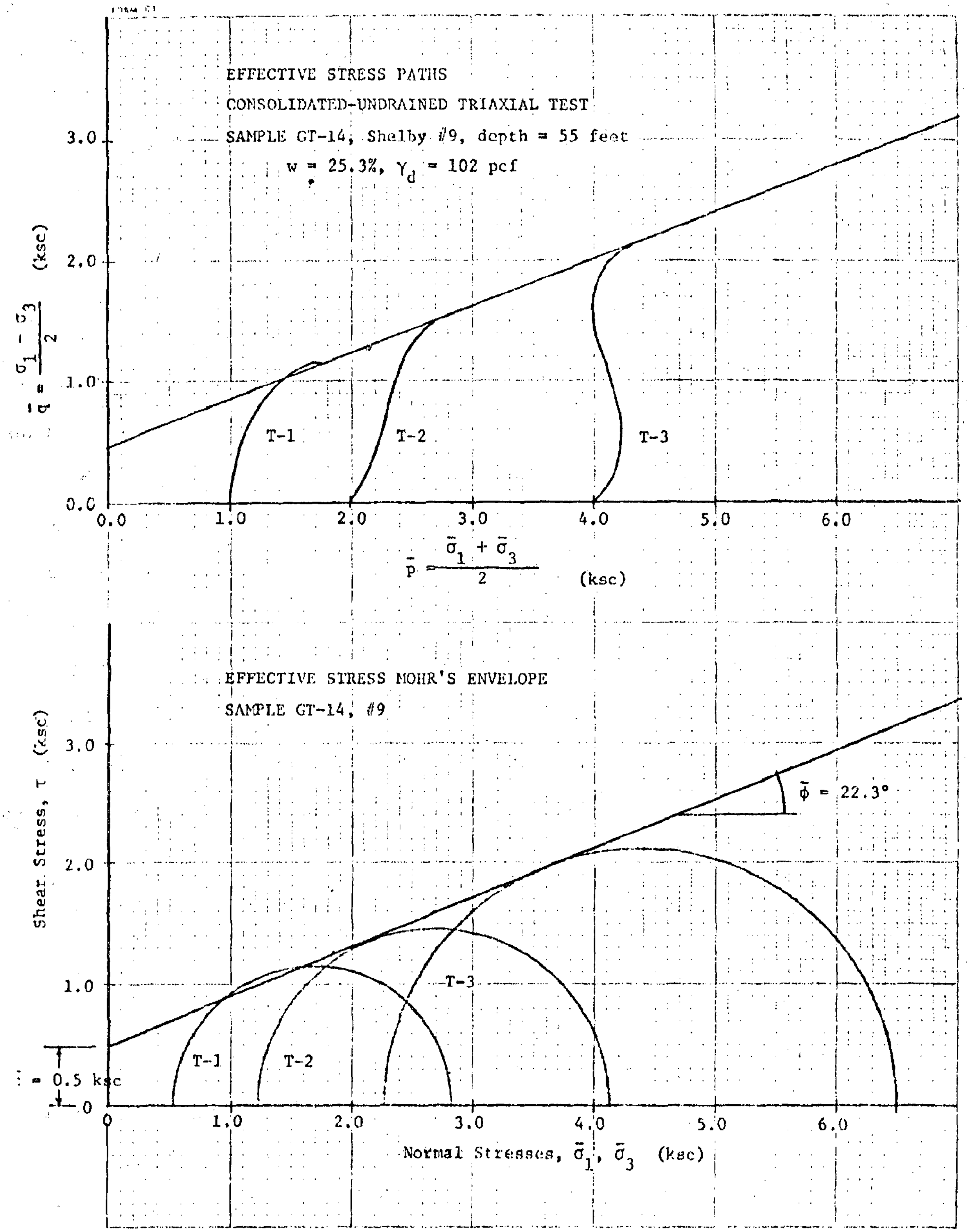


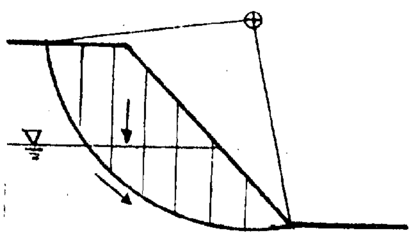
Figure 5. Effective stress for sample GT-19, #9

Stability Analysis

The relative slope stability of the bluffs along the Lake Michigan shoreline, its variations, extremes, and criticality due to changes in stratigraphy, material properties, bluff height, and slope angle, were the ultimate concern of the Geotechnical Engineering Group. Each bluff profile as measured by the geologic field parties, was analyzed using the effective stress parameters determined in the laboratory,

A modified Bishop method of slope stability analysis (Fig. 6) assuming circular, rotational failure has been found to model the slope failure phenomena along the coastline satisfactorily (Edil and Vallejo, 1977) and was therefore also used in this study. The procedure that this method follows is to divide the failure zone into slices, analyze the effective forces on each slice, then sum the moment of these forces about the trial failure circle center. Groundwater conditions and seepage forces are also considered in the stability analysis. The Safety Factor is then defined as the ratio of the sum of the moment of the driving forces (shear stresses) to the sum of the moment of the resisting forces (shear strength). The computer program employed was developed by the New York State Department of Transportation giving intermediate moment values, a simplified Factor of Safety, the modified Bishop Factor of Safety, and the critical failure circle. It also employs a search routine which checks for the minimum Safety Factor, and stops when this minimum is reached.

The ultimate angle of repose for a stable slope was determined by assuming a long-range equilibrium condition of the bluff whereby the cohesion reduces to zero due to weathering, and the angle of repose is then the angle of internal friction of the soil. Below the groundwater table, the stable slope angle is reduced due to the effects of water pressure, so that the stable angle, B, can



$$SF = \frac{\Sigma M_D}{\Sigma M_R} = \frac{\text{shear stresses}}{\text{shear strength}}$$

Figure 6. Illustration of modified Bishop Factor of safety method.

be computed by the equation

$$\tan B = \frac{SAT}{BOUY} \tan \quad = \tfrac{1}{2}\tan$$

and results in a slope angle about half that of the angle of internal friction. Artesian pressures and excess hydrostatic pressures due to seepage effects tend to decrease this stable slope angle even more; however, these conditions are not prevalent in the bluffs of this study.

Interpretation and Presentation of Results

The engineering properties of the soils along the Lake Michigan coastline were determined only at particular sites where the boreholes were drilled. The properties used in evaluating the slope stability of all the bluffs are a combination of averaging the properties of all tests on a given stratum and extrapolation of these properties over a large extent of shoreline based on engineering judgement.

Soil properties were therefore considered constant and homogenous for any given stratum. Stratification was considered horizontal at any given profile, and variations in stratification along the coastline were determined using the section reports of the geologic field parties.

The location of the groundwater table at a given profile was assumed based on the following criteria:

a. Stratification (Fig. 7). In fine-grained soils, the groundwater table is characteristically higher than in coarse-grained materials.

b. Piezometric readings. Piezometers installed at the boreholes allowed direct measurement of the actual groundwater level, which was then assumed horizontal to the face of the bluff. Piezometric records were applicable, however, only very near the borehole location.

c. Seepage zones. The lines or zones of seepage reported by the geologic field parties were often assumed as the groundwater table since these very often indicated a permeable layer over a less permeable one,

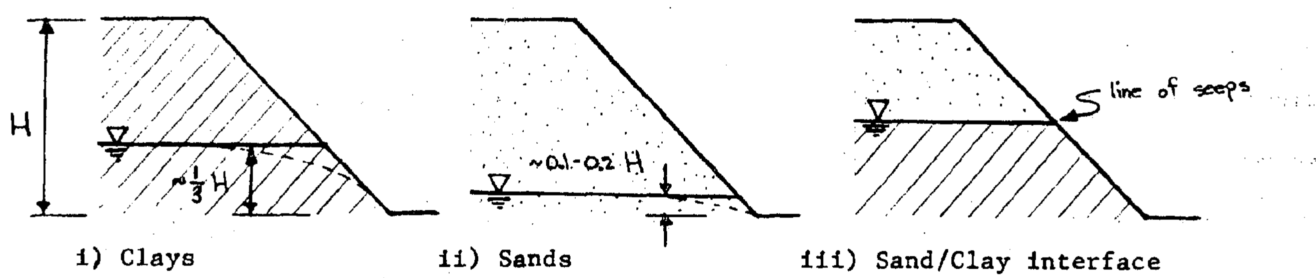


Figure 7. Diagram illustrating assumptions used for the position of the groundwater table under different conditions.

as in case iii above, in which the pervious stratum would conduct the flow of water, and therefore be the highest critical groundwater level.

Groundwater levels are generally much lower near the bluff than normally expected further inland since the water is trying to reach a minimum potential at the lake level, and therefore has a depressed water table. For the purposes of this study, the water table was assumed to be horizontal, since this is a more critical condition than a gradual reduction to lake level, and is very close to the actual shape of the phreatic surface in sands and sand or silt seams, a condition which frequently occurs in the bluffs of this study.

After extrapolating the stratigraphy, engineering properties, and groundwater levels to the recorded profile locations, a safety factor was obtained for each profile by computer analysis. This safety factor was then interpreted and again extrapolated over a particular stretch of shoreline. Interpretation of the Factors of Safety, and extrapolation of the results was based on the following criteria:

a. Value of the Safety Factor: A Safety Factor less than or equal to one was considered an <u>Unsafe</u> slope; that when water pressures build to an equilibrium value will most likely cause failure along the failure plane indicated. A Safety Factor between 1.0 and 1.25 indicated a slope of <u>Questionable</u> stability; that if assumptions made are grossly in error, if groundwater conditions change, or if wave erosion or surface degradation change the profile shape, that a failure of a segment of the slope may be possible. A Safety Factor greater than 1.25 was considered to indicate a safe slope condition with little probability of failure.

b. Vegetation cover. Vegetation affects the surface runoff conditions and slope washing, increases the apparent cohesion of the immediate slope face, and in general indicates a slope not undergoing active erosion. Therefore, the amount and type of vegetation was often considered in interpreting the stability of a particular stretch of shoreline.

c. Nature of failure. Based on the principles outlined above in determining stable slope angles, if the shape and nature of the slope profile seemed to indicate a stable slope despite the calculation of a low Factor of Safety, as in the case of accumulated slump material at the toe of the bluff, this was considered in the interpretation of the results.

Descriptive assessments of the slope stability along a long stretch of shoreline was made using the terms Unsafe, Questionable, or Safe, with modifications noted where applicable. Divisions between areas of different safety indicators were based on the visual observations described in the reach or section reports by the geologic field parties.

The level of confidence of the information available varies considerably along the shoreline, and is therefore also indicated on the section maps. The engineering properties of the materials, the groundwater conditions, and slope configurations are most accurate right at the boreholes, and are given the highest level of confidence. This information may be extended both north and south of the borehole with reasonable accuracy so long as the stratigraphy is known and is consistent, or the lateral distances are not too great; thus, these areas have been designated as a second level of confidence. The lowest level of confidence is then assigned to those areas where the stratigraphy is not at all apparent, or that are far from any borehole.

The stability line, neglecting wave erosion, was obtained by extending stable slope angles from the toe of the bluff to the top of the bluff, and the corresponding setback in feet of the bluff ridge measured. Thus, this setback indicates a minimum retreat of the bluff top necessary to insure stable slope conditions, provided the toe of the bluff is protected from further erosion.

There are a number of assumptions that have been made in analyzing the bluffs along the shoreline that require a certain amount of caution in assessing the absolute reliability of the engineering judgements made. All of the engineering properties have been averaged, assumed homogenous and consistent throughout any given stratum and the stratigraphy has been assumed horizontal and continuous. These conditions may prevail at a particular site, but may be drastically different from those in the near vicinity. Thus, the extrapolation of data is precarious, and the assignment of Unsafe or Safe slope designations must be viewed with a certain degree of scepticism. These extrapolations are to be used as a guideline or an indication of general conditions along the shoreline, but should not exclude detailed geotechnical subsurface investigations at any particular site to assess its slope stability. It should also be mentioned that these Safety Factors do not indicate large, dramatic failures, but consecutive failures of a smaller extent, thus the term "Unsafe" does not mean a catastrophic landslide always, but rather a high probability of subsequent erosion by mass wasting. Finally, the methods used in analyzing the stability of the slopes do not account for surface sloughing, solifluction, mass flows, slope wash , or wave erosion which must also be considered in determining the ultimate stability of the slope, or the ultimate rate of retreat of the bluff top.

SLOPE FAILURE AND BLUFF RETREAT

Causes of Slope Failure

On all hillslopes gravity acts to move material on the slope to a lower position. On most hillslopes which are undisturbed by man, and where streams or waves are not cutting at the base, an adjustment is reached through a fairly long period of time so that the slope angle is adjusted to the stresses acting to move material down the slope and to the resistance of the materials in the hill to the stresses. Thus on the bluffs on the Lake Michigan and Lake Superior shorelines two major variables control the rate of bluff recession and the angle of the slope at any given time. The nature of the materials (primarily the grain size distribution) and the amount of shear stress on the materials in the slope. The detailed discussion of the engineering characteristics of materials in the bluffs and the engineering data presented in the appendicies is discussed under engineering methods.

The shear stress of the materials in the bluffs is primarily determined by the bluff height and the angle of the slope. Undercutting at the toe of the slope by waves steepens the slope and increases the shear stress. Along the Lake Michigan and Lake Superior shorelines this is the process that is primarily responsible for causing slope failure within the slope itself. In the following section of this report we will look at processes acting at the toe of the slope which tend to increase shear stress on slope materials and then examine the resulting slope failure.

Processes at the Toe of the Bluff

As pointed out above, the basic cause of slope failure and bluff recession on the Great Lakes shorelines is wave erosion at the base of the bluff. The amount of wave erosion at the base of the bluff is directly related to the type of material at the bluff base and also to the energy of the waves which break against the toe. The amount of energy going into toe erosion is, in turn, related to the slope of the beach and offshore areas, the orientation of the beach as it relates to the orientation of large storm waves, the fetch or distance of water over which the waves can develop and the elevation of the water surface relative to the elevation of the base of the bluff. Both in Lake Superior and in Lake Michigan, storms with northeast winds tend to produce on average the largest waves, and therefore, beaches exposed to these waves generally have the most severe erosion problems.

Materials on the beach are moved up and down perpendicular to the shoreline as waves break and wash, then backwash, on the beach surface. Since waves usually strike the beach at an angle, there is usually net transport of material in one direction parallel to the beach. This movement is what is called longshore drift and occurs on the beach surface as well as in currents just off shore, which are called longshore currents. Thus, at any given place and time on the beach, material is being moved in from one direction and moved out in the opposite direction. Because waves and currents responsible for this sediment transport have a prevailing direction there is a net transport of sand in one direction over a period of time. Along most of the Wisconsin shore of Lake Michigan, the prevailing longshore drift is southward. In Lake Superior the prevailing drift is westerly along most the Wisconsin shoreline.

Because of the movement of sediment within the wave zone, the width of the beach and the size of materials on the beach vary with time. In natural situations where man has not interrupted the longshore drift system, the slope and size of the beach is often adjusted so that the material on the beach can be carried as longshore drift. Thus, beaches with coarse material are usually steeper and waves strike the beach with greater force than sand beaches with lower angles where waves break further away from the water's edge. Because most sediment in the longshore drift system is derived from erosion of the bluffs the volume of coarse material in the bluffs is important. If sufficient amounts of coarse sediment are available, a beach can be maintained and actual erosion of the toe is reduced. If the bluff material is relatively fine-grained, a large volume of bluff must be eroded for the waves to build a stable beach and maintain the longshore drift system.

Man-made structures can influence the longshore drift system in a number of ways. Breakwaters, those structures which are shore parallel and built in the water, prevent large waves from breaking against the shoreline. Thus, material transported by the longshore drift system tends to accumulate behind the breakwaters and the bluff behind the breakwater is protected. This can be seen in a number of areas along the Lake Michigan and Lake Superior shorelines (Fig. 8). Groins and some piers also tend to stop sediment which is moving in the longshore drift system. In these cases, sand accumulates as a fairly wide beach on the up-drift side (generally north on the Lake Michigan shoreline) and the base of the bluff is protected from breaking waves. Another result of these structures, however, is often an increase in erosion on the down-drift side of the structure. This takes place because waves strike the shoreline in this position and tend to move the sediment in the down-drift direction. Because the sediment supply has been cut off by a structure, the beach width is reduced or the beach is removed completely and increased erosion takes place at the bluff toe (Fig. 9). Thus, knowledge of beach process and the possible effect of any structure is necessary before structures are placed along the shoreline to prevent increased erosion.

Another way in which man can attempt to reduce the amount of erosion at the toe of the bluff involves direct protection of the toe from wave erosion. Usually the kinds of structures used are revetments, which are commonly piles of coarse rock debris, or concrete slabs along the toe of the slope, or bulkheads, or seawalls, which are generally made of poured concrete. These structures do not interrupt the flow of sand in the longshore drift system.

Figure 8. Oblique aerial photograph showing the effect of a breakwater. Note vegetated slope behind the breakwater and active erosion just to the left (south) of the breakwater. Location is T. 5 N., R. 22 E., Section 24, Reach 7, Milwaukee County (oblique R-21, 34).

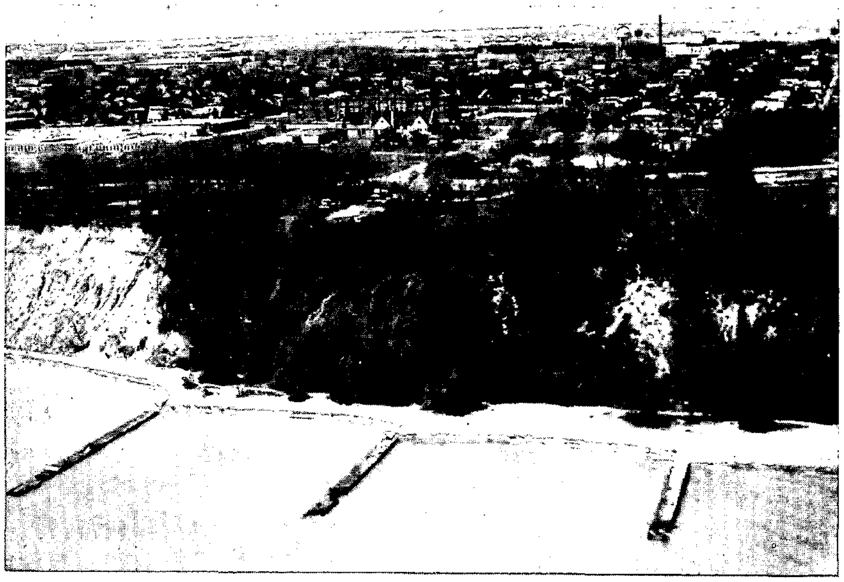


Figure 9. Oblique aerial photograph of the effect of a groin on shoreline erosion. Note the wide beach between the groins and the narrow beach and actively eroding bluff to the left (south) of the groins. Location T. 6 N., R. 22 E., Section 25, Reach 8, Milwaukee County (oblique R-20,23).

In many areas the beach in front of these structures is removed by erosion and the structures absorb fairly high wave energies. This can result in undercutting of the structures as waves erode the loose sediment at the base. As waves begin to break directly against the structure, the structures are often overtopped and water from the breaking waves can erode material behind the wall or infiltrate the area behind the wall and contribute to collapse of the structure (Figs. 10 and 11). Although at considerable expense, it is possible to artificially nourish the longshore drift system when insufficient quantities of material to form a beach are available.

The fundamental cause, then, of bluff retreat along our Great Lakes shorelines is erosion at the toe of the bluff. In most areas this is a natural process which has been taking place for thousands of years, especially at times of high water. In most situations any attempt at bluff stabilization will also have to control wave erosion at the toe. Even when this is controlled, however, bluff recession will continue until stable slope angles are reached. In areas of high bluff with relatively weak materials, hundreds of feet of bluff recession might be necessary before a stable slope angle is reached. Thus, in areas which are already developed close to the present bluff top, stabilization of the toe is not the only solution. We must look at processes on the bluff and materials in the bluff to predict what stable slope angles might be and to develop possible methods of slope stabilization. Although the methods of slope stabilization and estimates of cost will be discussed in another report, we will discuss the types of slope failure taking place and the kinds of materials in the bluffs.

Types of Slope Failure

Most bluff retreat takes place by slope failure (landslides in the general sense) rather than by erosion by surface water crossing the bluff. Although runoff from rainstorms can remove considerable material from the

Figure 10. Photograph of seawall showing old collapsed seawall in foreground and new seawall in background. Both walls are being overtopped by waves (note gravels above wall and erosion behind wall in center of photograph). Location is T. 9 N., R. 22 E., Section 20, Milwaukee County (structure 20.7)

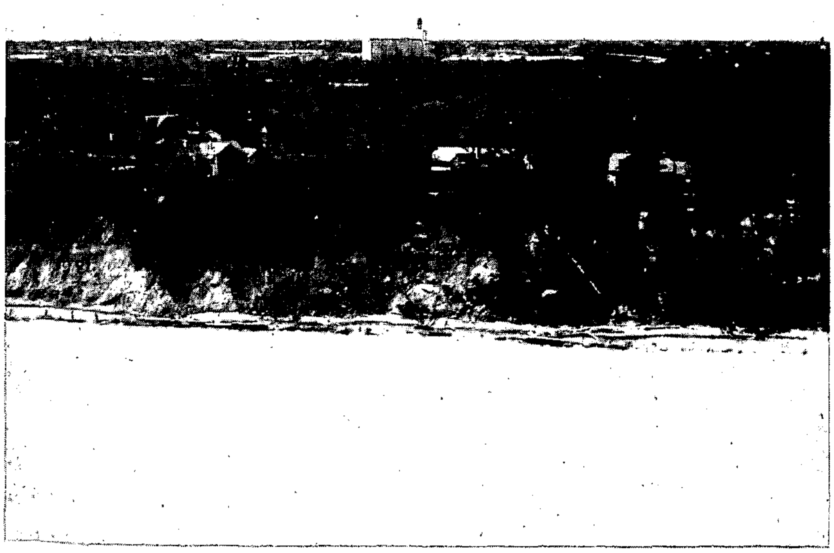


Figure 11. Oblique aerial photograph of collapsed seawalls. Note the amount of erosion that has taken place since the seawalls were built. Location is T. 8 N., R. 22 E., Section 33, Reach 10, Milwaukee County (oblique R-17, 20).

bluff face if the vegetation cover is sparse, the lack of vegetation is an indication that sliding of materials down the slope is also taking place at a fairly rapid rate. The terminology used in this report to describe various kinds of failure is that used by Varnes (1958). Three major divisions of slope failure are made in this classification. The first is rock or soil fall. This type of failure takes place when undercutting is extreme and near vertical cliffs are produced. Although some near vertical slope segments are present in many of the profiles along the eroding bluffs, these are generally fairly small and fall of material from vertical faces has relatively little importance except along some bedrock cliffs in Door County and on the Bayfield Peninsula.

The second type of slope failure is sliding. In this type of failure the material that is being moved is relatively undeformed and generally moves along a single slide plane. Two types of slides are very common along the bluffs of Lake Michigan and Lake Superior. On most of the slopes which have very little vegetation at the present time or vegetation is only present in patches, translational sliding is taking place (Fig. 12). This type of failure involves a surface layer several inches to one or two feet thick sliding either rapidly or fairly slowly down the bluff. Where recent slides have taken place slickensides or grooves left by the sliding mass are often present on the slope above. The growth of ice crystals within the soil during winter months weakens the structure of the soil and increases the possibility for this type of sliding and flows, especially during the spring as the intergranular ice melts. Along some parts of the shoreline, especially where much of the bluff is made up of massive lake sediment and fine-grained tills, this failure type is probably the most important in causing bluff recession. Without detailed measurements, it is impossible to quantify the effects of this process, nor can the process

Figure 12. Oblique aerial photograph showing bluff where shallow slides and some flows are the common mode of failure. Note the almost complete lack of vegetation on the slope. Location is T. 10 N., R. 22 E., Section 3, Reach 13, Ozaukee County (R-13,8).

be predicted in more than a general sense. Thus, the engineering analysis of factor of safety which is given in the Appendices excludes analysis of this type of slope failure and concentrates on another type of slide called slump.

The term slump is used when sliding of a fairly large mass takes place along the curved surface. The slide mass is actually rotated and often the top of the slump block is tilted back toward the hill slope (Figures 13 and 14). Slumping usually takes place fairly rapidly and the movement of one slump block can remove up to 50 or 100 feet of bluff top. Slump blocks this large occur in southern Ozaukee County (Reach 13) and remnants of large slump blocks are present in northern Milwaukee County (Reach 10). Thus, this type of failure could result in the loss of human life and considerable property damage. The analysis of prediction of this type of failure is discussed under Engineering Methods.

The third major type of failure is flow. With this kind of slope failure large amounts of water are present and the soil mass actually liquifies and flows like a fluid. Some flow commonly occurs at the toe of slump blocks during and relatively soon after failure. Since slump blocks do show rotation and the top of the block is often tilted back toward the bluff surface water can accumulate in these depressions and saturate the underlying soil. This often creates an unstable situation and flows away from the base of the slump block are relatively common. Minor shallow flows also occur when intense rains saturate the surface layer of soil or in the spring as intergranular ice melts near the soil surface and very wet conditions occur.

Minor flows can also be seen where groundwater discharges along the bluff face in silt or fine sands. If these slightly more permeable units occur between less permeable units, this removal of sediment by flow due to groundwater discharge is referred to as sapping, and can cause undercutting which creates an unstable slope in which slumping or sliding will occur.

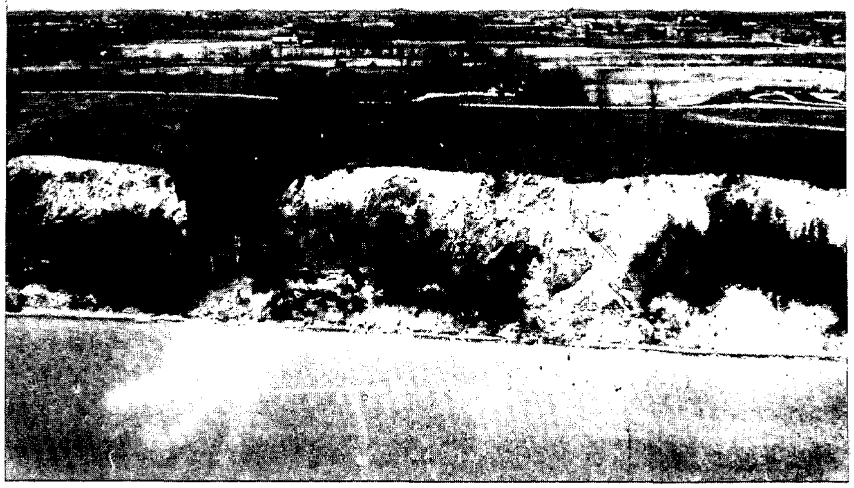


Figure 13. Oblique aerial photograph showing relatively large slump blocks. Note the scalloped nature of the bluff top produced by this mode of failure. In right center of the photograph is a flow which took place after failure by slumping. Location is T. 10 N., R. 22 E., Section 21, Reach 13, Ozaukee County (R-13, 25).

Figure 14. Oblique aerial photograph of bluff showing numerous closely spaced failure plains. These failures may be fairly deep-seated. But failure is along numerous plains as opposed to along a single plain as in Figure 15. Location is T. 5 N., R. 22 E., Section 25, Reach 13, Milwaukee County (R-22,12).

Effects of Groundwater on Slope Stability

Rainwater falling on the ground surface landward of the bluff face often percolates through the soil and enters the groundwater system. In most areas along the Great Lakes shorelines this water moves toward the lakes and discharges either at or below the base of the bluff directly into the lake, or out of the bluff at some position above lake level. The presence of groundwater in soil materials of the bluff can affect stability in several ways. Just the presence of water below the water table where all of the pores between grains are filled with water decreases the grain-to-grain contact pressure in the soil and reduces the frictional resistance of the material to a stress. If water is removed from the soil the bluff materials become more resistant to slope failure. If the groundwater table slopes toward the lake, as it does in most of the bluff areas, groundwater moving between the grains also creates a seepage pressure in the direction of water flow. This pressure is especially important in granular soils such as sands and silts and is less important when the content of clay is fairly high. Assumptions made in the engineering analysis about the groundwater movement and water level are discussed in the section on engineering methods.

If groundwater actually discharges along the bluff face some undercutting of materials also occurs. If the amount of water is sufficient, sapping of material will actually take place and this contributes to the amount of bluff recession. Removal of bluff materials by ground water is especially important when sand units are either interbedded with fine grained materials or are present at the bluff top. When present at the bluff top large amounts of water percolate through the sand until a less permeable material is reached and the water then travels laterally toward the bluff face. In some cases relatively large semi-circular ravines are cut along the bluff top due to this process. An excellent example of this (Fig. 15) is just north of Grant Park in southern Milwaukee County.

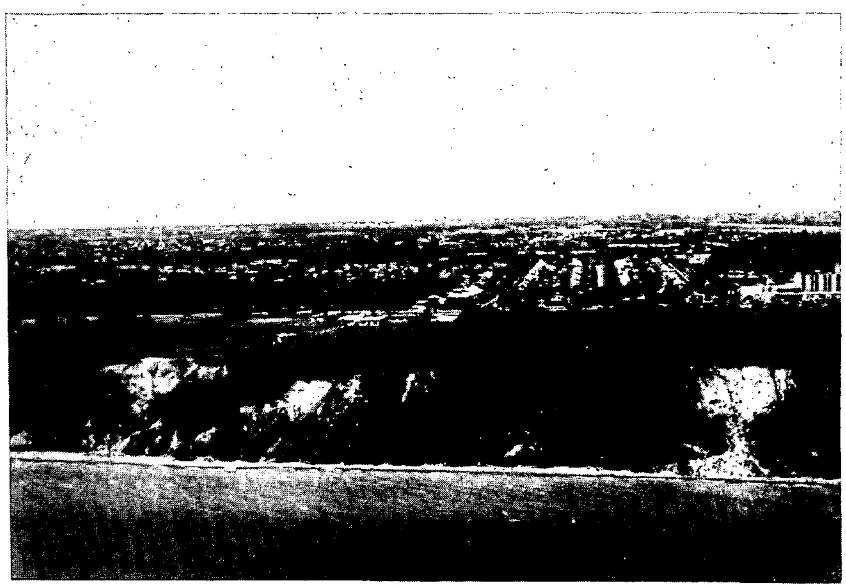


Figure 15. Oblique aerial photograph showing failure taking place because of groundwater sapping beneath sand. Water enters the groundwater system through sand which is the surface material here and flows outward along fine-grained material. Sand is then carried by flows to the beach as groundwater discharges along the edge of the bluff. Location is T. 6 N., R. 22 E., Section 36, Reach 8, Milwaukee County (oblique R-20, 34).

Effects of Vegetation

The presence of vegetation, especially forest vegetation, along the bluff face indicates fairly long term stability. Bluff faces in the protected terrace areas (Fig. 16) show a nearly continuous vegetation cover and very little evidence of active slope failure. It should be noted that the vegetation cover is present because the toe is not being undercut and because the slope is stable and not that the slope is stable because of the presence of vegetation. The presence of vegatation does affect the amount of erosion that takes place by sheet wash or overland flow of rain water. It probably also has some effect in decreasing slow types of mass movement such as soil creep. The vegetation will not, however, decrease the amounts of bluff recession that are due to sliding and relatively deep-seated slumps unless the toe of the slope has been protected and the slope angle has reached a fairly stable position.

Changes in Slope Failure and Bluff Recession through Time

Changes in rates of bluff recession and types of slope failure take place over time. Lake level fluctuations change rates of toe erosion. In addition, styles of failure on the bluffs change over even shorter periods of time.

It has been shown (for example, Berg and Collinson, 1976) that high water levels in the Great Lakes cause more rapid recession of the bluffs. When water level is low, wave energy is expended as waves break along the beach. When water levels rise, waves begin to beat directly on the toe of the bluff and energy from the waves erodes the bluff material. The base of the bluff is then undercut creating unstable conditions in the slope above. This is followed at some later time by slope failure and the movement of material down to the base of the bluff. As water levels in the Great Lakes decrease, the beach again widesn and much of the wave energy is taken up by beach sediment transport. There is a time lag, however, after the water drops because materials in the bluff take time to form a stable slope. It is for this reason that recent that studies (Berg and

Figure 16. Oblique aerial photograph of wooded bluff behind natural terrace. Most of the terrace edge is protected from erosion by revetments. The bluff behind the terrace is stable. Location is T. 8 N., R. 22 E., Section 21, Reach 10, Milwaukee County (oblique R-16,27).

Collinson, 1976) have shown that there is about a 4-year time lag between water level highs and corresponding high rates of erosion and water level lows and corresponding low rates of erosion along the Illinois shoreline of Lake Michigan. Thus, even after water levels begin to fall and wave erosion is decreased, bluff recession continues at a fairly high rate until the bluffs have reached a stable slope angle. It can be seen then that knowledge of the nature of the material in the bluffs and the kinds of failures that are taking place is important in determining any short-term measures to reduce the rate of bluff retreat.

Short-term changes in rates of toe cutting and bluff retreat also occur. During the winter, ice often protects the toe from wave erosion and relatively little cutting takes place. In spring, melting of intergranular ice produces wet conditions and shallow slides and flow are common. Edil and Vallejo (1977, in press) have done detailed studies of bluff retreat at Port Washington and Kewaunee. They suggest that in moderately high bluffs at Kewaunee where the middle and lower bluffs consist of silty clay, slope evolution is by nearly parallel retreat in the middle parts of the slope, caused by shallow translational slides and flow (Fig. 17). Port Washington, where higher bluffs occur, the slope seems to begin evolution by a series of slumps working their way from the toe up to the bluff top. This changes a convex bluff profile to a concave one with a steep top and a flatter lower portion (Fig. 18). The next phase is retreat takes place by slumping in the upper parts of the bluff terminating in a uniform slope.

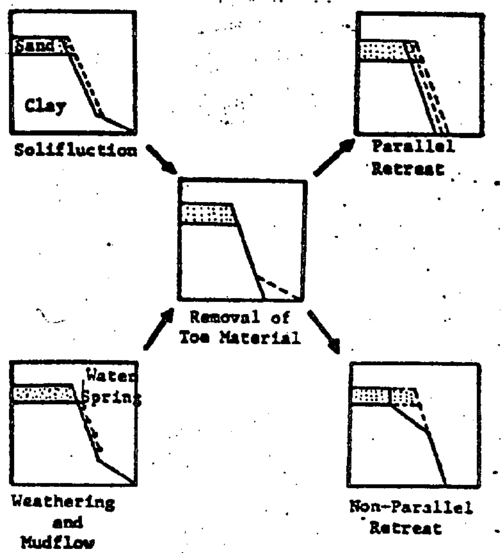


Figure 17. Diagramatic sketch of slope evolution along the bluffs at Kewaunee, Wisconsin (from Edil and Vallejo, in press).

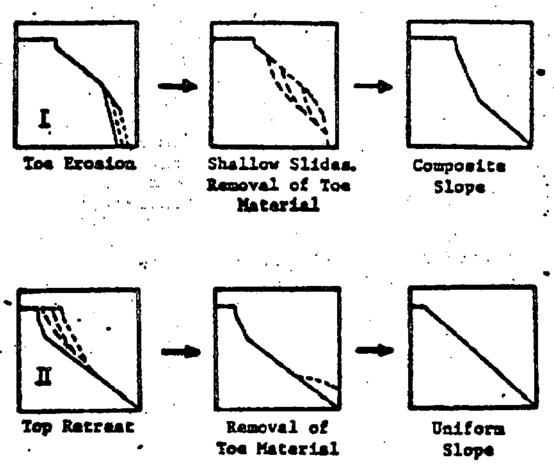


Figure 18. Diagramatic sketch showing slope evolution along the bluffs at Port Washington in Ozaukee County (from Edil and Vallejo, in press).

GENERAL SHORELINE CONDITIONS

Throughout the reaches studied during this investigation, a wide variety of shoreline types and associated erosion processes were described. Although detailed information about specific localities is available in the appendices and should be used if available, in this section we discuss general shoreline conditions of Lake Michigan and Lake Superior, and provide some specifics on reaches examined in detail.

Very little of the shoreline is bedrock. In Bayfield County, especially on the Bayfield Peninsula, bedrock makes up the lower or sometimes the complete bluff. This bedrock, primarily Precambrian-age sandstone, is somewhat more resistant to wave erosion than the unconsolidated glacial desposits. There are, however, areas where erosion of the sandstone is taking place. Similar sandstone bluffs occur on Madeline Island and other of the Apostle Islands. Paleozoic age dolomite bedrock outcrops occur on the beach in a few places in Racine, Milwaukee, Sheboygan, and Manitowoc Counties, but bedrock does not make up a substantial amount of the bluff in any of those areas. In Door County numerous bluffs are made up of dolomite, but these areas were not studied in this project.

Since past glaciation is primarily responsible for the presence of bluff materials, the glacial history of the Great Lakes is discussed before the individual reach descriptions.

Glacial History

The Great Lakes basins were deepened and widened during glaciation which took place over the last one to two million years. Glaciers flowed out of the north and northeast down the Lake Michigan basin into Illinois, down the Green Bay-Lake Winnebago lowland to a position near Madison, and down the Lake Superior basin into northern Wisconsin and Minnesota (Fig. 24). Successive ice advances and retreats have left a series of unconsolidated deposits which, except in the bedrock areas of Door County and the Bayfield Peninsula, make up the bluff materials. Lakes larger than today's formed in the basins between each succeeding glaciation and so the layering which is observed in the bluffs records a geologic history of alternating lakes and glacial cover. In some places where glacial deposits are relatively thick or are at higher elevations, the height of the bluff is well over 100 feet. In other places where glacial deposition and erosion left the land surface at lower elevations the bluff heights are considerably lower or are nonexistent.

Lake Michigan

Although numerous ice advances contributed to the formation of the Lake Michigan basin, only the last few have left a record of deposits which are now exposed in the eroding bluff. Materials deposited directly by glacial ice are called till. Till is usually poorly sorted (has a large range in grain size) and it usually does not show stratification or layering that is typical of water-deposited sediment. The till deposited by a single ice advance is usually relatively uniform over a fairly large area and thus mapping and correlation of the tills allows the development of a stratigraphic framework which gives some order and predictability to the aerial and vertical distribution of deposits.

Details of the distribution of glacial deposits in the area along Lake Michigan are given in Alden (1918), Goldthwait (1907), Thwaites and Bertrand (1957), Brunning (1970), and Mickelson and Evenson (1975). Many tills have been named in Illinois (Willman and Frye, 1970; Lineback, Gross, and Meyer, 1974), but in this report tills will be numbered and correlation with Illinois tills will be suggested. A summary of these units is shown in Figure 19. Grain size of the tills is given in Figures 83, 84, 85.

The oldest till exposed along the Lake Michigan shoreline is a coarse, sandy till (usually over 40% sand) with a large number of cobbles and boulders (till 1A, Fig. 19, 20, 21). This was probably deposited before 14,000 years ago, and probably correlates with the Haeger till of Illinois. In the southern part of

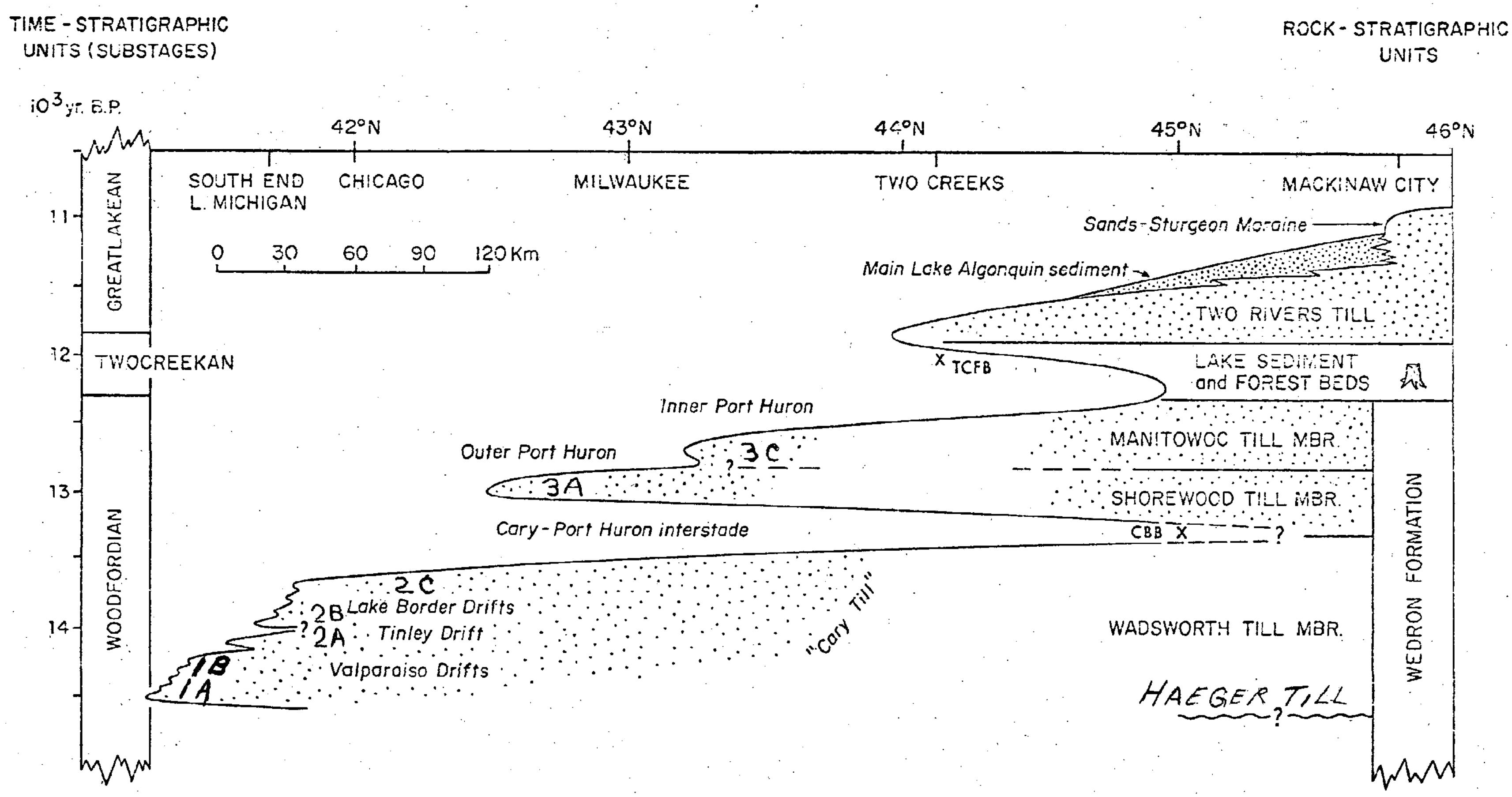


Figure 19. Time distance diagram showing the extent of glacier ice in the Lake Michigan basin during late Wisconsin time. Terminology used on the right is that used in Illinois, with the exception of the Two Rivers till which has been formally named in Wisconsin. The numbered units are used informally in this report. Note that distances of advance are in center of lake and extent on Wisconsin shore is somewhat less than shown. Modified from Evenson (et al., 1976).

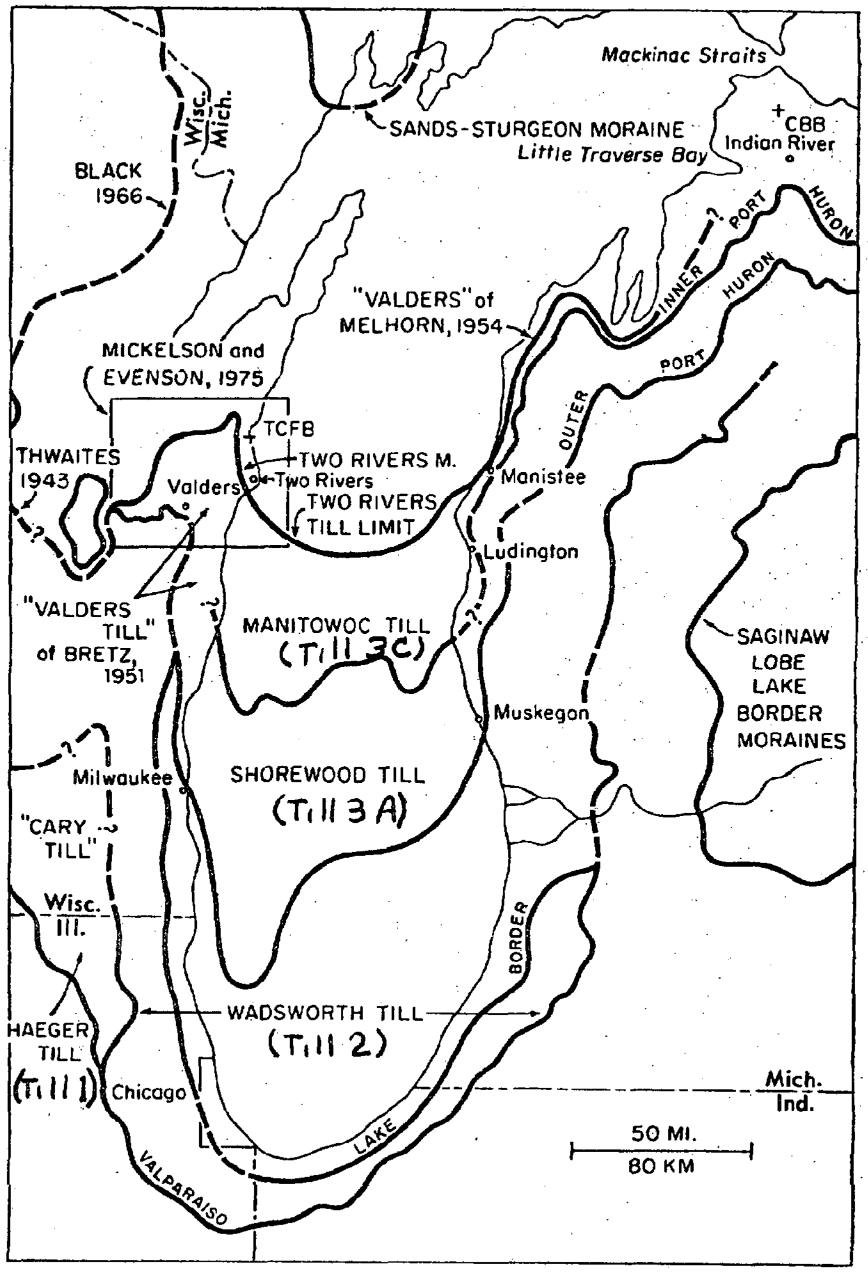


Figure 20. Map of the Lake Michigan basin showing the approximate extent of tills mentioned in this report. Modified from Evenson et al., 1976.

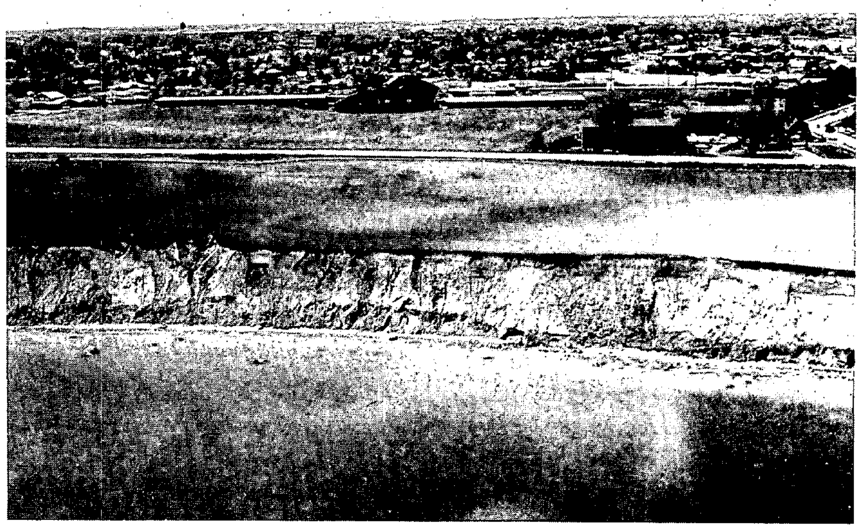


Figure 21. Oblique aerial photograph of the bluff showing beach littered with boulders where till 1 is exposed at the base of the bluff. Location is T.6N., R.22E., Section 24, Reach 8, Milwaukee County (oblique R-20, 14).

the state, in Racine and Kenosha Counties, this till is below lake level and the southernmost exposure of the till is just south of the city of Milwaukee in Reach 8, Sections 23 and 24 (see next chapter). Here it is exposed in the lower 10 feet of the bluff where it contributes a great deal of coarse material to the adjacent beach (Fig. 21). North of the city of Milwaukee, till 1 is exposed more commonly near the base of the bluff all the way into Kewaunee County.

Till 1B, a thin, grey, usually sandy-silty till (Fig. 19) directly overlies till 1A at many localities. This till is generally much less cobbley and bouldery than 1A. It is usually only 6-10 feet thick. It is not clear whether a till correlative with this occurs to the south in Illinois or on the surface west of Lake Michigan in Wisconsin. Since no large amount of lacustrine sediment has been seen between tills 1A and 1B, they may represent the same episode of glaciation. As the ice which deposited this till retreated into the lake basin an ice marginal lake existed for a short period of time throughout the area of the present lake. However, another glacial advance which took place approximately 13,500 years ago came out of the lake basin at all points and destroyed much of the evidence of these former lakes. This later advance deposited a much finer grained till, (till 2), probably because of the incorporation of the lake sediments which had been deposited earlier (Fig. 19). This till (till 2) is called the Wadsworth till in Illinois and it makes up much of the bluff in Kenosha, Racine and Milwaukee Counties. It is also present, although much thinner, towards the north at least into Ozaukee County. The ice advance which deposited the Wadsworth till was actually probably several ice advances very closely spaced in time and in some places lake sediment is between nearly identical till units (Fig. 19).

Units A, B, and C of till 2 can be distinguished in some places such as southern Milwaukee County (see next chapter) but, because the units are so nearly identical, they cannot be separated without physically tracing the units. In northern Racine County and north of Milwaukee, exposure is insufficient to subdivide the units within till 2. For all practical purposes, the units are the same as far as their physical and engineering properties.

As the glacier which deposited this till retreated into the northern part of Lake Michigan Basin, a lake (called Glacial Lake Chicago) filled the southern part of the basin and drained through an outlet near Chicago into the Mississippi River. The elevation of the highest shoreline features and lake deposits from this lake are now at an elevation of 640 feet (called the Glenwood Stage, Fig. 22) or about 60 feet above the present lake level. Fairly well developed beaches are present in Racine and Kenosha Counties and also in southern Milwaukee County where they exist as ridges of sand roughly parallel to the 640-foot contour. Thus, all of the bluff south of Milwaukee which is at an elevation of less than 640 feet has till 2 capped by sediments deposited in this lake. The grain size of the sediments varies from sand near the edges of the former lake to silts and clays which were deposited in deeper, quieter water.

Approximately 13,000 years ago glacier ice again advanced (Fig. 19) down the Lake Michigan basin and this time stopped just at the city of Milwaukee. The texture of the till of this advance (till 3A) is roughly the same as that of till 2 although it has more sand and a reddish cast which is not present in Racine and Kenosha Counties (Fig. 19). South of the glacial border of this so-called Port Huron advance (Fig. 22), glacial Lake Chicago remained at the Glenwood (640') level throughout the time ice was in the Lake Michigan basin. Another similar reddish till (till 3C) was deposited by a slight readvance of ice very shortly after this. In a few places between (see reach reports) a sandy unit (till 3B) exists. This may represent a readvance of ice or simply debris dropped from floating ice.

As the ice finally retreated out of the northern part of the basin a new outlet developed at the Straits of Mackinac and the level of the lake dropped from the Glenwood Stage to some level below present water level. At this time

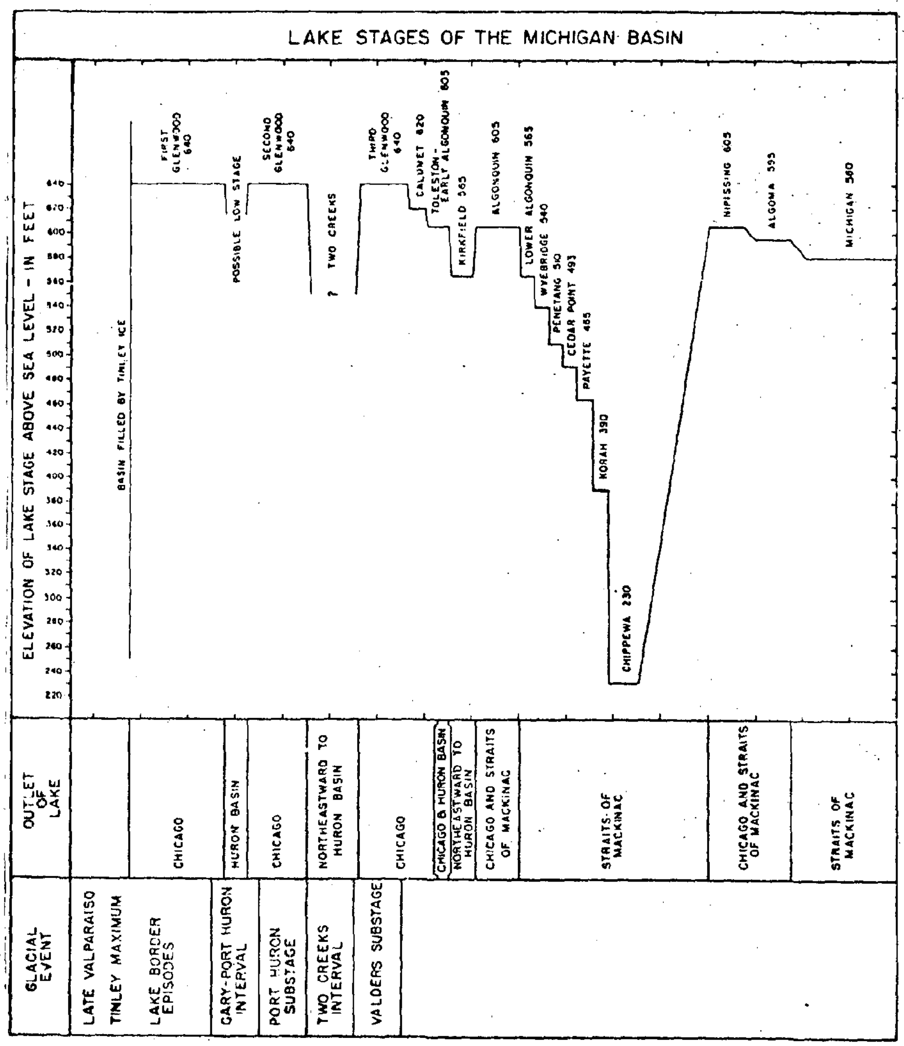


Figure 22. Diagrammatic sketch showing the fluctuation of lake levels in the Lake Michigan basin after the retreat of glacier ice. From Hough, 1958.

(about 12,000 years ago) spruce forests were present along the edge of Lake Michigan and as ice again advanced into the Lake Michigan basin near the Straits of Mackinac, the northern outlet was blocked and the water level rose flooding the spruce forest and killing the trees. Parts of this buried forest are preserved today in the lake bluff in Manitowoc and Kewaunee Counties (Black, 1970). At one location at the Manitowoc-Kewaunee county lines (Black, 1974) this Two Creeks forest bed is being preserved as a state park. When lake level rose again it probably returned to the Glenwood level, but while ice was still at its terminal moraine near the city of Two Rivers the water level dropped to the lower Calumet stage at approximately 620 feet (Fig. 22). The level of the lake did not rise again to the Glenwood level; thus, there are no Glenwood shorelines north of the city of Two Rivers (Fig. 23). This ice advance (Fig. 19) which covered the Two Creeks forest bed deposited a clayey, red-brown till (Two Rivers Till) with very few pebbles or coarse material. After about 11,000 years ago ice retreated from the Lake Michigan basin for the last time.

Since that time, lake levels in Lake Michigan have fluctuated because of changes in outlet position, erosion of the outlets, and changes in elevation of the outlets due to glacial rebound. Although for short periods of time the lake was at a variety of different levels the best beaches that developed in these later lake stages are at an elevation of about 605 feet (Fig. 22). These were cut during three stages of Lake Michigan, the Toleston stage, the Algonquin stage, and the Nipising stage. At the present time, old lake bluff and a wave cut terrace at this elevation at some locations. Most of the terraces which are 15 to 20 feet above present lake level in the Lake Michigan counties are due to erosion at this time.

Lake Superior

Early glacier advances of the Lake Superior lobe into northern Wisconsin deposited a sandy, bouldery till much like that deposited in the 15,000 year old

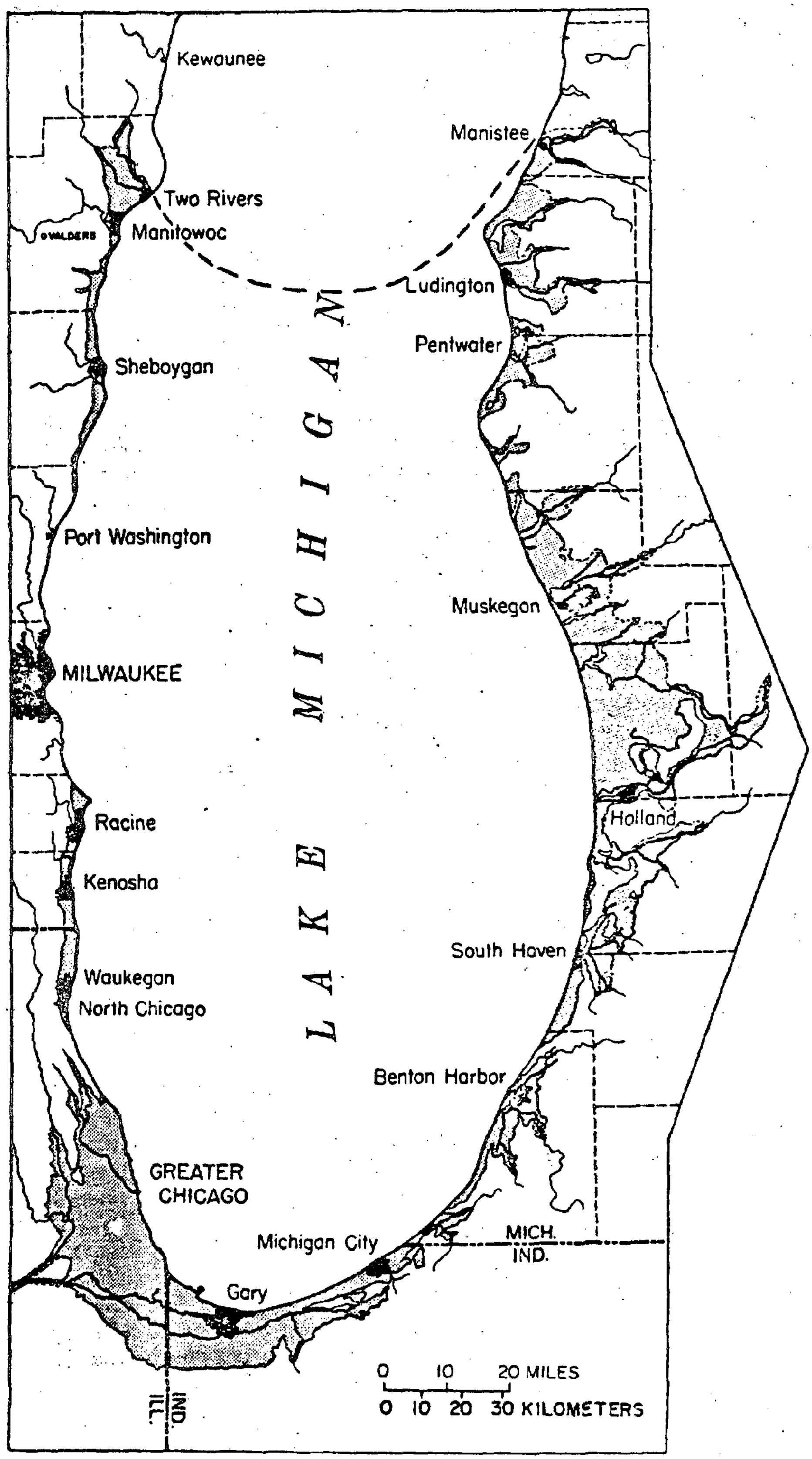


Figure 23. Map showing the extent of the Glenwood Stage (640' elevation) of Glacial Lake Chicago. The dashed line represents the furthest extent of ice which deposited the Two Rivers till and destroyed earlier beaches at this elevation. From Evenson, 1973.

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Wisconsin Coastal Management Program

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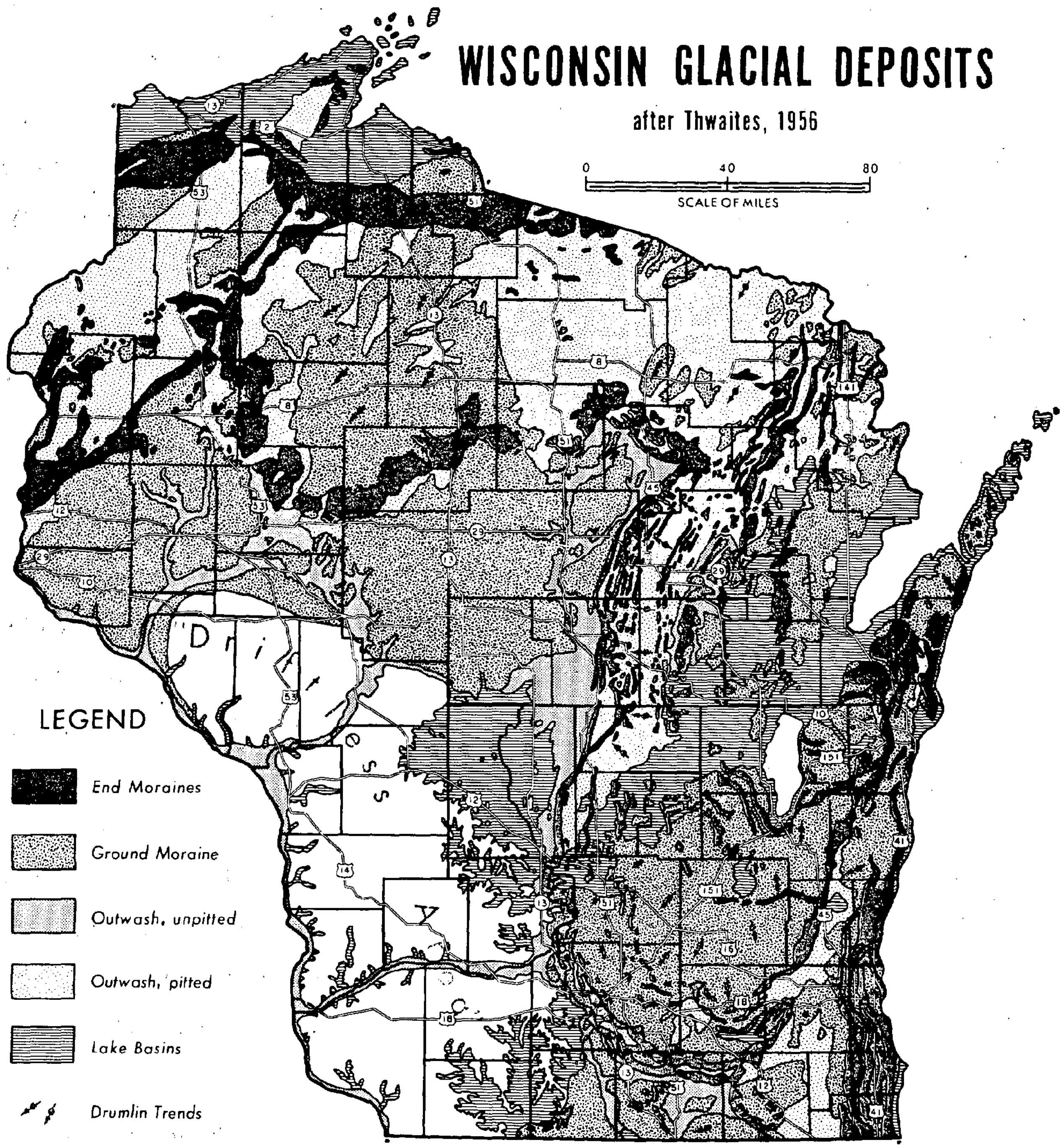
advance in the Lake Michigan basin, except that it is red-brown instead of buff in color. This till extends to a terminal moraine which enters the state from Minnesota near the town of Hudson and continues eastward just north of Eau Claire to the town of Antigo in Langlade County (Fig. 24). Although the date of this advance is not confirmed, radiocarbon dates in Minnesota (Wright, 1971) suggest that ice was at its terminal position between 16,000 and 18,000 years ago. As in the Lake Michigan basin, the ice retreated from its maximum position in a series of steps with minor readvances between. Most of the till present along the shoreline of Lake Superior in Wisconsin is more clayey and silty than earlier tills and was deposited during these later stages of ice retreat. The extent of these readvances has been well documented in Minnesota (Wright, 1969), but relatively little is known about the extent of these advances in Wisconsin, although some work has been done (e.g., Leverett, 1929; Farrand, 1969; Mengel, 1970).

At some point during the retreat of glacial ice, a lake called Glacial Lake Duluth (Fig. 25) formed along the ice margin and this lake was present throughout much of late glacial time in the Lake Superior basin. The highest shorelines of this lake exceed 500 feet above present lake level and can be seen on topographic maps in Douglas, Bayfield and Ashland Counties. In this areaa thick sequence of lake sediment primarily composed of silt and clay makes up the bluffs. In some locations the underlying till is exposed fairly close to water level. Compared to Lake Michigan very little coarse material is available to the longshore dirft system within the lake, and with the exception of areas around incoming streams, shoreline erosion is prevalent in the areas where unconsolidated material makes up the bluff.

The great extent of fine-grained lake sediment and till back from the shoreline creates a large volume of suspended material which enters the stream system and then enters Lake Superior. Silts and clays in the eroding bluffs also contribute

Figure 24. Glacial map of the state of Wisconsin. Note the extent of lake sediment around the Lake Superior shoreline.



University of Wisconsin

Wisconsin Geological and Natural History Survey

George F. Hanson, Director and State Geologist

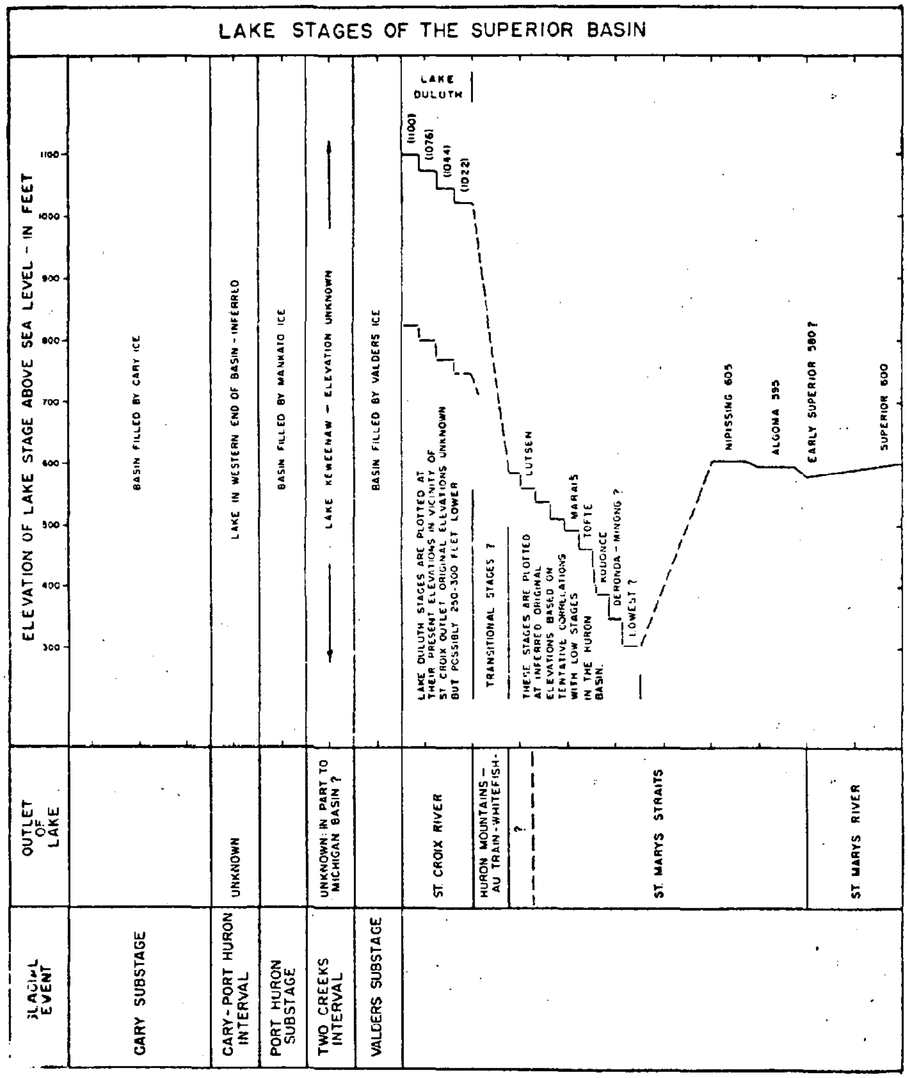


Figure 25. Diagrammatic sketch showing the fluctuations of lake levels in the Lake Superior basin from glacial time to present. From Hough, 1958.

to a high-suspended sediment load in coastal Lake Superior water, especially off Douglas and western Bayfield Counties.

Glacial Lake Duluth did not rise and fall in a series of stages as Lake Michigan did, but remained at a fairly high level (about 1,000 - 1,100 feet above sea level along the Wisconsin shoreline) (Farrand, 1969) while drainage from the lake went through the St. Croix River system and into the Mississippi drainage. As the retreating glacier ice reached the Keweenaw Peninsula water from the ice-dammed lake began to drain across the Michigan Peninsula and into the Lake Michigan basin. A minor readvance, possibly correlative with the post-Two Creekan readvance in the Lake Michigan basin evidently took place at about this time because in eastern Ashland and Iron Counties a thin, red-brown, clayey till overlies the lake sediment in the bluff.

As the ice continued to retreat lake levels in Lake Superior dropped in a series of short-lived stages (Fig. 25) to an unknown level when water began draining out the present Lake Superior outlet. By this time glacier ice had retreated from the Lake Michigan basin and Lakes Michigan and Superior stabilized at a level of 605 feet (Nipissing stage). Since that time lake level probably dropped for a few thousand years and then has risen to its present level of about 600 feet above sea level. Throughout much of the lakeshore, lake level continues to rise very slowly (with fluctuations due to climate) because of the glacial rebound of the lake outlet.

REACH DESCRIPTIONS

This chapter includes a general description of the shoreline from the Illinois state line to Manitowoc on Lake Michigan and the Wisconsin part of the Lake Superior shoreline. Much more detailed information is available in county appendices (see list of appendices at beginning of this report) which can be obtained from the State Planning Office.

Reach 1

Erosion reach 1 of the Lake Michigan shoreline is located in southern Kenosha County, in Township 1 North, Range 23 East (Fig. 26). The reach is about $4\frac{1}{2}$ miles long and extends from the Illinois state line on the south to the Kenosha city limits on the north; it thus includes the entire stretch of shoreline known locally as Carol Beach. This $4\frac{1}{2}$-mile segment is considered to be the most critical reach of the entire Lake Michigan coast in terms of shore damage and recession rates; it has the highest priority of all reaches, with a per-mile value of 32. The reach is discussed in detail in Appendix 1.

The northernmost half-mile of the reach is owned by the Wisconsin Electric Power Company and is currently unused except by trespassing motorcycle enthusiasts, who have desecrated a beautiful and scientifically valuable coastal area of sand dunes and natural prairie. Except for this power company property and the Trident Marina development at the extreme south end of the reach, the entire reach is subdivided into residential lots. Although the density of houses is considerably lower than in some other non-urban segments of the shoreline, new home construction was very apparent during the summer of 1976. In contrast, during the past few years a number of houses have been destroyed as a result of shoreline recession or have been relocated in order to prevent their destruction.

Beach widths in Reach 1 range from 0 to about 110 feet. Variations in beach width over short distances are common throughout the reach, most of the changes being controlled by shore protection structures. In one area, for example, the

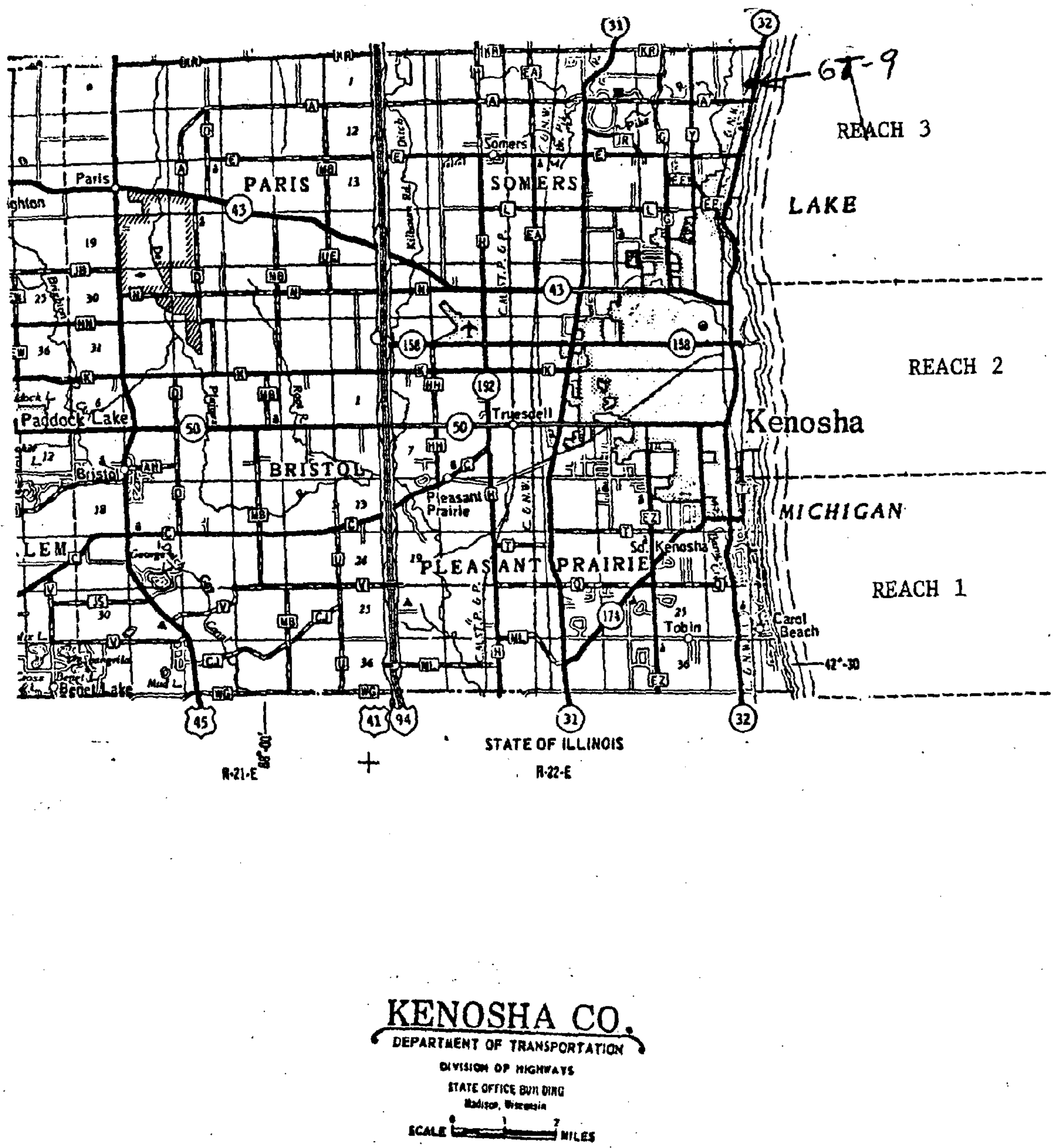


Figure 26. Map of Kenosha County showing the locations of Reaches 1, 2 and 3, and geotechnical site 9.

beach widens from 15 feet to 110 feet in less than a quarter-mile; at another locality, the width increases from 10 to 100 feet in a still shorter distance. In both situations virtually no beach is present immediately to the north or south. Man's extensive modification of the shoreline is largely responsible for those changes. Natural beach materials everywhere consist mostly of sand with smaller quantities of gravelly constituents (pebbles and small cobbles).

The bluff in this reach is low. Typically, it is only 4 or 5 feet high and nowhere does its height exceed 20 feet. In many places a bluff, as such, does not actually exist, the rise from lake level to the upland surface being nothing more than a gentle beach slope. In other places, however, a distinct bluff is present, generally ranging in height between 5 and 10 feet. The highest bluff occurs in section 17 at the north end of the Carol Beach area adjacent to the power company property, where the bluff is 18-20 feet high.

Throughout this entire reach, the bluff is composed of fine-to coarse-grained sand. Genetically, most of the sand is beach sand deposited during an earlier and higher lake stage (Fig. 22), but in some places, particularly where the bluff is higher, the upper part of the bluff is made of dune sand. Thin organic horizons, mostly organic sands, are interbedded with the beach sands at several exposures. No deposits of till or fine-grained lacustrine deposits were observed in any of the bluff exposures.

Shore protection structures are very abundant in Reach 1. Approximately 175 such structures were identified and described, despite the fact that a single structure--a newly constructed dolomite rip-rap revetment--protects the shore for the full half-mile of the electric company's shoreline at the northern end of the reach. For the remaining 4 miles of the reach, the density of protective structures averages about 42 per mile; in one section alone (section 17) there are nearly 60 individual shore protective devices. This is undoubtedly the highest density of individual structures along the entire Wisconsin coast.

Slope failures in Reach 1 occur mainly through the mechanism of slump, induced by oversteepening of the bluff face by wave action at the toe. As a result, the bluff edge in many places is finely scalloped, particularly where shore protection structures are absent. Sand slides and sandflows do not appear to present a severe problem, despite the presence of seep zones within the sand units that compose the bluff.

Reach 2

Reach 2, in Townships 1 and 2 North, Range 23 East, covers 3 miles of shoreline in central Kenosha County (Fig. 26). It is virtually coextensive with the City of Kenosha, extending from the southern end of Southport Park northward through the downtown and harbor area to the north end of Lake View (Kennedy) Park. The entire shoreline is protected with stone revetments and other structures, with the exception of short segments of public bathing beaches at Southport and Simmons Island Parks. For this reason and also because of the low rank accorded this reach--priority rank number 28 with a per mile value of 4, the only part examined systematically was a half-mile stretch of shoreline at Southport Park. Data on beach conditions and shore protection structures were also obtained in Eichelmann Park. These are given in Appendix 1.

Except for the bathing beach area, where the beach is 50 to 100 feet wide, no beach is present in the Southport Park segment. The bluff is only 5 to 10 feet high, and both bluff and toe materials are everywhere concealed by a continuous stone revetment. Although materials are not exposed, the bluff is probably composed of sand. The segment is marked by approximately 12 additional structures, most of which are old groins that are today largely non-functional and in need of repair. Small areas of sand accumulation are found adjacent to one or two of these groins, but even here the beach is less than 5 feet wide.

Reach 3

Erosion reach 3 of the Lake Michigan shoreline is located in northern Kenosha and southern Racine Counties, in Townships 2 and 3 North, Range 23 East (Fig. 26). It is one of the longer reaches of the shoreline, having a grid length of exactly 6 miles and an actual shoreline distance of approximately $6\frac{1}{2}$ miles. Geographically, the reach can be thought of as a suburban coastal corridor that connects the City of Kenosha on the south with the City of Racine on the north. Except for only three or four small areas, including the Town of Mount Pleasant fire station and park property near the north end, the entire northern three-fourths of the reach is subdivided; most of the lots are occupied by single-family residences, but a few are used for apartments and small businesses. Immediately to the south is the campus of Carthage College, which extends along the shoreline for a distance of more than one-half mile; the rest of the southern quarter is reserved for recreational use and is the site of Alford and Pennoyer Parks, which together are about 6,000 feet in length.

Reach 3 was ranked as the ninth most critical stretch of Wisconsin's Lake Michigan shoreline, with a per mile value of thirteen. In view of the considerable property damage and shoreline recession that is currently taking place throughout much of this reach, it would appear that the reach should be assigned a somewhat higher priority. Details on the reach are given in Appendix 1.

Beach conditions in this reach are extremely variable. Beach width, in particular, exhibits great variability, ranging from complete absence of a beach in many places to the presence of an extensive beach that exceeds 275 feet in width. The most marked change in conditions occurs near the south end of the Carthage College campus, approximately 6,000 to 6,500 feet north of the southern boundary of the reach. North of here the beach generally ranges from 0 to 40 feet high, but at the south end it is generally 10 feet or less in height. Whereas the bluff is virtually continuous throughout most of the reach, in the southernmost mile it is distinctly discontinuous, as a result of the upland surface near the shoreline having been narrowed and in places completely removed by normal erosional processes near the mouth of the Pike River.

Bluff and toe materials in this reach also exhibit a systematic change from north to south. In the upper part of the reach the lower two-thirds to three-fourths of the bluff is composed of calcareous silty clay till (till 2); the till is overlain by interbedded fine sands, silts, and clays of lacustrine origin (Fig. 27). Nearly one mile south of the Racine-Kenosha County line the till-lacustrine contact descends to lake level, with a corresponding thickening of the lacustrine sediments, and thence disappears below lake level to the south (Fig. 27). Still farther south, the lacustrine deposits tend to become more massive in character and also finer grained. The bluff is everywhere capped by fine to coarse-grained sand deposits, which were probably deposited in a beach environment. At the southern end of the reach, however, the low bluff appears to be composed almost entirely of sand, suggesting that the contact between the sand and the underlying lacustrine sediments has also dipped below modern lake level.

Shoreline protection structures are very abundant in the northern three-fourths of reach 3. Approximately 180 individual structures were identified and described in the 5-mile segment of shoreline that lies north of Carthage College. These structures consist of a great variety of both shore-parallel and shore-normal devices, as well as earthen and man-made materials used for fill. The Carthage campus is protected by a continuous dolomite rip-rap revetment. South of here, in Alford and Pennoyer Parks, modern shore protection structures are absent, the only structures being a series of 40-year old semi-permeable groins that are largely destroyed or buried beneath the broad accretional beach deposits described above.

Except for the Alford and Pennoyer Park areas, shoreline recession and slope failure are serious problems throughout the entire reach. Some houses have, in fact, collapsed during the course of the present study and many additional homes

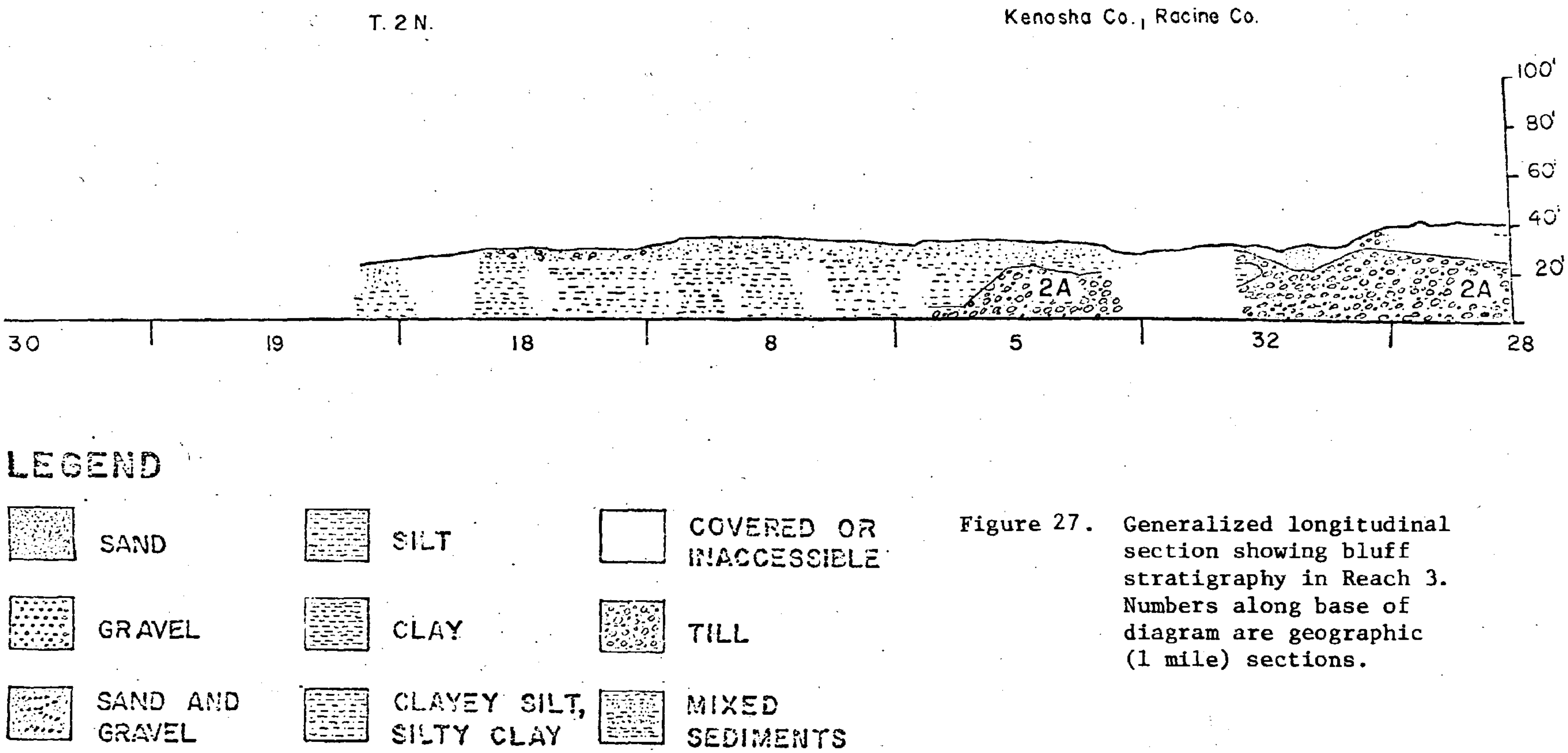


Figure 27. Generalized longitudinal section showing bluff stratigraphy in Reach 3. Numbers along base of diagram are geographic (1 mile) sections.

situated near the bluff edge are in danger of being destroyed within the near future. Toe erosion by wave action, gully cutting by small streams and by storm-water drainage spilling over the bluff, rotational and planar motion of small to moderate size slump blocks at the bluff edge, sapping and undercutting within the bluff caused by water issuing from the more permeable layers--especially at the contacts between layers of differing permeability within the lacustrine sequence, and mudflows in the clay-rich till and fine-grained lacustrine sediments are all active mechanisms of slope failure in this reach.

Reach 4

Erosion reach 4 extends through the southern and central parts of the city of Racine in Township 3 North, Range 3 East, Racine County (Fig. 28). It is approximately $3\frac{1}{4}$ grid miles and 3 3/4 shoreline miles in length. The northern two-thirds of the reach is marked by continuous shore protection structures, principally in the form of offshore breakwaters and shoreline revetments. These structures provide protection for the Racine harbor facilities and industrial sites on the north, Pershing Park and the downtown business district in the central part, and residential properties farther south. As a direct and indirect consequence of these structures, reach 4 received a relatively low priority for the purpose of this study, ranking twenty-ninth on the priority list with a low value per mile figure of three. Accordingly, only the southern half of the reach was examined in our investigation and the following summary of conditions is restricted to this portion. The northern and southern parts of this segment are residential in character, with the longer intervening strip being occupied mostly by the City of Racine sewage treatment plant and the J. I. Case Co. tractor plant. Detailed maps are given in Appendix 2.

Most of the shoreline has no beach, mainly because of man's past and current activities. For the most part, the shore is armored with extensive stone (dolomite) revetments constructed at the base of the bluff and steel (sheet piling)

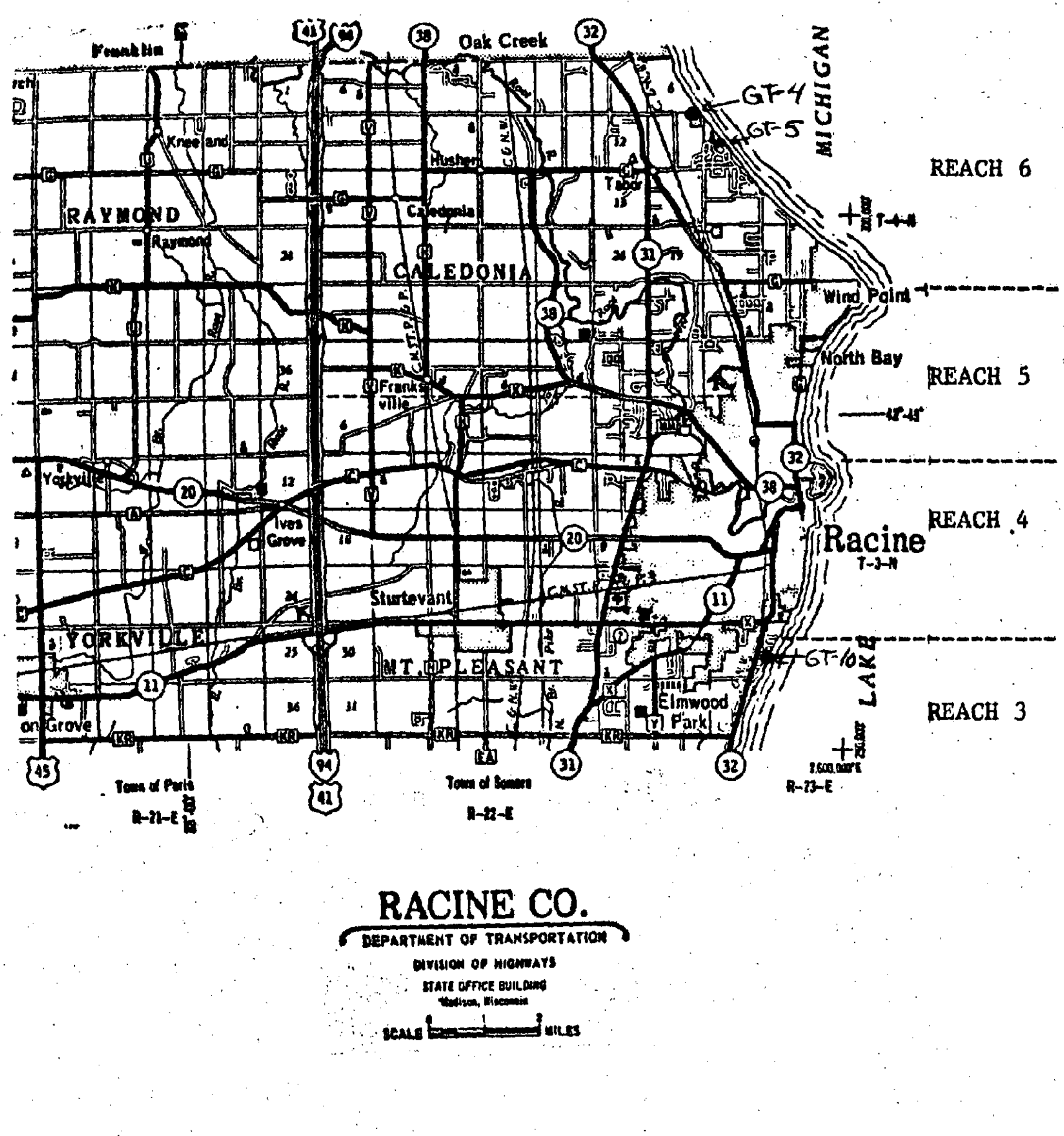


Figure 28. Map of Racine County showing the locations of Reaches 3, 4, 5 and 6, and geotechnical sites 4, 5 and 10.

bulkheads built some distance offshore and completely backfilled to form made land. In some places, however, notably south of the Case tractor plant, a narrow and discontinuous beach does exist. Nowhere was it found to be more than 10 feet wide and generally it is between 0 and 5 feet in width. Beach materials consist of gravel, broken concrete, stone, broken asphalt, dead trees, old lumber, cinders, iron, and slag from the old Case foundry.

The height of the bluff in the southern part of reach 4 nearly everywhere is about 40 feet. Bluff materials and toe materials in all but the southernmost 1,500 feet of the reach appear to consist mostly of artificial fill composed of stone, brick, glass, concrete, iron, slag, and garbage. In places where natural deposits can be seen, chiefly at the south end of the reach, the bluff is made of inter-bedded clays, silts, and sands of lacustrine origin overlying calcareous gray silty clay till (till 2). The contact between the till and the overlying lake sediments occurs about a third to half-way down from the top of the bluff (Fig. 29).

Although much of the bluff has been graded and grassed and appears to be fairly stable, slope failure is evident in several places. It is most severe along the virtually unprotected shoreline south of the Case factory at the southern end of the reach. Much of the failure is directly related to the presence of multiple seep zones within the more permeable beds, especially the sand layers, in the lacustrine sequence, particularly where the more permeable layers rest on the clay till and on a massive pink clay layer in the lower part of the lacustrine unit. Failure occurs mainly in the form of flows and small slump blocks. Toe erosion is also an important erosional process.

Reach 5

Reach 5 runs through the northern part of the City of Racine, through the village of North Bay, and about half-way through the village of Wind Point, in Townships 3 and 4 North, Range 23 East, extending from the north end of the Racine harbor structure to the mid-line of the Wind Point headland (Fig. 28). The grid

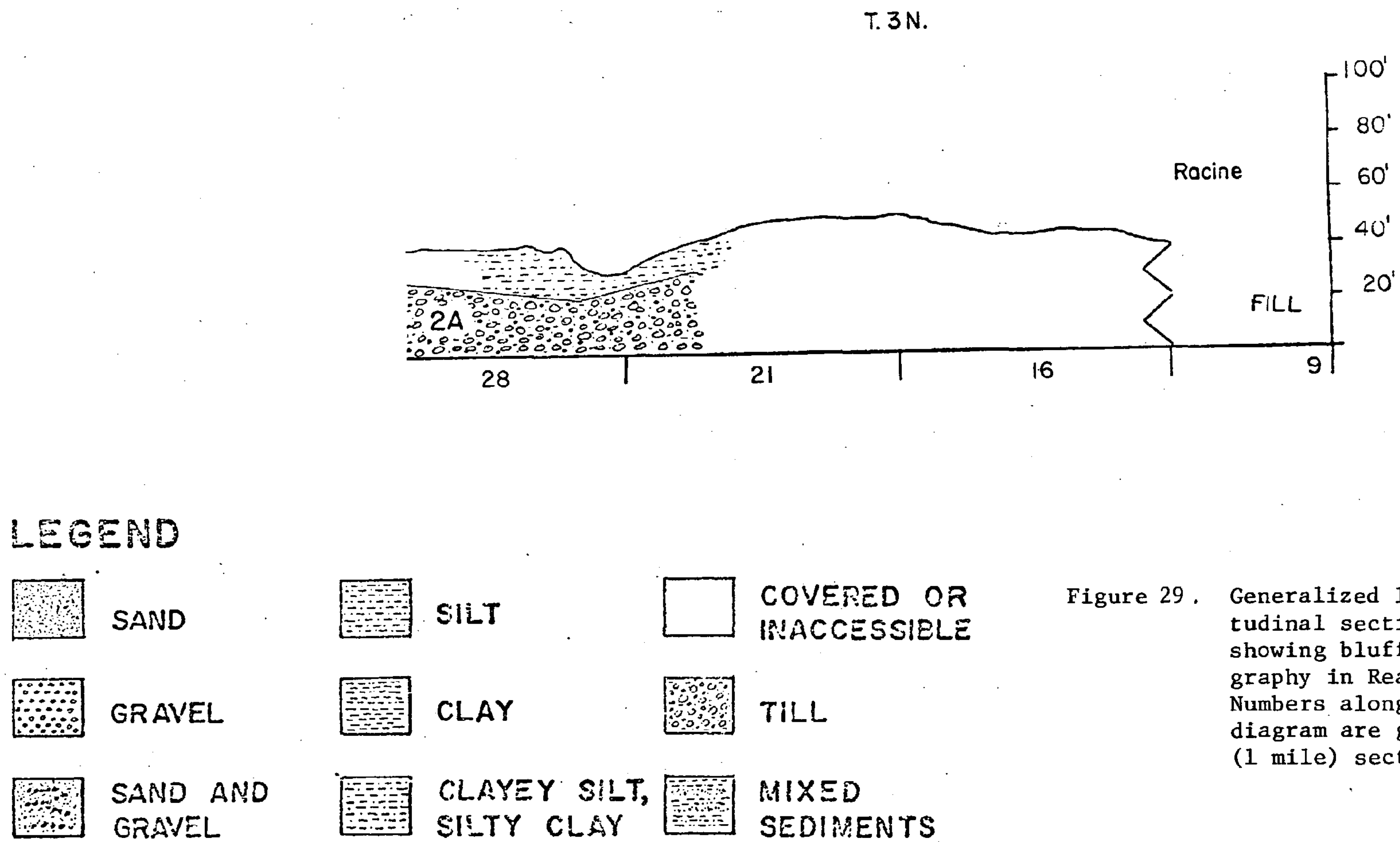


Figure 29. Generalized longitudinal section showing bluff stratigraphy in Reach 4. Numbers along base of diagram are geographic (1 mile) sections.

length of the reach is 3 miles; the shoreline distance is $3\frac{1}{2}$ miles.

About 55% of the reach is public land. The southern mile is occupied by the Racine public beach, Lake View Park, and the Racine Zoological Park. Shoop Park is at the north end of the reach. The remaining 45% of the shoreline is residential in character, with most of the properties in northern Racine and North Bay being in the $100,000-plus category. Reach 5 was rated tenth in the ranking of critical erosion areas, with a per-mile value of 13, the same as Reach 3. Detailed mpas are given in Appendix 2.

The beach in Reach 5 ranges in width from 0 to almost 300 feet. It is widest at the south end, where the north-south longshore current is obstructed and the sand supply is effectively trapped by the harbor structure. Low dune ridges indicate that some of the sand has been reworked by the wind. Northward the beach gradually narrows to zero within a mile. Elsewhere in the reach, however, abrupt and very substantial changes in beach width are common.

Much of the shoreline is heavily armored with various types of shore-parallel and shore-normal protective structures, especially in the residential segment. Approximately 85 such structures were identified and described in slightly less than 2 miles between the Racine Zoo and Shoop Park. The effectiveness of these structures, especially the more recently built groins, is readily apparent from the abrupt changes in beach width and the locations of eroding and non-eroding shoreline segments. Virtually all of the well constructed groins are trapping sand on their updrift (north) sides, and it is this process that accounts for the common and abrupt changes in beach conditions. Poorly protected and unprotected segments of the shore are subject to severe wave erosion at the toe of the bluff, debris fall and flowage higher on the slope, and slump at the top of the bluff; scalloped bluff edges are not uncommon in this reach, even though much of the bluff has been graded and grassed.

Bluff height ranges from slightly under 20 feet to just over 30 feet.

Exceptions occur at stream mouths, in places where the bluff has been terraced or otherwise modified by man, and at the northern end of the reach in Shoop Park. Here the bluff splits, and a low natural terrace separates the shoreline from the main upland surface. At the northern end the terrace is about 750 feet wide. The shore bluff along the terrace is generally between 5 and 10 feet high, but it is virtually absent at the northern boundary of the reach.

Much of the bluff is covered by vegetation, and in many places it is composed of artificial gray (where unoxidized) or tan (where oxidized) silty clay till (till 2) overlain by lacustrine deposits (Fig. 30). At several places a thin layer of water-bearing sand or sand and fine gravel occurs slightly above mid-bluff height, between the till and pinkish-brown lake clay. Water seeping from this horizon, and also from other zones within the lacustrine beds, are undoubtedly a major cause of slope failure involving slump.

Reach 6

Erosion reach 6 is located in Townships 4 and 5 North, Range 23 East, in northern Racine County and southernmost Milwaukee County (Fig. 28). It extends from the mid-line of the Wind Point headland northwestward to the north end of the bulkhead that protects the coal stockpile for the Oak Creek power plant. Although the north-south grid distance of the reach is about 4.6 miles, the coastal distance is fully one-third again as long--more than 6.1 miles-due to the northwest-southeast orientation of the coastline. Detailed maps are given in Appendix 2.

Reach 6 has one of the highest priorities of the entire Lake Michigan shoreline, ranking third in the listing of critical erosion areas, with a value per mile of 25. Land use and shoreline characteristics cover a wide range. Much of the land is residential property, but some is used for agricultural purposes, some is un-developed to partially developed recreational land (including both County of Racine and Town of Caledonia park properties), some is industrial land, and until recently some of the shoreline was owned by educational institutions.

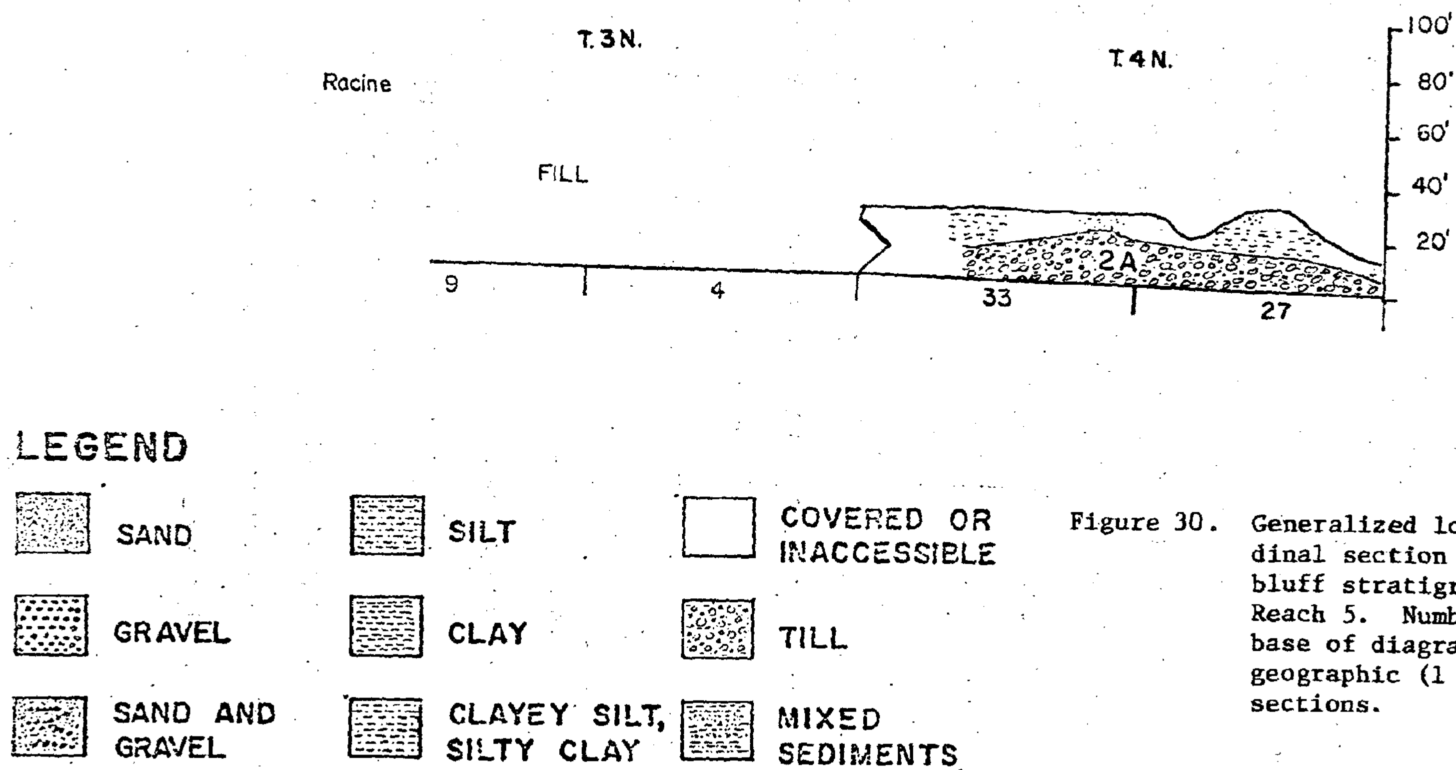


Figure 30. Generalized longitudinal section showing bluff stratigraphy in Reach 5. Numbers along base of diagram are geographic (1 mile) sections.

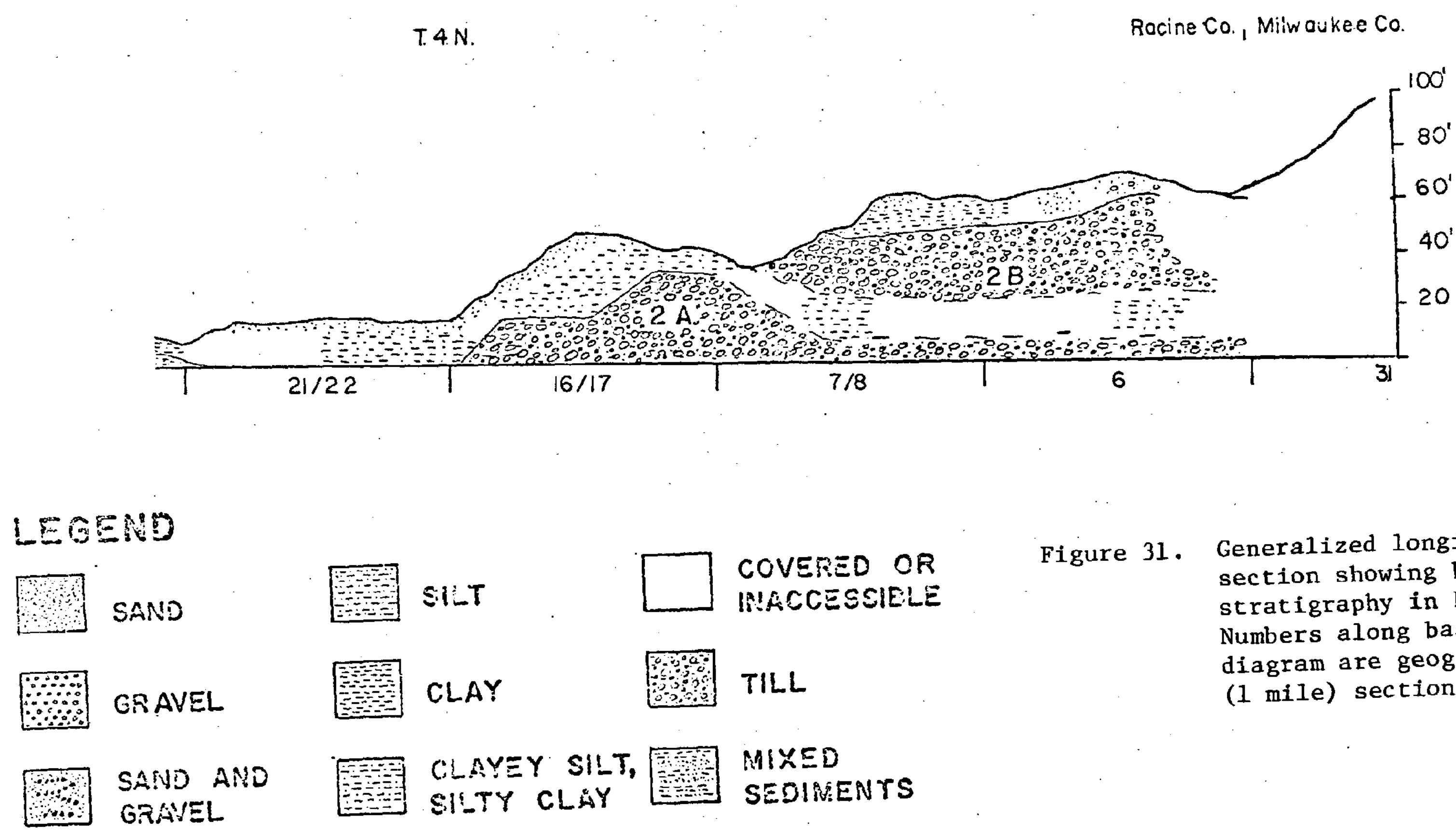


Figure 31. Generalized longitudinal section showing bluff stratigraphy in Reach 6. Numbers along base of diagram are geographic (1 mile) sections.

Beach width ranges from 0 to 75 feet; much of the beach is between 10 and 40 feet wide. The beach is widest just south of the mouth of the small valley near the middle of the reach, where a compound shore-protection structure consisting of four on-shore groins attached to a dolomite stone revetment is responsible for active beach accretion. In contrast, numerous segments exist where either no beach whatever is present or where the beach is less than 10 feet wide. Beach materials also exhibit a wide range in caliber, from nearly pure sand to nearly pure gravel. The coarsest beach in all of Kenosha and Racine Counties is that at Wind Point just north of the lighthouse, where beach sediments consist almost entirely of pebbles and cobbles.

Much of the coastline in Reach 6 lacks shore protection structures of any kind, some of it is moderately well protected, and part is marked by a fair abundance of protective devices. Except for the compound bulkhead that protects the Oak Creek power plant at the north end of the reach, only three protective structures, none of which is effective, are present in the entire north half of the reach. The density of structures is therefore about one per mile (in contrast to segments of several other reaches farther south, where the density is 40 or more per mile). Structures are much more abundant and generally well constructed, however, in the southern part of Reach 6.

Bluff height ranges from 5 to 85 feet. The bluff is highest in the northern part of the reach where the shoreline intercepts the proximal slope of the innermost Lake Border moraine; in this area the bluff nearly everywhere is very steep and in excess of 70 feet high. In the southern part of the reach, on the other hand, at and just north of Wind Point the low terrace that separates the shoreline from the main upland surface is generally 8 to 14 feet above lake level, and in most places no real bluff exists along the shore; where present, the bluff is only 5 to 10 feet high. The terrace is also present as a narrow belt half a mile upshore. Throughout most of the reach, between the north end of this low terrace and the Lake Border moraine, the bluff is moderately to very steep and ranges from 30 to 70 feet high, progressively increasing in height from south to north. The upland surface behind the bluff in this segment is a lacustrine terrace that represents the Glenwood stage of glacial lake Chicago.

The materials in the bluff consist mainly of fine-textured sediments, including compact silty clay till (till 2) and silt and clay of lacustrine origin, with lesser amounts of fine-grained sand (Fig. 31). Individual till and lacustrine units range in thickness up to about 55 feet, but unit thicknesses appear to be highly variable. The upper part of the bluff commonly exposes sand or gravel or sand and laminated lacustrine silts and clays, which overlie the much thicker till and lacustrine deposits below. Except for this general relationship, no consistent stratigraphy is apparent; in some places lacustrine sediments overlie till, at other sites the relationship is reversed, and at still other localities the deposits are interbedded. In the southern third of the reach, however, no till whatever, seems to be present in the bluff (Fig. 31).

Slope stability also shows a range in conditions. In places where the bluff has been terraced or graded and sodded, the slope appears to be quite stable. In a great many other places, however, bluff failure is rapid and severe. Moderate-sized to massive slump blocks, commonly of a compound character, impart a distinctly scalloped pattern to the raw, sharp bluff edge through much of the reach. Mudflow, debris slide, debris fall, seep sapping, gully cutting, and toe erosion are all significant processes causing bluff failure and shoreline recession. Single profiles commonly show evidence of slump at the bluff edge, flow in mid-bluff, and wave erosion at the base of the cliff.

Thus, in virtually all categories, the Reach 6 shoreline presents a wide variety of conditions--undoubtedly the widest range of conditions of any reach in Kenosha and Racine Counties.

Reach 7, South Subreach

The south subreach of Reach 7 is defined as a segment of shoreline, approximately 3,500 feet long, that extends from the end of Oakwood Road to the south boundary of the reach in section 31, Township 5 North, Range 23 East, at the north end of the bulkhead that encloses the coal stockpile for the Oak Creek power plant (Fig. 32). Detailed maps are given in Appendix 3.

Bluff conditions in this subreach are generally similar to bluff conditions in the remainder of the reach. The bluff is approximately 100 feet high, and bluff materials consist mainly of compact silty clay till (till 2) and interbedded lacustrine deposits that include clays, silts, and fine sands (Fig. 33). Several of the coarser, more permeable layers act as seep horizons from which water issues at the bluff face, thereby contributing directly to slope failure by sapping and flow processes. Flowage appears to be the most important mechanism of bluff failure in the subreach at this time. Slump is also a significant mechanism, however, as indicated by the presence of scalloped bluff margins and abundant slump blocks, most of which pass downward into flow structures. Toe erosion and debris fall are important where the beach is narrow.

Beach conditions in the northern third of the subreach are also similar to those elsewhere in the reach. The beach is quite narrow, generally ranging in width from 10 to 20 feet, although in a few places it is less than 10 feet wide. Beach materials consist of sand and gravel. No shoreline protective structures exist.

Approximately 1,000 feet south of Oakwood Road a definite change in shoreline aspect occurs, a change that becomes progressively more pronounced toward the south, with the result that the south end of the subreach is quite different from the north end. The major differences are in beach width, in distance from the shore to the base of the bluff, in the character of the sediments in this shore-bluff zone, and in vegetation. Whereas wave erosion and a narrow beach characterize

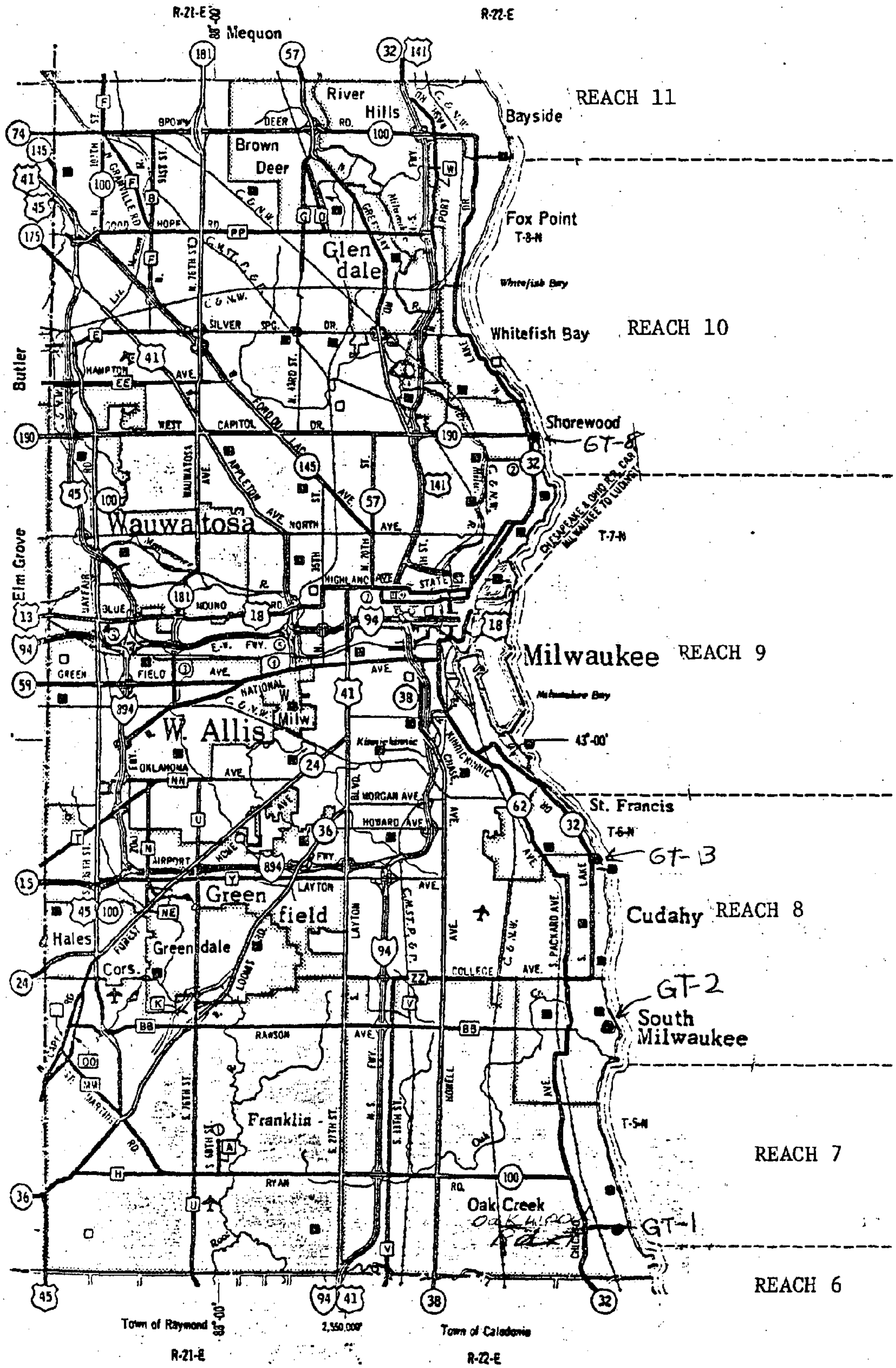


Fig. 32. Map of Milwaukee County showing the locations of Reaches 6, 7, 8, 9, 10 and 11, and geotechnical sites 1, 2, 3,

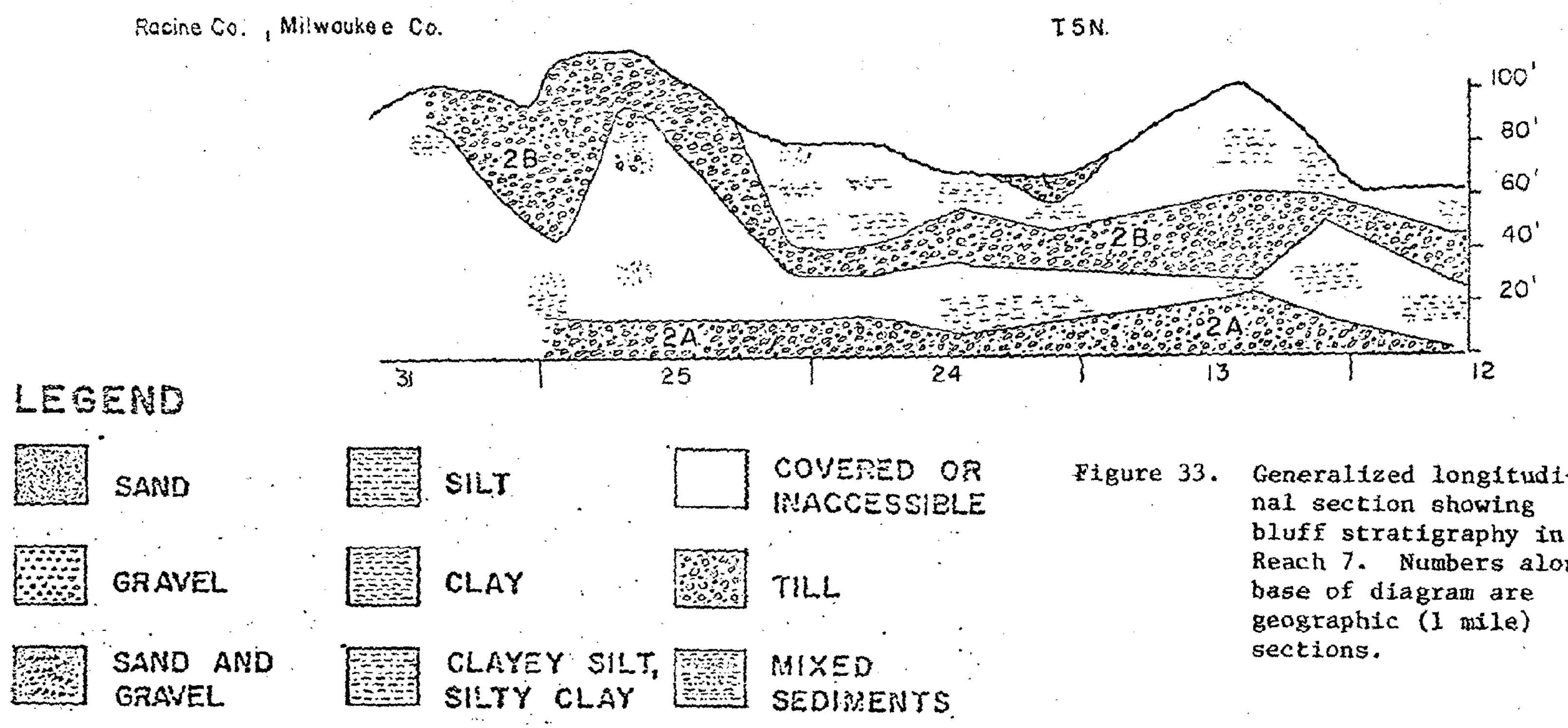


Figure 33. Generalized longitudinal section showing bluff stratigraphy in Reach 7. Numbers along base of diagram are geographic (1 mile) sections.

the northern part, active accretion of beach material is occurring in the southern part, where the beach is nowhere less than 20 feet wide. The width of the shore-bluff zone progressively increases from less than 10 feet in the north to several hundred feet in the south, thereby forming a distinct wedge-shaped area. This area, in addition to recent beach deposits, consists of a flow terrace, underlain mostly by water-logged silts, at the base of the bluff and an abandoned beach and dune complex between the flow terrace and the modern beach. A progressive north-south change in the vegetative pattern is also obvious. This marked difference in shoreline character between the north and south ends of the subreach is attributed to the Oak Creek power plant complex and particularly to the coal stockpile, which acts as a massive groin that serves to interrupt the longshore transport of beach deposits from north to south and traps the sediment on its north side. The situation is generally similar to that involving the Racine harbor structure and associated beach accretion in Reach 5.

Reach 7, North Subreach

Reach 7, approximately $4\frac{1}{2}$ miles long, extends from the Oak Creek Power Plant near the southern boundary of Milwaukee County north to the Water Treatment Plant in Section 12, T. 5 N., R. 22 E. (Fig. 32). It is ranked number 4 on the priority list, and it has a value per mile of 23 (see introduction for discussion of priority determination and value per mile). Erosion rates within the reach are up to 2 feet/year over the long term and 6 feet/year over the short term. The reach is discussed in detail in Appendix 3. Much of the southern third of the reach is in Bender Park owned by Milwaukee County. This land is wooded or pasture land and some areas are in row crops. North of this a sewage disposal plant and several industries are located along the shoreline.

In the southern part of the reach the beach width is 5 to 20 feet and there are no structures present. In the central and northern parts of the reach, beach width is considerably narrower, except where structures such as groins and small breakwaters have created a beach up to or greater than 25 feet wide.

The bluff height within the reach ranges from 125 feet in the southern part of the reach to about 60 feet in the northern quarter. In the southern part of the stratigraphic section (Fig. 33), the bluff consists of a lower, gray, silty clay till with few pebbles (till 2A). Where exposed, the till ranges from 6 to 20 feet thick and contains a few inclusions of lacustrine material. This till is overlain by a sequence of lacustrine deposits consisting primarily of silts interbedded with fine sand. This sequence changes laterally to some extent within the reach. Near the middle of the reach some interbedded fine gravels are present and silt is fairly thin (15 feet).

The silts are overlain by till (till 2B) in all locations except in part of Section 25. Here a wedge of medium sand and silt interbedded with fine sand is about 60 feet thick. This wedge is local and was probably deposited in front of the advancing ice front which deposited the upper till. The upper till (till 2B), identical in the field to the lower till (till 2A) in sequence, ranges from 10 feet thick to nearly 70 feet thick within the reach. The thick till is located at the intersection of the bluff with a moraine and it coincides with the highest part of the bluff in the reach. In the very northern part of the bluff, sediment from Oak Creek is present in terraces at a level of 640 feet (Glenwood Stage of Glacial Lake Chicago).

In the southern part of the reach the bluff top is scalloped (Fig. 34) and fairly large slump blocks displace material at regular intervals. Failures are seated in or at the base of the silt and the interbedded fine sand unit just above the lower till. Northward in the central part of the reach few discreet slumps are present, but numerous small slump blocks are present down the bluff surface (Fig. 14). Because of the rotation of the block surface, these trap water and there are many wet areas along the bluff. In the northern third of the reach most of the eroding slopes are straight and the primary type of failure is sliding. In places the bluff

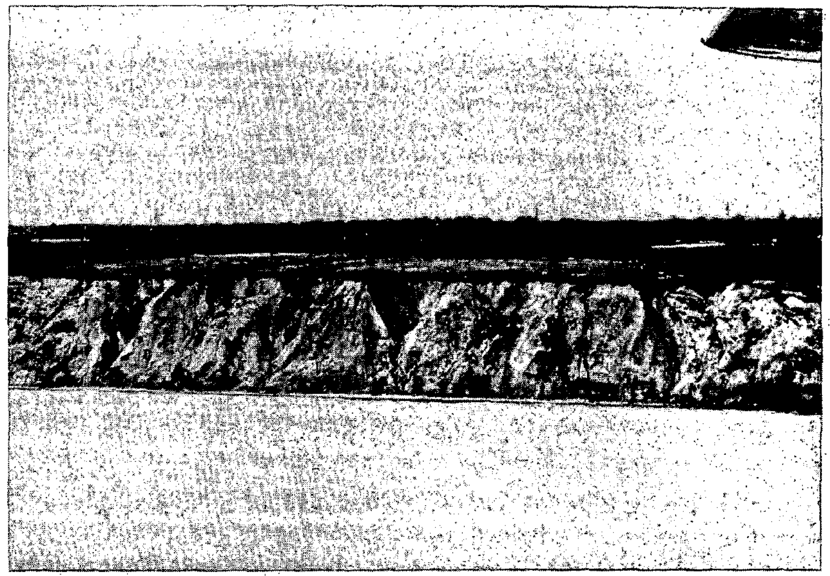


Figure 34. Oblique aerial photograph of the bluff in the southern part of Reach 7. Note the scalloped nature of the bluff top because of shallow slumps in the upper part of the bluff. Location is T.5N., R.22E., Section 25, Reach 7, Milwaukee County (oblique R-22, 13).

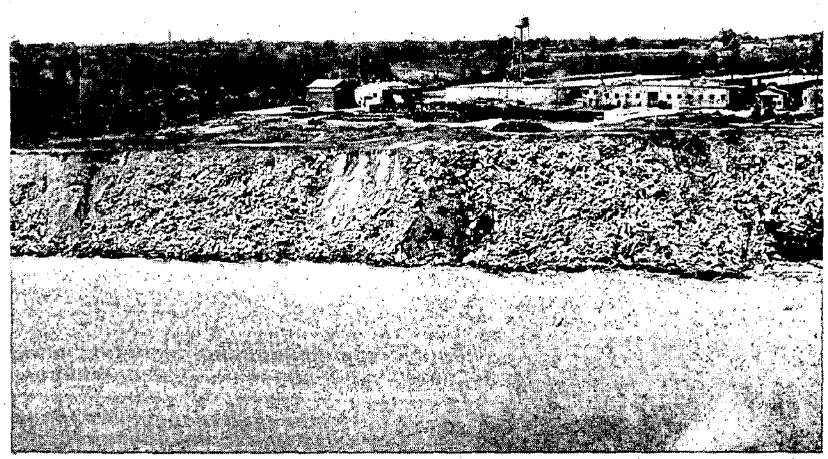


Figure 35. Oblique aerial photograph of the bluff in the northern part of Reach 7. Note the revetment of concrete blocks dumped from the top of the bluff. Location is T.5N., R.22E., Section 24, Reach 7, Milwaukee County (oblique R-22, 2).

is protected by concrete rubble dumped from the bluff top (Fig. 35), and in places the slope has been graded.

Reach 8

This reach is located in townships 5 and 6 north, Range 22 East in southern Milwaukee County (Fig. 32). It is approximately 5 miles long and is discussed in more detail in Appendix 3. Its priority in the ranking of critical areas was eleven, with a value per mile of twelve (see introduction for discussion of priority determination and value per mile). Long term erosion rates measured are up to 1 foot/year and short term rates are up to 2 feet/year. Although some of the land near the top of the bluff is used for industrial development, much of this reach is in open space. Grant Park is in the southern part of the reach and Sheridan Park is near the northern part of the reach.

Beach width through the reach is variable and in places is up to 50 feet where groin fields interrupt the longshore drift. A wide beach has developed in the south part of the reach just updrift from a fairly large groin at the mouth of Oak Creek. The bluff height in the reach varies from less than 60 feet along the Glenwood terrace near the mouth of Oak Creek to slightly over 100 feet in the central part of the reach. The Glenwood stage shoreline (640 feet elevation) again intersects the present shoreline in the northern part of the reach just north of Sheridan Park.

In the southern part of the reach two grey, silty clay tills (tills 2A and B) are present with interbedded silt and fine sand (Fig. 36). The upper till is overlain by interbedded silts and sands up to 20 feet thick. At the base of the bluff in Grant Park approximately 10 feet of sand occurs just above beach level beneath till 2A (Fig. 36). About half-way through the reach another grey, weathering to buff or pink clayey, silty till (till 2C) appears. This is then present at or very near the top of the profiles almost to the northern end of the reach. In the northern part of the reach a sandy till with many cobbles and boulders appears

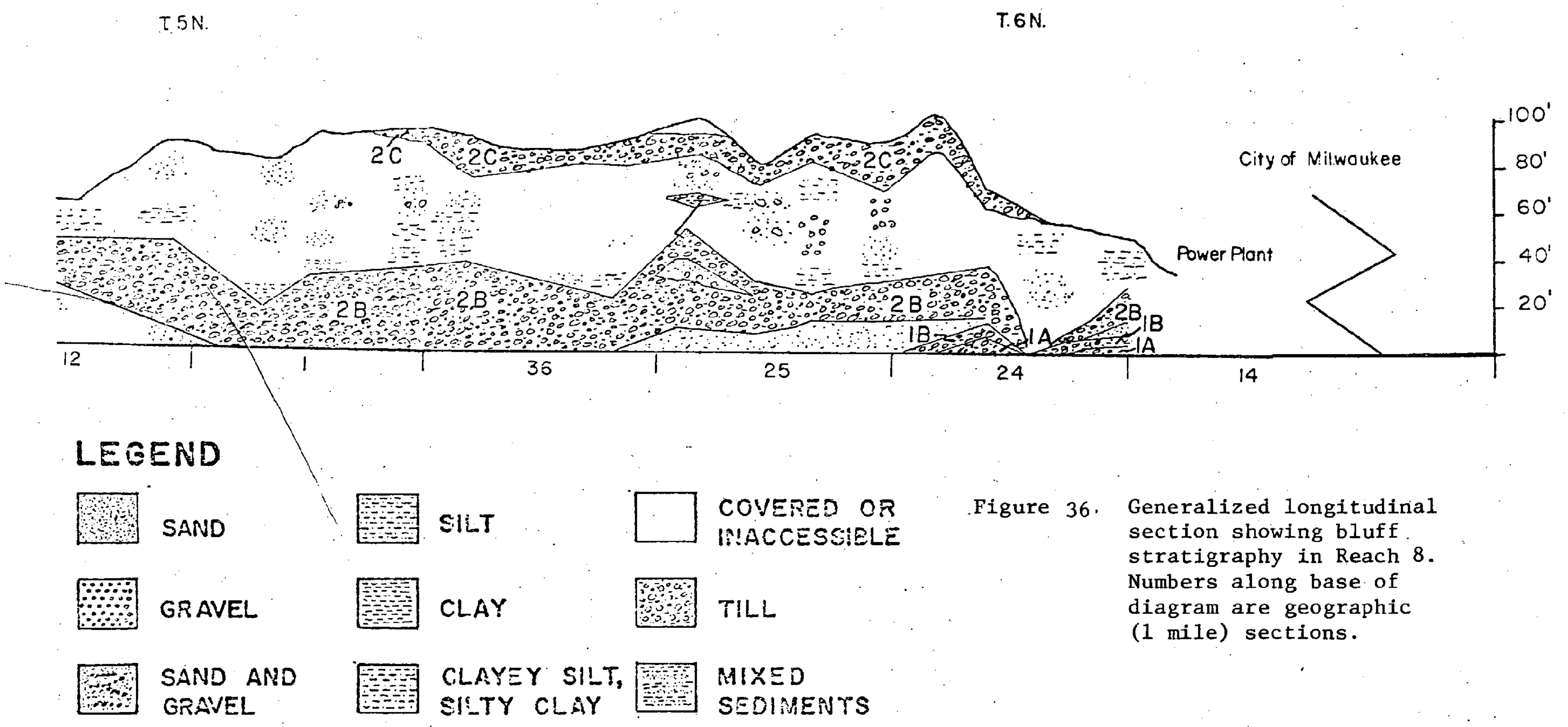


Figure 36. Generalized longitudinal section showing bluff stratigraphy in Reach 8. Numbers along base of diagram are geographic (1 mile) sections.

at the base of the bluff. This till is referred to in this report as till 1A and may be correlative with the Haeger till of Illinois (Fig. 19). The bouldery nature of this till can be seen by the large number of boulders present in the bluff along the beach at this location (Fig. 21). Directly above this a thin, fairly sandy till with fewer boulders is present (till 1B). The erosion rates in the reach are lowest in Grant and Sheridan Parks where groin fields and associated beaches protect the base of the bluff. At the south end of the groin field at Sheridan Park a marked change in bluff stability can be seen as the beach narrows (Fig. 9). Most of the failure on the bluffs in this reach is shallow sliding and flows where water is present. In the central part of the reach the gravel unit contains water and sapping occurs in this unit causing collapse of the overlying silts and till. Some sapping also occurs in the southern part of the reach where sands and silts make up the top of the bluff (Fig. 15). Small ravines due to sapping cut approximately 30 feet back into the top of the bluff.

Reach 9

Reach 9 (Fig. 32) covers the Milwaukee Harbor area which is entirely protected by a large breakwater system. Because of the shore protection structures this reach was not examined in detail. The reach has a priority of 32 and a value per mile of 0 (see introduction for methods used in determining priority and value per mile).

Reach 10

Reach 10 is located in Townships 7 and 8 north, range 22 east in northern Milwaukee County (Fig. 32). The reach is about 6.5 miles long and extends northward from the structured part of Milwaukee Harbor to Fox Point. Land use in the reach is limited to residential areas (Shorewood, Whitefish Bay, Fox Point) and parks and open space (Shorewood, Buckley, Big Bay, Silver Springs, Klode and Doctors Parks). The reach is ranked number six on the priority list and has a value per mile of twenty. Long term erosion rates in the reach are up to 3 feet/year.

No short term rates were measured. Beach conditions in the reach vary greatly depending upon the protective structures present. Where groins exist, wide (60 foot) sand beaches protect the toe of the slope. Where only sea walls exist, there is a small sand and cobble beach or the waves are breaking against the front of the sea wall (Fig. 11). In front of most of the revetments there is no beach unless the shoreline is also protected by a groin.

The bluff height in Reach 10 varies from 116 feet in the southernmost section to about 70 to 80 feet in the central areas and then rises to almost 120 feet in the northernmost parts of the reach.

The characteristic stratigraphy of the entire reach is an upper red-brown clayey, silty till (till 3A) separated from three lower tills by a sequence of silt and interbedded sand and silt (Fig. 37). In the southernmost section the natural exposures are very poor but from boring logs the upper till is at least 60 feet thick and the lower tills extend upward to a few feet above lake level. Between the lower tills and the upper tills 20 to 30 feet of lacustrine silt and sand are present. About one quarter of the way northward through the reach the lower tills rise until they are almost in contact with the upper red-brown till (3A). North of this point to the end of the reach the lower tills drop in elevation and are separated from the upper red-brown till by an increasingly thick wedge of lacustrine deposits. About three quarters of the way northward through the reach the lacustrine silt and interbedded silt and sand reach a thickness of 90 feet.

The southernmost mile of the reach is relatively stable and most of the bluff is tree covered. North of this, bluffs are intermittently wooded but some failure is taking place. Two types of slope failure are taking place within the reach. In one type rapid toe erosion at the base of the bluff causes steep lower slopes and shallow translational slides on the more gentle upper slopes (Fig. 38). In this case the toe material is usually in place (tills one or two

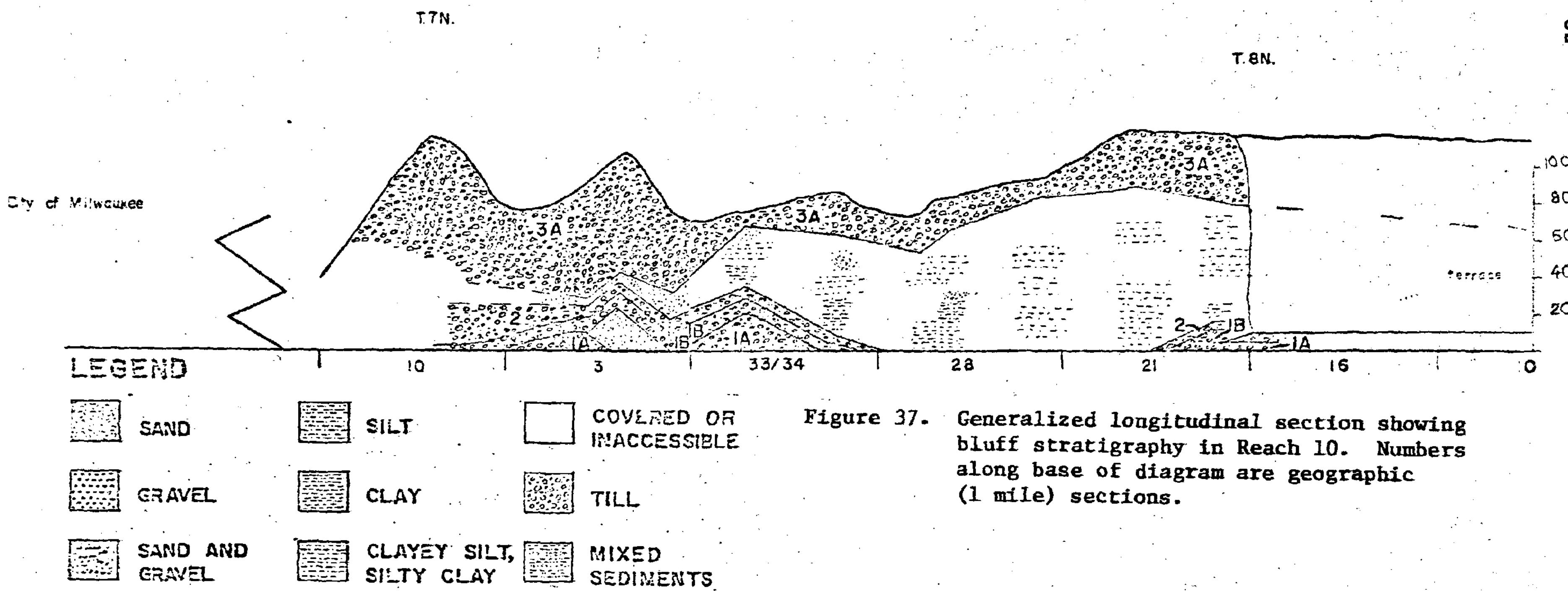


Figure 37. Generalized longitudinal section showing bluff stratigraphy in Reach 10. Numbers along base of diagram are geographic (1 mile) sections.

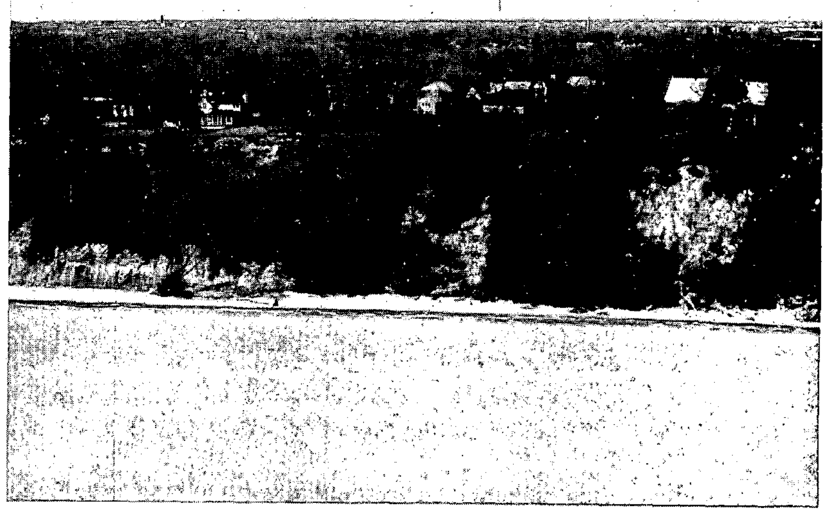


Figure 38. Oblique aerial photograph showing areas where rapid toe erosion is taking place and failure is primarily by shallow slides. Location is T.8N., R.22E., Sections 33 and 34, Reach 10, Milwaukee County (oblique R-17, 13).

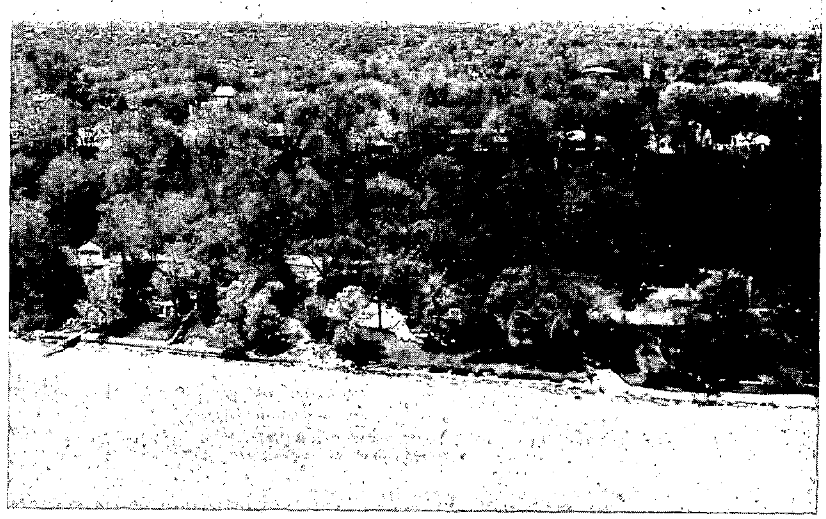


Figure 39. Oblique aerial photograph showing Nip ising Age (605' elevation) terrace. Terrace is protected by revetments and seawalls. The bluff behind the terrace is vegetated and stable. Location is T.8N., R.22E., Section 21, Reach 10, Milwaukee County (oblique R-16,28).

or silt). The slide material is carried away as rapidly as it falls from the bluff. Less often there is a small quantity of upper red-brown till or silt debris covering the toe.

Slumping, the other type of failure is caused by toe erosion coupled with the presence of seeps and lubricated rotational failure planes. Slopes exhibiting this type of failure usually have large blocks of slump debris covering the toe. Slump blocks pile up at the base of the bluff and then are slowly removed by way of action. The topographic profiles (Appendix 3) of these slopes show a gentle lower slope and a steep upper slope. Small scarps were observed on even the most stable appearing slopes such as those protected by seawalls, groins and terraces. These may be at the heads of old, very large, deep-seated slumps because remnants of old slump blocks are present along the base of the bluff in places.

Throughout the reach several minor seeps occur in the low part of the bluff either on top of the tills (tills 1A or B) or over a less permeable silt or clay layer. The presence of the seeps with their sapping action probably does not greatly add to the erosion problem.

The northern one-quarter of the reach in Fox Point has a natural terrace which is probably Nipissing in age (elevation 605 feet). This old wave cut terrace is based on the lower two tills (till 1A and B) and has a thin (3 to 6 foot) layer of sand above. Most of the terrace is protected by revetments and small groins. The bluff in back of the 200 to 300 foot wide terrace is vegetated and stable (Fig. 39). Slopes on the bluff range from 19 to 24°.

Reach 11

Reach 11 (Appendix 4) is about 3 miles long and extends north from Fox Point in northern Milwaukee County to Virmond Park in southern Ozaukee County (Fig. 32, 40). It is in townships 8 and 9 north, range 22 each. Reach 11 is number 5 on the priority list of erosion reaches with a value/mile of 23 (see introduction for disucssion of priority and value/mile). Land use at the top of the bluff is either residential or is park land.

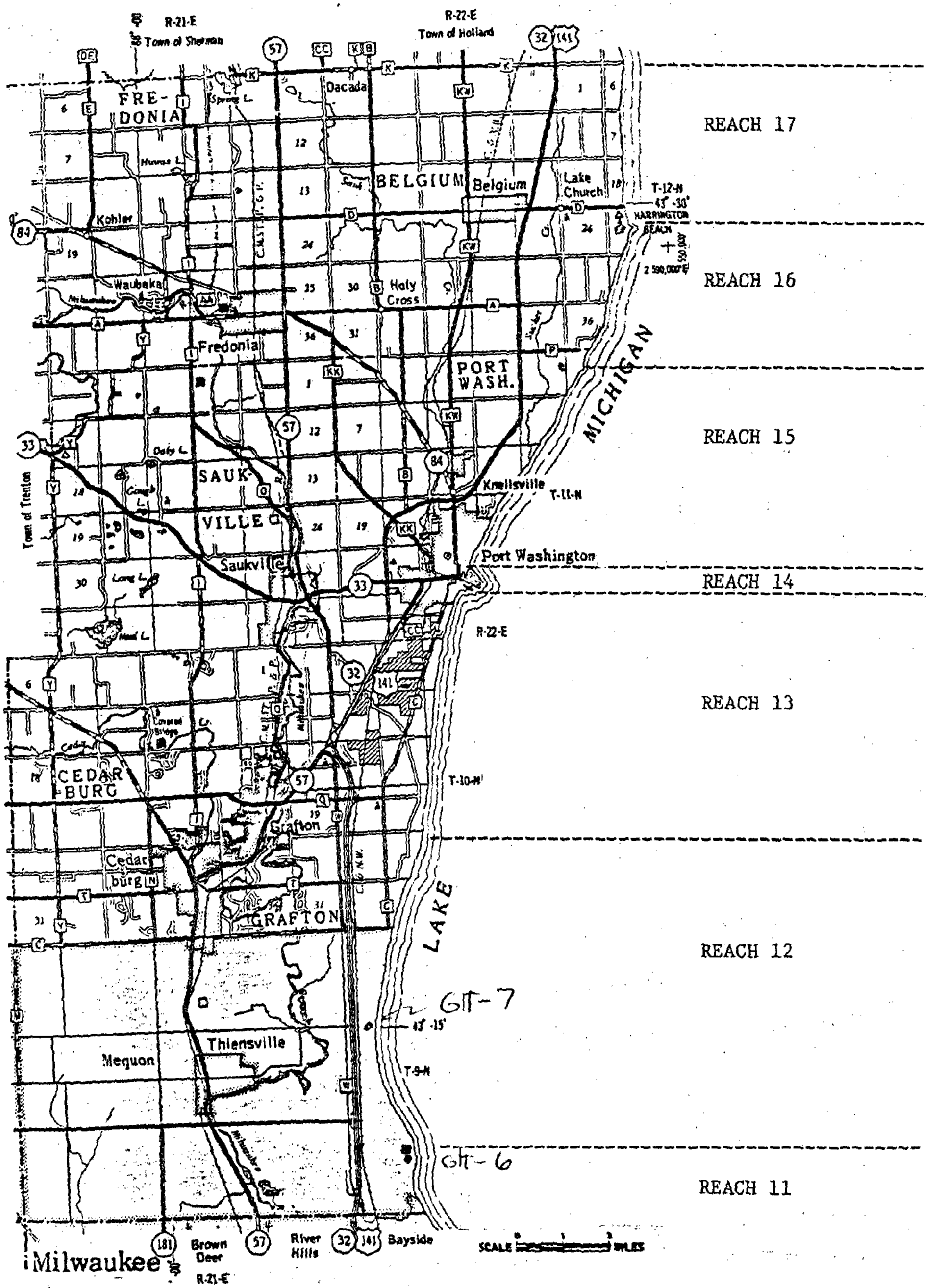


Figure 40. Map of Ozaukee County showing locations of Reaches 11, 12, 13, 14, 15, 16 and 17, and geotechnical sites 6 and 7.

The width of the beach varies from less than 5 feet in the central part in northern parts of the reach to greater than 20 feet in other areas (Appendix 4). Several small groins and revetments protect the toe of the bluff in some areas but much of the reach is unprotected. The southernmost third of the reach is wave-cut terrace of Nipissing age that is 100 to 200 yards wide (similar to Fig. 39). Much of this is vegetated although some small dunes have blowouts where active wind erosion is taking place. The terrace here is within the Audubon Bird Sanctuary and there is no residential development as there is on the terrace south of Fox Point. Vegetation covers the bluff above the terrace.

Bluff height in the reach ranges from approximately 70 feet at the northern end of the terrace area to 140 feet at the northern edge of the reach. Several large gullies cut the bluff although no large perennial streams enter the lake within the reach. No stratigraphy is visible in the bluff in the terrace area. North of this, red-brown silty till (till 3A) up to 60 feet thick is present at the surface throughout the reach (Fig. 41). This is underlain in the central part of the reach by a sand and gravel sequence ranging in thickness from 10 to 30 feet which overlies silts and interbedded fine sand. In the north central part of the section till 1B is exposed just above water line in a few places.

The bluff adjacent to the terraced area in the southern part of the reach is relatively stable. North of this through the rest of the reach shallow slides are common. Lacustrine material from the middle and lower parts of the profiles slides off the bluff and is accumulating at the toe where it is not being actively eroded. As the bluff rises to the north sliding continues to take place on the lower parts of the profile but shallow slumps also occur in the upper part of the bluff and seem to be seated at the base of the till unit. Small scarps and rotated masses of soil occur along the upper and middle parts of the bluff. At the northern edge of the reach, wave erosion is taking place at the base of the bluff and slopes are very active.

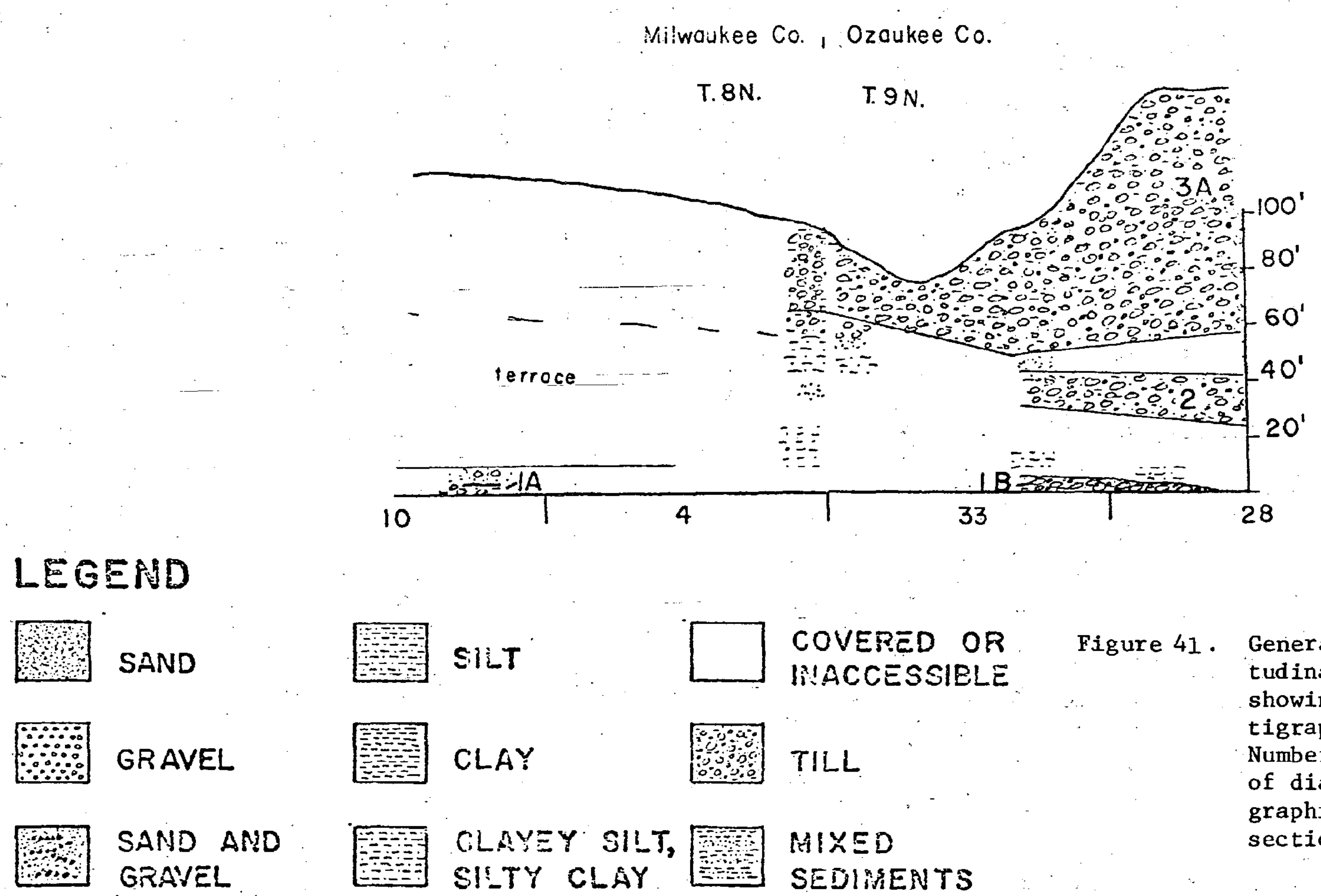


Figure 41. Generalized longitudinal section showing bluff stratigraphy in Reach 11. Numbers along base of diagram are geographic (1 mile) sections.

Reach 12

Reach 12 is located in townships 9 and 10 north, range 22 east in southern Ozaukee County (Fig. 40). The reach is about $6\frac{1}{2}$ miles long and extends from Virmond Park north to a point east of the towns of Cedarburg and Grafton. Land use in the reach is primarily residential although there are some parks. The reach is ranked second on the erosion priority list with a value per mile of 27 (see introduction for discussion of priority ranking and value per mile). The high priority is based on short term recession rates which range from 2 to 6 feet per 10 year period, the very high bluffs present, and the large number of residences located along the bluff top (up to 29 per mile). Throughout much of the reach the beach is narrow but is very variable and is best viewed on the section maps in Appendix 4.

The bluff height in reach 12 ranges from 140 feet in Virmond Park at the south edge of the reach to about 75 feet in the central part of the reach. In the northern end of the reach the bluff rises to over 100 feet and the entire reach has a uniformly high-bluff character. Tills 2 and 3A are present in nearly all profiles through the reach and in many places make up most of the bluff section (Fig. 42). In the southern part of the reach they are separated by about 20 feet of sand, gravel and silt which wedges out within the first mile north of the southern edge. In the next two miles north, nearly all of the bluff is made up of tills 2 and 3A although till 1B is exposed at the very base of the bluff in the northern part of section 17. North of this to the northern part of the reach a unit consisting of sand, sand and gravel and sand interbedded with silt appears between tills 2 and 3A in the central part of the bluff and reaches a thickness of nearly 80 feet (Fig. 42).

The slope failure type in this reach includes both sliding and slumping. In general the bluff in the southern part of the reach is more subject to sliding. The area around Virmond Park owes its rapid recession rates primarily to this type of failure. The northern areas seem to be marked by more slumping. There

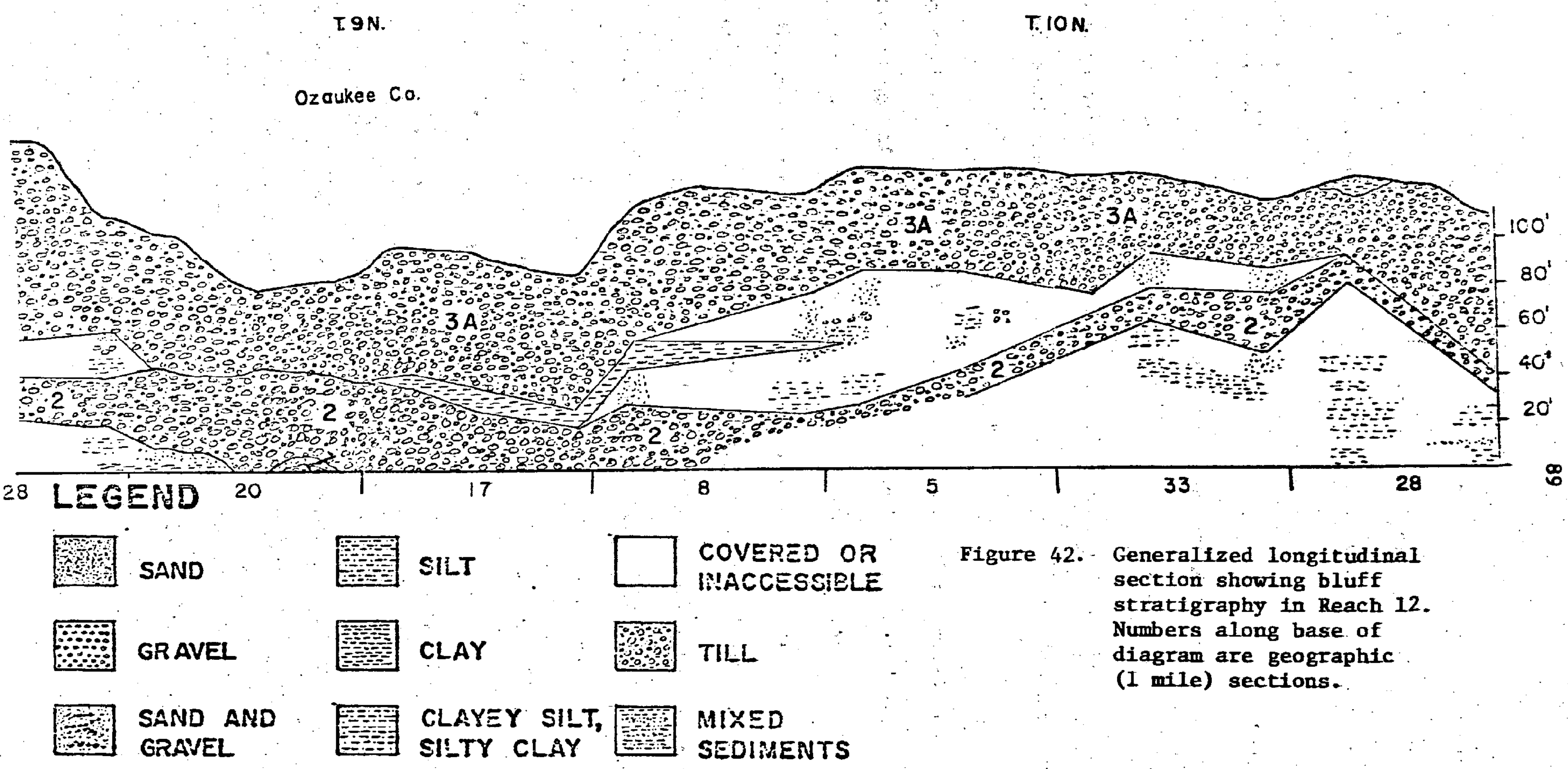


Figure 42. Generalized longitudinal section showing bluff stratigraphy in Reach 12. Numbers along base of diagram are geographic (1 mile) sections.

are large slump blocks resting at the base of the bluff and erosion of these blocks is now taking place (similar to Fig. 44). These evidently represent very large slumps, possibly seated below the water level of Lake Michigan. Their age is unknown.

Vegetation within the reach is partly dependent on failure type. Where the slope has failed by sliding there is very slight vegetation cover and surface erosion during rain storms is great. In the areas of slump the bluff is more highly vegetated, especially on the slump block. There are however barren scarps and the toes of the slopes which are being eroded by waves are vegetation-free.

Reach 13

This reach begins in Section 21, T.10N., R.22E. and extends through Section 33, T.11N., R.22E. in Ozaukee County (Fig. 40). The reach is approximately 5 miles long and is No. 7 on the shore erosion priority area list with a value per mile of 18 (see introduction for discussion of priority determination and value per mile). The land use in this reach is almost entirely agricultural, but new homes are built fairly close to the top of the bluff in a few places.

Within the reach, bluff height varies from 100 feet to 125 feet. Much of the reach has scattered vegetation along the bluff, and stratigraphy is difficult to interpret in many places. The surface stratigraphic unit is red-brown silty till (3A) up to 40 feet thick overlying interbedded sands, sand and gravel, and silt (Fig. 43). Beneath this, in the southern part of the reach, slightly more gray silty till clay (till 2) underlies the sand and silt units. Throughout the southern part of the reach large slump blocks are located at the toe of the bluff and no stratigraphy can be seen (Fig. 44). In the central and northern parts of the bluff, where the toe is exposed, the more gray silty till (Till 3A) is present just above water level.

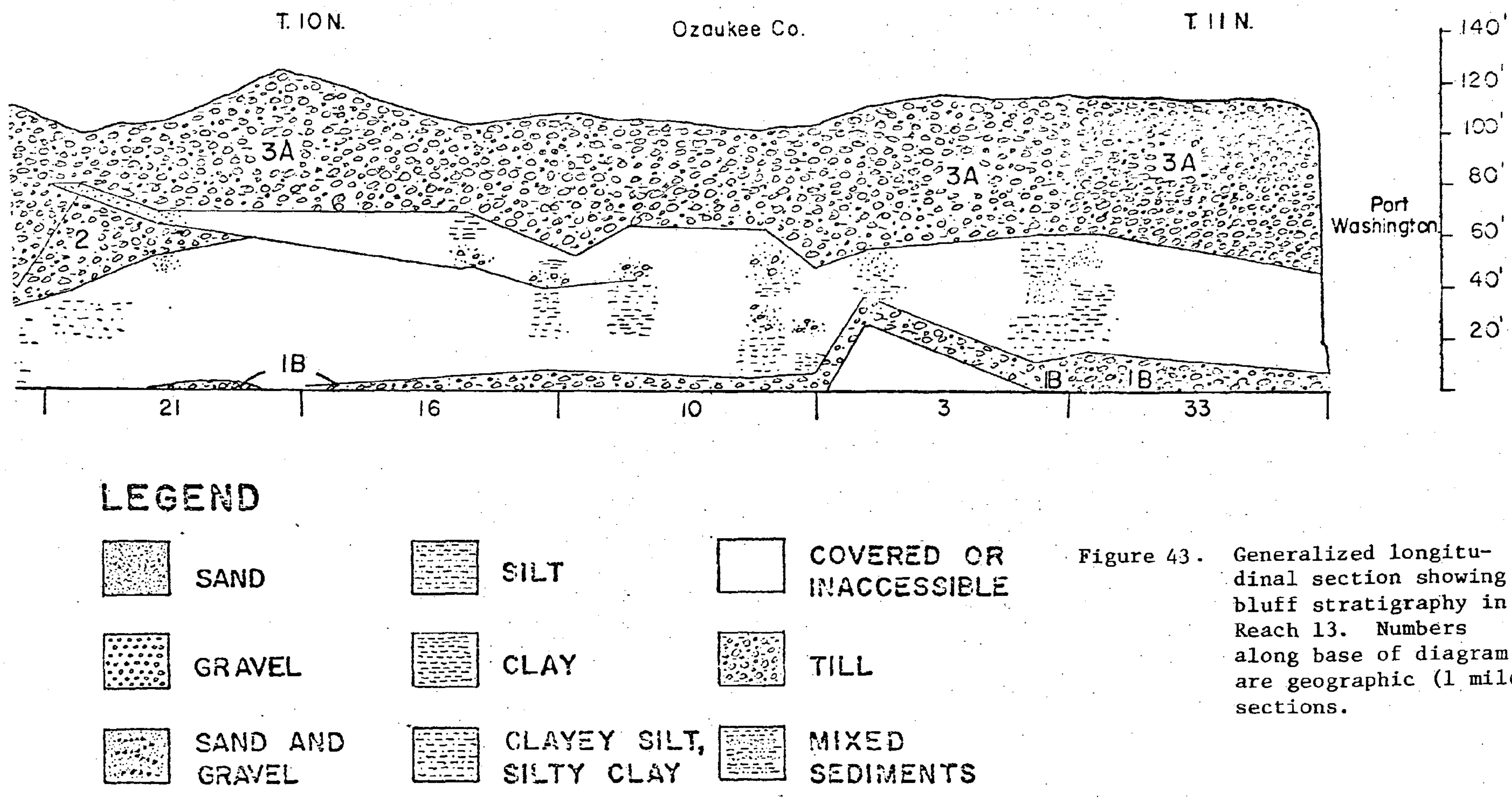


Figure 43. Generalized longitudinal section showing bluff stratigraphy in Reach 13. Numbers along base of diagram are geographic (1 mile) sections.

Figure 44. Oblique aerial photograph showing very large slump blocks in Reach 13. Much of the slump block is vegetated and is presently being eroded at its toe. Location is T.10N., R.22E., Section 16, Reach 13, Ozaukee County (oblique R-13, 20A).

In the southern third of the reach, slope failure is primarily by large deep-seated slumps. The base of the bluff, like that in reach 12, is made up almost entirely of slump material which is still vegetated and which traps water coming out of and down the bluff (Fig. 44). This slump block (Fig. 44) is being eroded presently by waves along its shoreward edge. At one location, where stratigraphy near the base can be seen, sands overlie a fine-grained till or lacustrine unit, and excessive sapping takes place in the sands. In the northern two-thirds of the reach, failure is primarily taking place by shallow translational slides down the bluff face (Fig. 45). Very few slump blocks are present along the toe, and in places where the beached narrow, in-place materials at the toe can be observed. In places where the beach is wider, a thin layer of low and slide debris occurs along the toe. In this part of the reach several bowl-shaped cuts (Fig. 46) extending from the surface two-thirds of the way down the bluff are vegetated and stand out as distinctly different from the steeper bluffs on either side. These have formed where undercutting due to sapping in the sands and surface water flowing over the bluff top have cut through the till and produced wide, roughly equi-dimensional gullies.

In the southern part of the reach, beach width is narrow and waves are eroding the toe of slump material in many places. In the central part of the reach the beach widens to about 20 feet and is primarily sand, although a cobble line does exist at water level. North of this, toward Port Washington, the beach narrows, coarser materials are present, and much of the beach is made up of pebbles and cobbles. An exposure of dolomite bedrock creates a small point in the northern part of Section 3. Very few structures exist in the reach.

Reach 14

Reach 14 is the harbor area of Port Washington in Ozaukee County (Fig. 40). The harbor is protected by a power plant and groins on the south side, and by a large breakwater attached to the shore on the north side. There are no natural exposures within this reach.

Figure 45. Oblique aerial photograph showing steep nearly unvegetated slope where most failure is taking place by shallow translational slides and flow. Some small slumps occur near the top of the bluff. Location is T.10N., R.22E., Section 3, Reach 13, Ozaukee County (oblique R-12, 33).

Figure 46. Oblique aerial photograph showing bowl-shaped depressions in the bluff top that have formed where groundwater sapping is taking place. Location is T.10N., R.22E., Section 10, Reach 13, Ozaukee County (oblique R-12,32).

Reach 15

Reach 15 is located in T.11N., R.22E. in central Ozaukee County (Fig. 40). The reach is about 4.5 miles long and extends northward from structures in the Port Washington harbor to a lake terrace (605') in Section 1, T.11N. Land use on the bluff top and terrace is either residential farm land or forest. Reach 15 is ranked 15th on the priority list with a value per mile of 10 (see introduction for discussion of priority determination and value per mile). This value is based on short term recession rates that vary from 3 to 8 feet per 10 year period and a fairly high ranking of importance by the public.

The beach width in the reach varies greatly. In places it is over 70 feet wide (Section 22), but in many areas it is 5 to 20 feet wide; and in some places waves are eroding the toe of the bluff throughout much of the year. Most of the beaches are made up of coarse-grained material such as pebbles and cobbles, although sand is present in some areas, especially high on the beach.

Bluff height varies from a maximum of 116 feet to about 85 feet in the southern two sections of the reach. The northern 3 sections have a bluff height between 50 and 85 feet. Within the reach are 3 areas of old lake terrace (Nipissing, or 605 feet elevation). The largest occupies the middle of Sections 14 and 15 and 11. At the northern end of the reach in sections 2 and 1 the terrace begins again and continues northward through reaches 16, 17, and 18.

The stratigraphy within the reach is rather uniform (Fig. 47). At the base of the bluff, in most localities, is a gray, silty sandy till with many cobbles and pebbles (Till 1B). At the top of the bluff, throughout reach 15, is a red-brown, silty, pebbly till (Till 3C). Sandwiched between these two tills is a variable sequence of lacustrine and fluvial silts, sands and gravels. The thickness of the units changes greatly, depending on the location, but in general the lower gray silty till increases from 4 feet at the southern edge of the reach to about 27 feet in Section 22. The till then decreases in elevation so that it is not

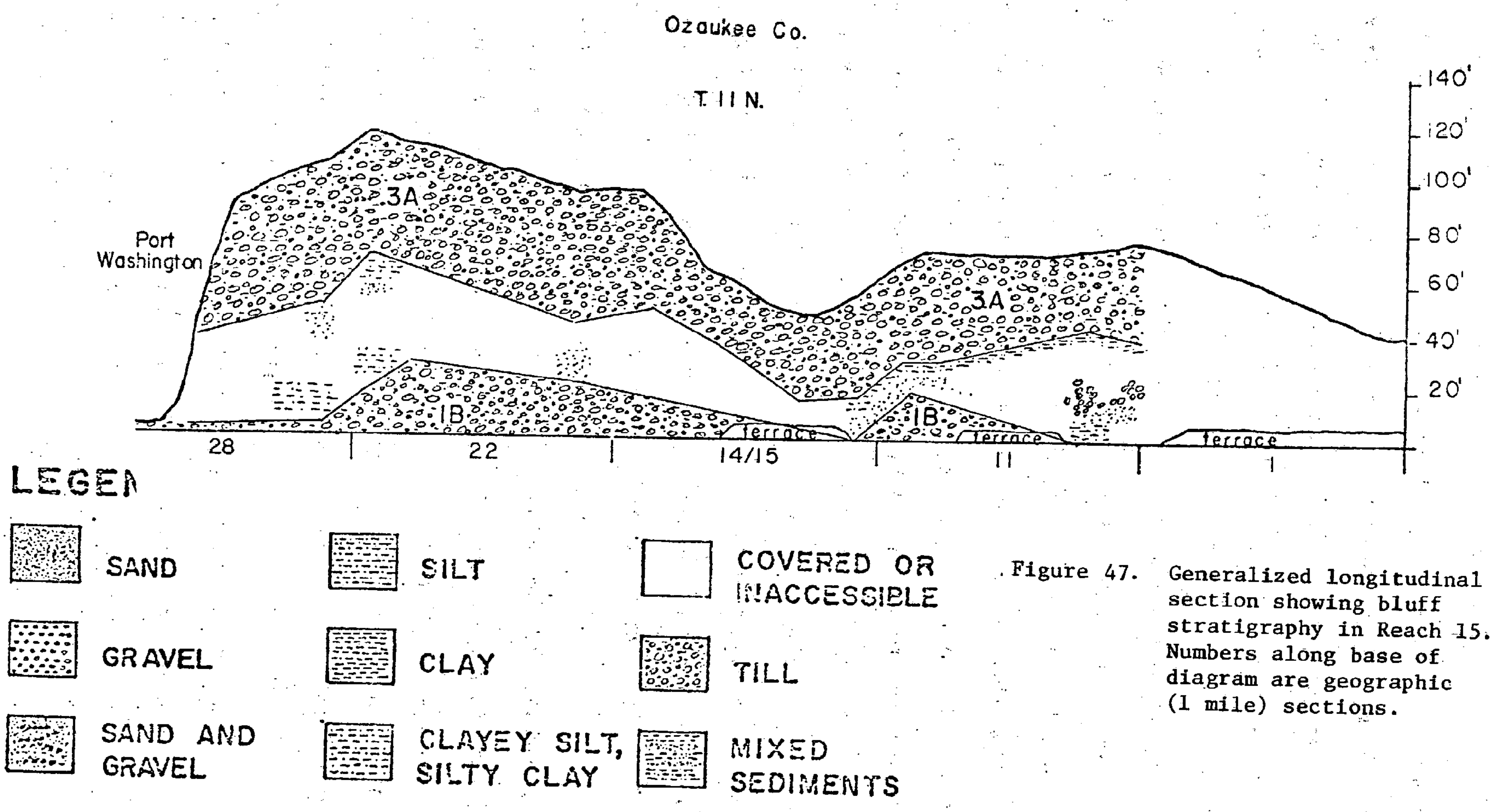


Figure 47. Generalized longitudinal section showing bluff stratigraphy in Reach 15. Numbers along base of diagram are geographic (1 mile) sections.

exposed in the northern quarter of the reach. The separating fluvial and lacustrine sediments are generally about 40 feet thick with most of the thickness (about 30 feet) being made up of silt in the southern half of the reach, and most being made up of gravel in the northern half of the reach. In many places the gravel layer is highly cemented into a hard dense conglomerate. The upper red-brown till (3C) varies in thickness with bluff height and is thickest (40 to 50 feet) in the high bluff area in the southern part of the reach. In the northern half of the reach the thickness varies between 30 and 40 feet.

Slope failure within the reach is primarily slumping with a little sliding in the southern half (Fig. 48) and sliding only in the northern half. Many of the slump blocks are vegetated and there are few completely bare slopes, as there are in reaches to the south.

Reach 16

Reach 16 is a 3-mile stretch of Nipissing Age lake terrace (605 feet elevation). The reach is located about halfway between Port Washington and the Ozaukee-Sheboygan County line (Fig. 40). The reach is ranked No. 12 on the priority list of erosion areas, and has a value per mile of 12. Land use on the terrace in this reach is entirely park land and residential. About half of the homes are used in the summer only and half have year-round occupancy.

At the southern boundary of reach 16 is a small but prominent point formed because of an exposure of resistant dolomite bedrock. At the point itself there is no beach, but a 20 foot wide shelf of bedrock dissipates the wave energy. North of this point the beach is made up of cobbles and pebbles, except for a small sand beach just north of the point.

The terrace ranges in width from about 250 feet to 500 feet. Behind the terrace the bluff is about 50 feet high and is entirely vegetated and stable (Fig. 49). Very little stratigraphy is exposed in the terrace and probably much of the terrace material is sand. At the north end of the reach a bedrock point extends into the lake from the terrace (Fig. 50).

Reach 48. Oblique aerial photograph typical of the bluff in the southern part of Reach 15. Slumping takes place in the upper part of the bluff and shallow slides are more typical of the lower part of the bluff. Location is T.11N., R.22E., Section 22, Reach 15, Ozaukee County (oblique R-12, 8).

Figure 49. Oblique aerial photograph showing terraced areas typical of Reaches 16 and 17. The low bluff behind the terrace is vegetated and stable. Location is T.12N., R.23E., Section 25, Reach 16, Ozaukee County. (oblique 9,14)

Figure 50. Oblique aerial photograph showing the exposure of dolomite bedrock at the boundary between Reaches 16 and 17. Location is T.12N., R.23E., Section 19, Reaches 16 and 17. (oblique 9,35)

Reach 17

Reach 17 is a $3\frac{1}{2}$ mile long reach of Nipissing Age lake terrace (605 feet elevation). It is located at the northern end of Ozaukee County and extends from the point at Harrington Beach north to the Ozaukee-Sheboygan County line (Fig. 40). Reach 17 is ranked No. 13 on the erosion study priority list and has a value per mile of 11. Like reach 16, the land use on the terrace is residential and park.

At the southern boundary of the reach, a bedrock point extends into the lake. Here there is no beach, but a 20 foot wide bedrock shelf extends a short distance north to a sand beach. Extensive sand bars also occur offshore and are probably present because the bedrock point acts as a natural groin. These conditions occur northward throughout the reach. The terrace is over 500 feet wide in the southern part of the reach, and is approximately 1,000 feet wide near the northern edge of the reach.

The bluff, where present behind the terrace, is vegetated and stable. No stratigraphy was observed within the reach, and probably most of the terrace materials are sand overlying bedrock.

Reach 18A

Reach 18A lies in Sections 30 and 31 of T.13N., R.23E., in extreme southern Sheboygan County. It is roughtly two miles in length, extending from the county line on the south to a point directly east of the town of Cedar Grove. The reach has an overall priority of 18 which is the fourth highest priority of those reaches lying north of the Sheboygan County line (Fig. 51).

Figures 52 through 56 constitute a generalized longitudinal profile of the high bluff area lying between the cities of Sheboygan and Manitowoc. These are supplemented by Figures 63 and 74, which are profiles of isolated areas of high bluffs elsewhere in the study area.

Reach 18A (along with Reaches 18B and 18C) lies on the prominent terrace that extends from north of Port Washington to near the southern city limits of Sheboygan. This terrace was formed by shoreline erosion along the shores of an ancient glacial lake at a time when the lake level was about 605 ft. above sea level. This is about 25 feet higher than modern Lake Michigan. The surface of the terrace is made up of a series of roughly parallel ancient beach ridges and is bordered on the west by an ancient wave cut bluff. This bluff is identical in origin to the steep bluffs that are found along many sections of the modern Lake Michigan shoreline in Sheboygan County and elsewhere. The terrace is of Nipissing Age.

At the Sheboygan-Ozaukee County line, which is the southern border of this section, the terrace is roughly 1000 feet in width and terminates to the west at a relatively steep and well defined bluff which is between 30 and 40 feet high. Although the ancient bluffs were not studied in detail, the few exposures that were studied indicated 10 to 20 feet of red till over lacustrine sand and gravel.

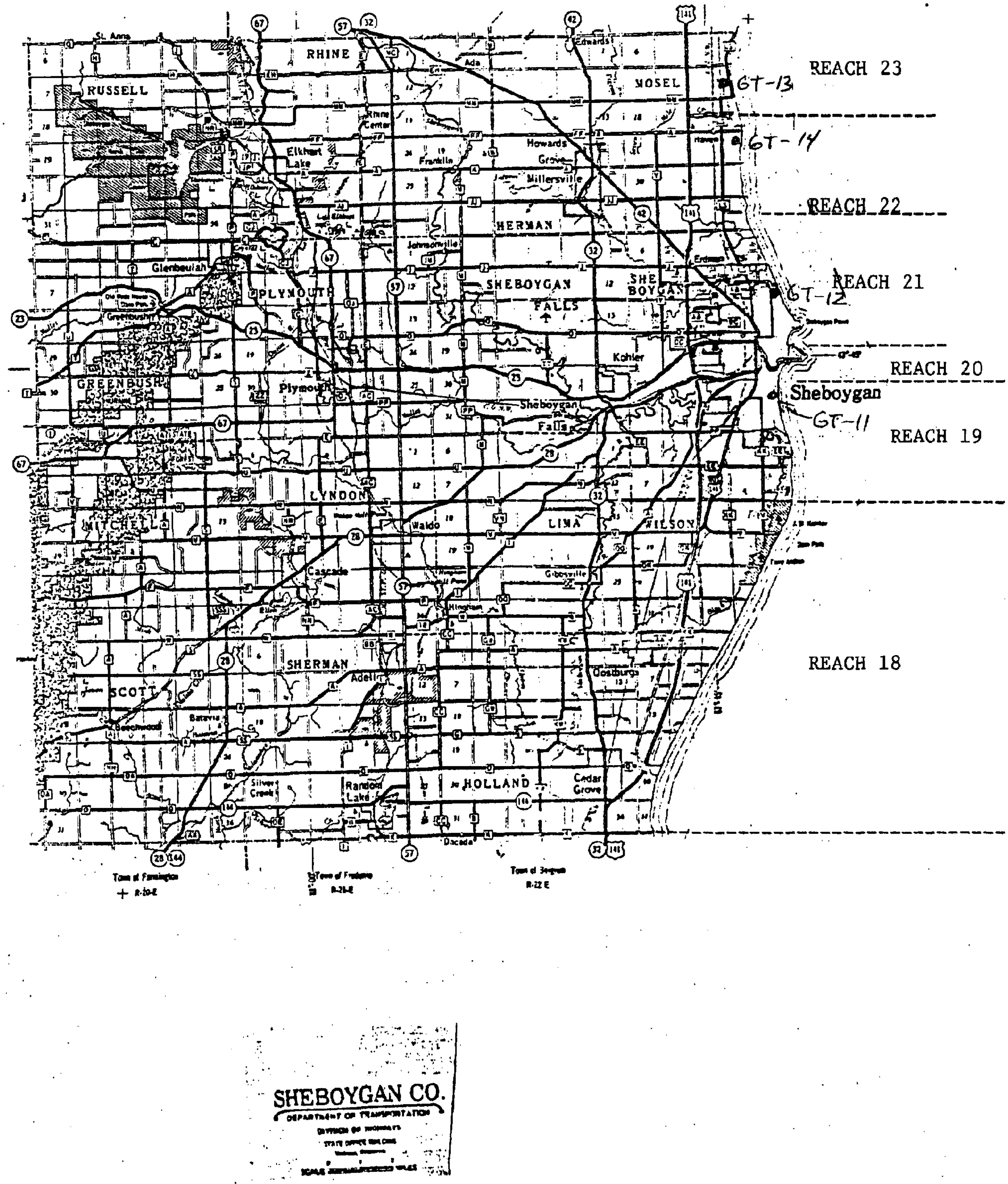


Figure 51. Map of Sheboygan County showing the locations of Reaches 18, 19, 20, 21, 22 and 23, and geotechnical sites 11, 12, 13 and 14.

Figure 52. Generalized longitudinal profile of bluffs.

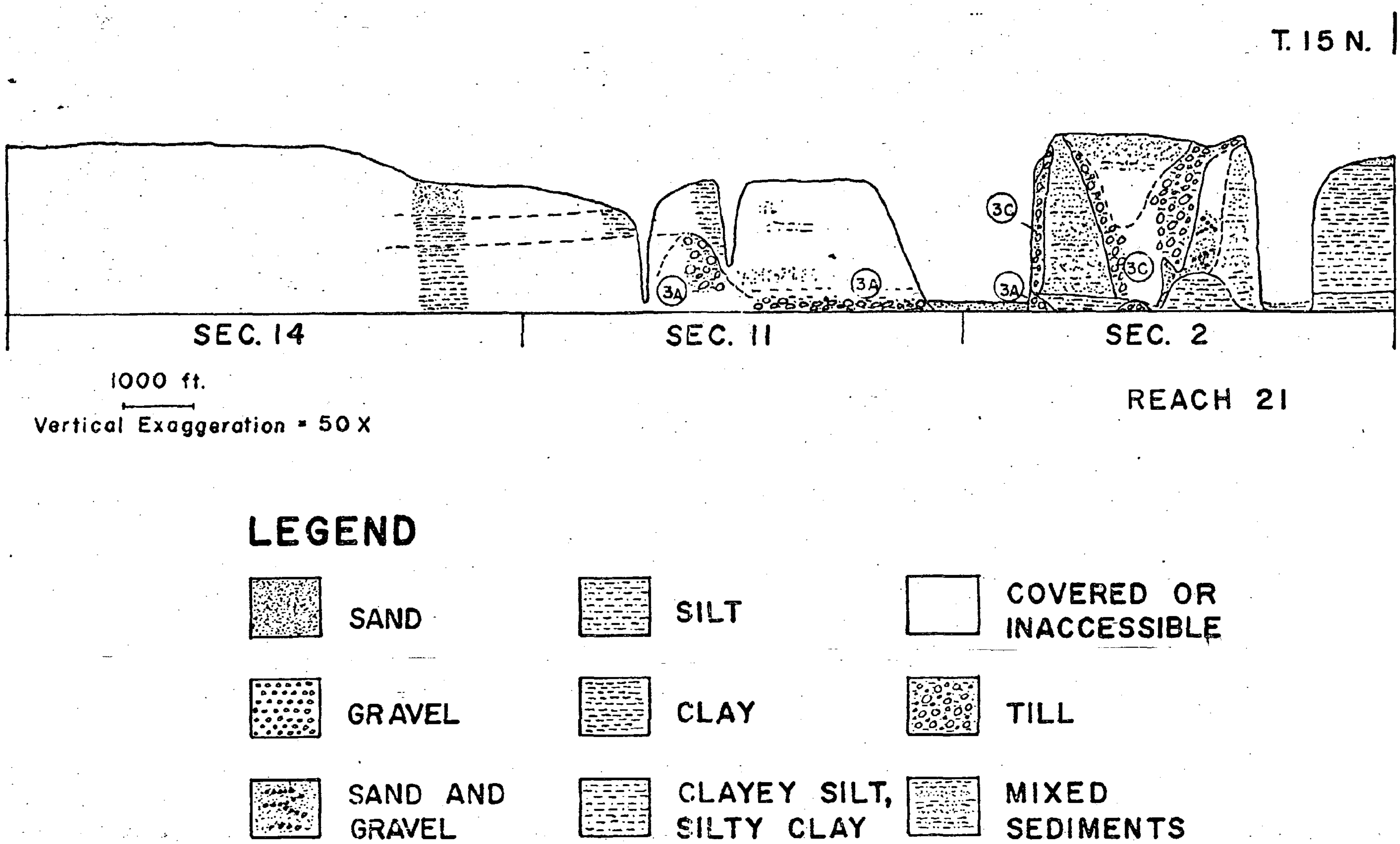


Figure 53. Generalized longitudinal profile of bluffs.

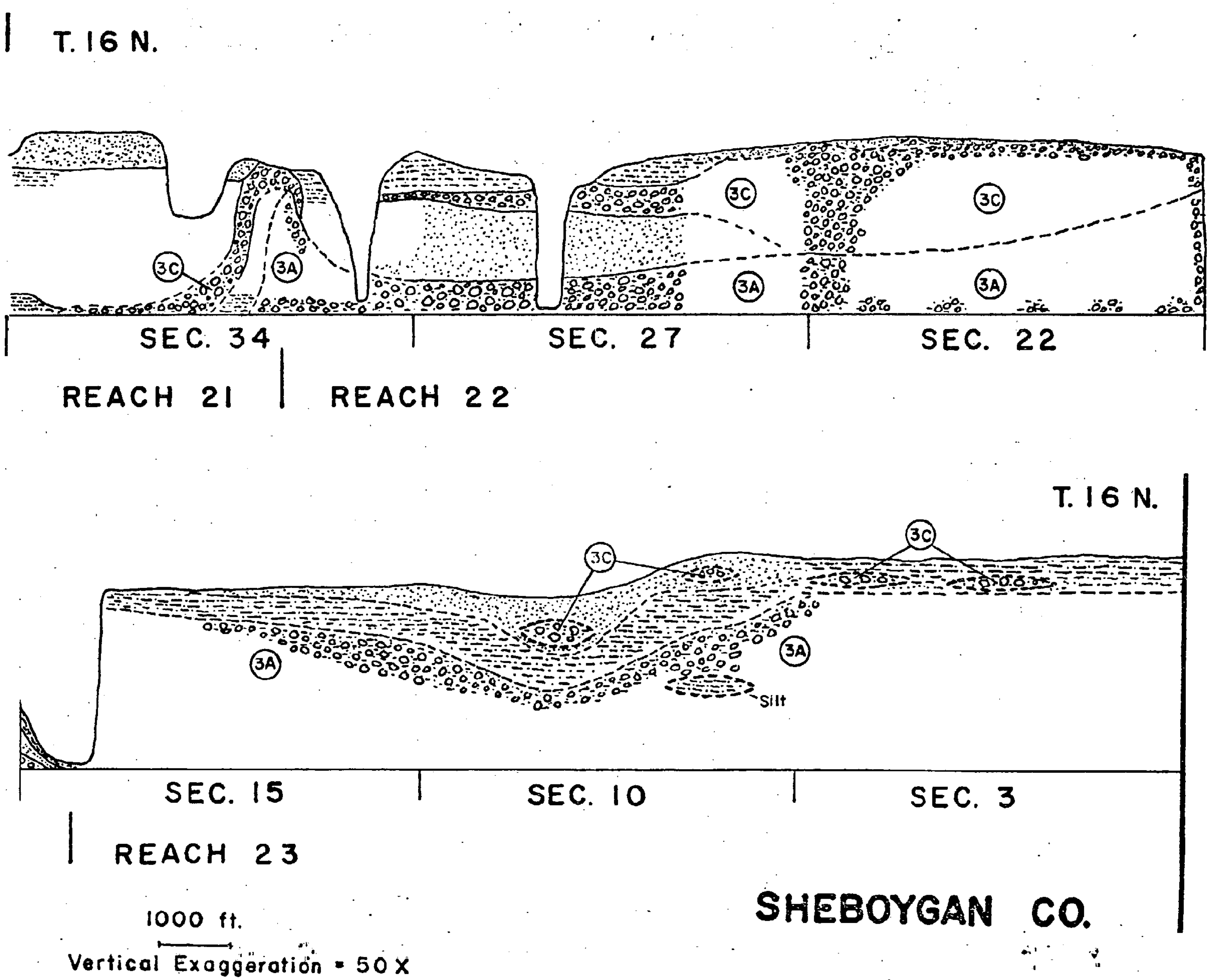


Figure 54. Generalized longitudinal profile of bluffs.

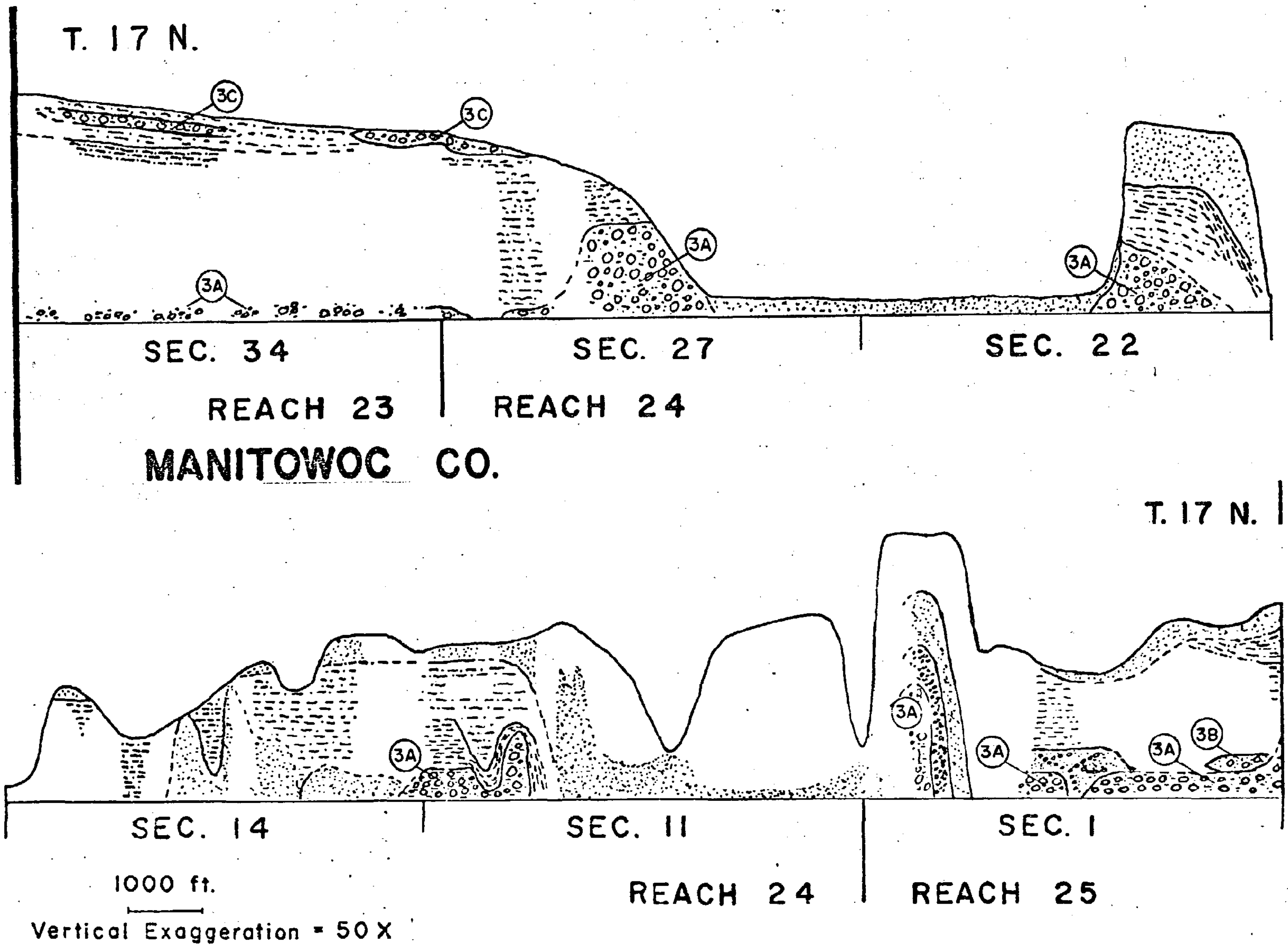


Figure 55. Generalized longitudinal profile of bluffs.

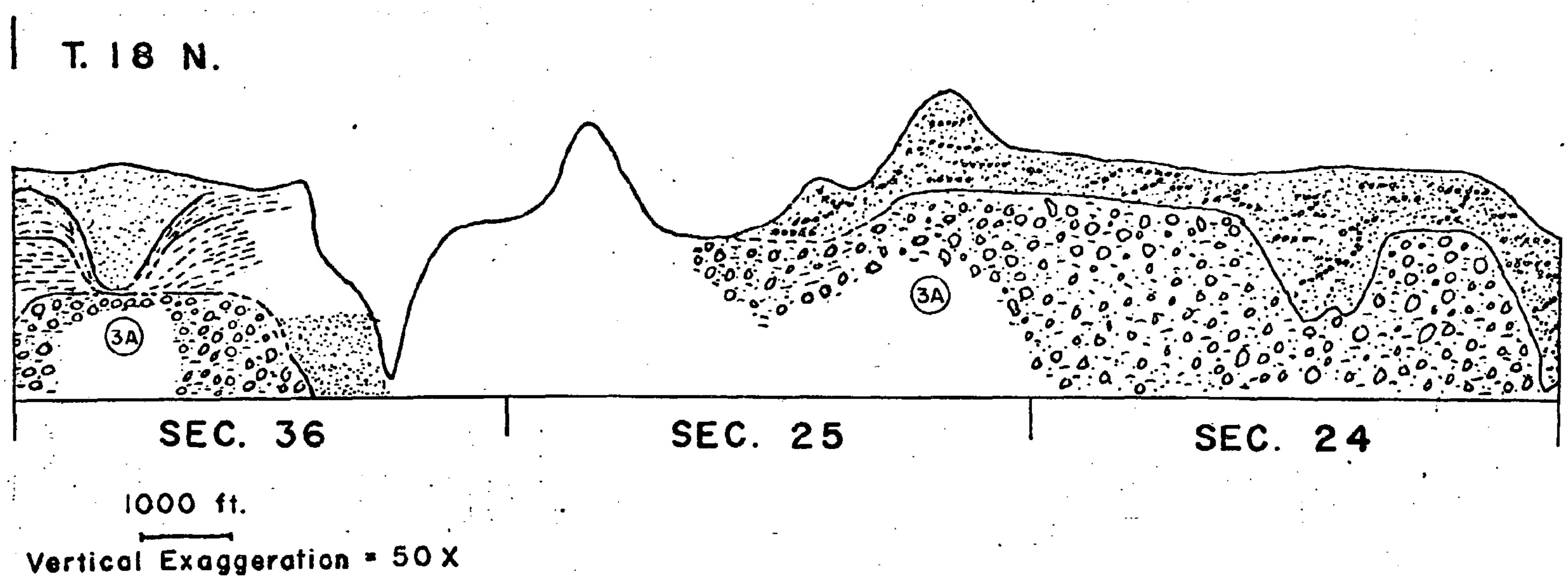
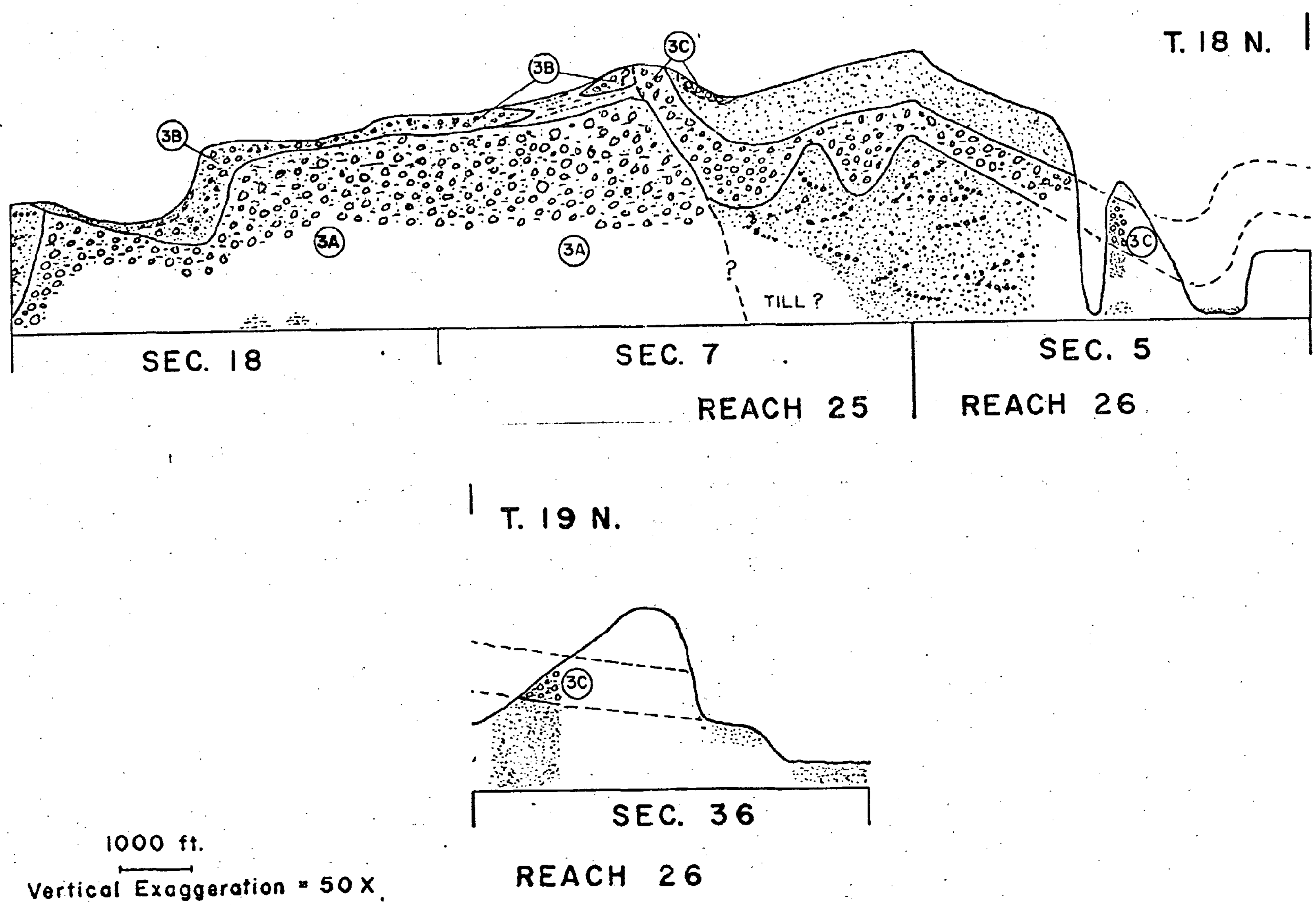


Figure 56. Generalized longitudinal profile of bluffs.



Land use within Reach 18A is almost exclusively private residential, although a small township park is located on the northern end of Sec. 31. Some summer cottages or second homes were observed, but most of the properties appear to be permanent residences. Housing density averages 12 residences per mile.

Beaches along this section of terrace are well developed, ranging from about 30 to more than 100 feet in width. They are striking in that they are made up almost exclusively of sand. Particles of pebble size or larger are almost completely absent.

Throughout much of Reaches 18A, B, and C, there are three very well developed sand bars lying off shore. At the time the shoreline was studied one of these sand bars merged with the beach in the southern portion of Section 31. Because of this, the water is quite shallow immediately off shore. Five foot water depths lie between 100 and 200 feet from the shoreline throughout section 31, and between 85 and 165 feet from shore in section 30.

Erosion along this reach is the result of the removal of sand from the beaches by storm waves. Measurements of erosion rates at two stations in the reach showed rates of 1.2 and 2.7 feet/year over about the last ten years. At the northern station, however, one hundred year averages show a small overall accretion.

Figure 57 is an oblique aerial photograph showing the general character of the shoreline in Reach 18A. The lack of beach in front of the revetment protecting the home in the foreground demonstrates the retreat of the shoreline in the reach.

Reach 18B

Reach 18B encompasses all or part of Sections 19, 20, 17, 8, 9, and 4 of T. 13 N., and Sections 33 and 34 of R. 14 N., R. 23 E. The reach has an overall priority rating of 8 which is the highest of any reach north of the Sheboygan County line. Land use is almost exclusively private residential. Housing density varies from a low of 10 to a high of 45 residences per mile with an average density of about 27 residences per mile.

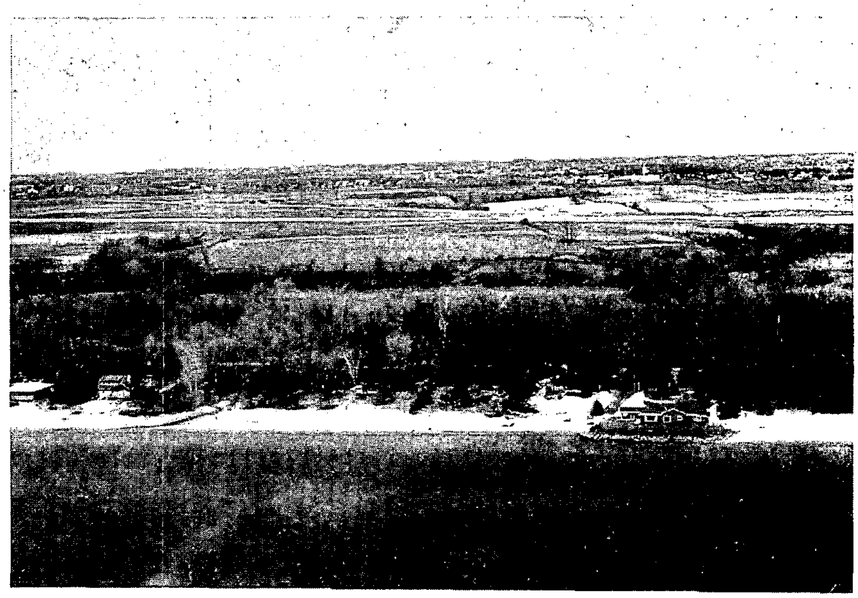


Figure 57. Oblique aerial photograph showing the general character of the shoreline in Reach 18A. The absence of beach in front of the revetment protecting the home in the foreground demonstrates the retreat of the shoreline along this reach. (oblique 8,19)

In the southern portions of the reach the beaches are well developed but as one progresses northward, the beaches narrow and many of the residences in the northern portion of the reach would suffer rapid and severe erosion losses if they were not heavily protected. The beaches are still predominately sand when present with pebbles and cobbles significantly more abundant in the northern portion of Reach 18B than was true to the south. In the extreme northern portion of the reach, beaches once again are present and range up to 65 feet in width.

As was the case in Reach 18A, the near back shore area is made up of sand dunes and beach ridges with cut faces ranging up to 18 feet in height.

Ancient bluffs lie approximately 1000 feet to the west of the present shore line in the southern portions of the reach. These bluffs are sharp and well defined in this area. As we move to the north the terrace broadens to about a quarter of a mile and the bluffs become obscured due to erosion by streams tributary to the Black River. Annual erosion over about the last 10 years has been measured at between 2 and 3 feet per year while 100 year averages are significantly lower with values of about 0.5 feet per year.

Figure 58 is an oblique aerial photograph showing the nature of the shoreline in the northern portion of Reach 18B. Storm waves have gone over the low revetments in this area, causing some structural damage.

Reach 18C

Reach 18C extends for a distance of 3 miles and consists of the shoreline along sections 27, 22, and 14, T. 14 N., R. 23 E. The reach has an overall priority rating of 24, and ranks ninth out of the twelve reaches north of Ozaukee County. This low ranking is primarily due to the fact that a large proportion of the shoreline within the reach is incorporated in the Terry Andrae-Kohler State Park Complex. As a result there are only 20 private dwellings along the shoreline of the total reach, leaving much of this reach undeveloped and essentially in its natural state.

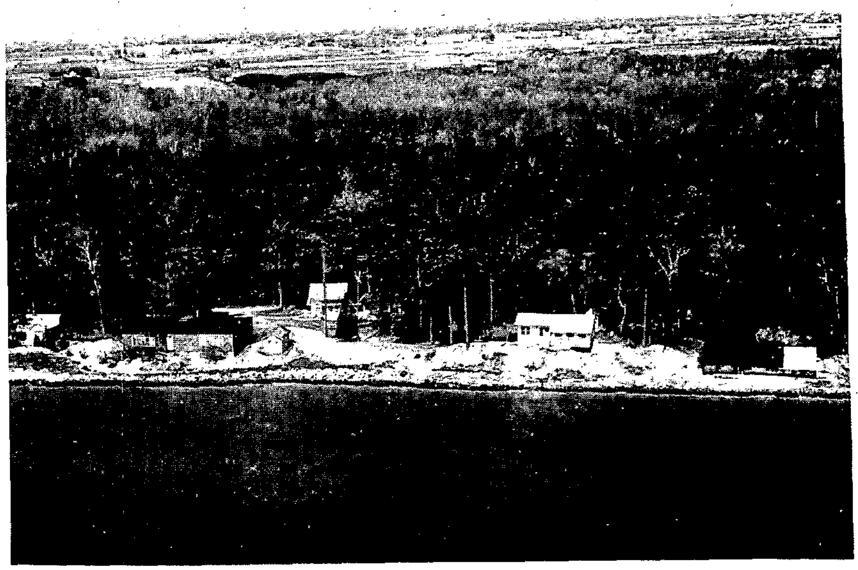


Figure 58. Oblique aerial photograph showing the nature of the shoreline in the northern portion of Reach 18B. Storm waves have gone over many of the low revetments found in this area resulting in considerable erosion and some damage to homes. (oblique 6,33)

In contrast to the more highly developed area immediately to the south in 18B, the beaches in Reach 18C are relatively wide, ranging up to 100 feet in width. Pebbles are much more abundant than in Reaches 18A and 18B. The back shore area consists primarily of terrace sands. In some areas sand dunes in excess of 30 feet high have developed. Erosion behind the beaches has produced cut faces in many areas which, when present, are normally between 10 and 15 feet high.

As was the case in Reach 18B to the south, the ancient bluffs marking the western limit of the terrace have been largely destroyed by the erosion of streams tributary to the Black River.

The principal mechanism of erosion throughout this reach is the removal of easily eroded sands through the action of storm waves. Ten year erosion averages were determined at two stations within the reach, and values of 2.2 feet/year and 1.4 feet/year were obtained. A single hundred year measurement was made within the reach, giving a value of 0.6 feet/year. A typical shoreline segment is shown on Figure 59.

Reach 19

Reach 19 is a little over 2 miles long in a north-south direction and includes the shoreline along Sections 11 and 12 of T. 14 N., R. 23 E., and of Section 35 and a portion of Section 26 of T. 15 N., R. 23 E. The reach has a priority of 19, making it the 5th highest ranking reach in the Sheboygan-Manitowoc study area.

This reach is a zone of transition in terms of geology, geomorphology and in its land use. The southern portions of the reach are a continuation of the terrace that extends southward almost to Port Washington. Northern portions of the reach are in an area of moderately high bluffs, typical of much of the area north of Sheboygan.

In terms of land usage, the southern portion of the area is one of year around beach residences, fronted by a moderately wide sand beach. Housing density is 61 residences per mile. In the central portion of the reach this residential

Figure 59. Oblique aerial photograph showing typical undeveloped shoreline in Reach 18C. (oblique 4,19)

area gives way to the grounds of the Edgewood Power Plant and the sewage disposal facilities for the City of Sheboygan. Immediately north of the sewage plant the land is largely urban in character, consisting of roughly a quarter mile of park lands which give way to closely spaced urban housing on top of the bluff.

Figures 60, 61, and 62 show the contrasting nature of the shoreline in these three areas.

Till is first encountered in this study area at the southern boundary of the sewage treatment plant, where about a foot of highly oxidized red till, believed to be till 3C, is exposed. The till is exposed intermittently for a short distance along the shoreline. Throughout this small area the till is overlain by sand. North of this point, the bluff attains a height of about 50 feet, and the stratigraphy of the bluff is almost totally obscured by fill that has been dumped over the edge of the bluff, as well as granular fill placed behind a large revetment and groin complex that protects this portion of the shoreline. A boring taken at the crest of the bluff revealed 20 feet of sand, which became progressively finer with depth, overlying a till unit (3C) about 20 feet thick. The till was found to be underlain by sand to well below the lake level. A generalized longitudinal profile of the northern portion of the reach is included as Figure 63.

A ten-year average erosion rate of 2.5 feet per mile was obtained in the southern portion of Reach 19, with a one hundred year average of about one foot per year. In the northern two-thirds of the reach, the shoreline is almost completely protected by structures and little if any evidence of erosion was noted.

Reach 20

This reach consists of the area including and immediately surrounding the harbor at Sheboygan and is fully protected from shoreline erosion by structures. It is the second lowest priority reach in the total project and has the lowest rank of any reach in the Sheboygan-Manitowoc study area. It was therefore excluded from the study with the exception of about 1000 feet which was included in order to complete the southernmost section in Reach 21.

Figure 60. The southern portions of Reach 19 are typified by year around residences fronted by sand beaches along the terrace. (oblique 4,6)

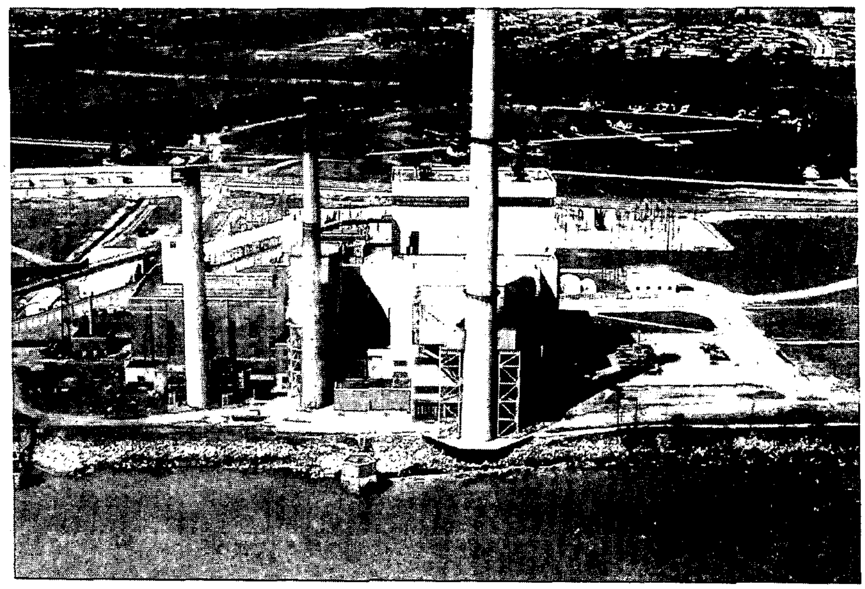


Figure 61. In the central portion of Reach 19, the ground elevation increases and land use is largely industrial. (oblique 3,19)

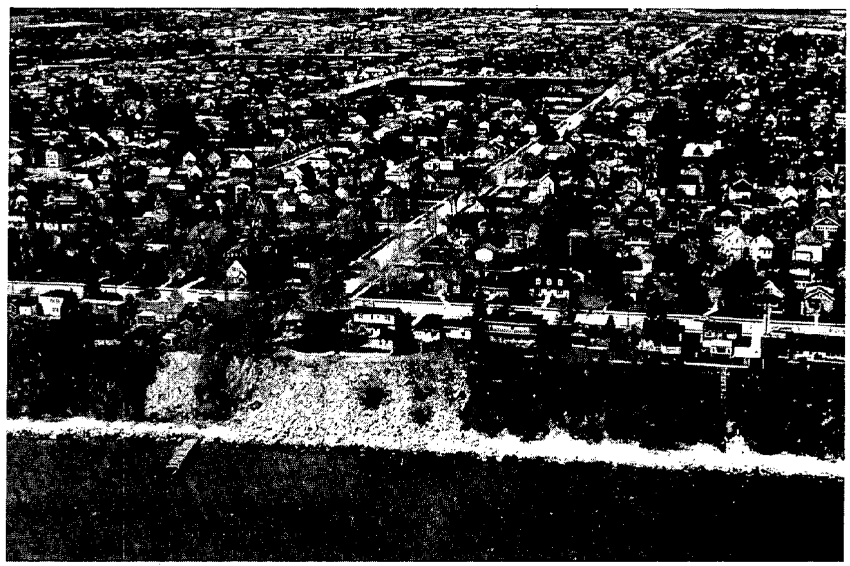
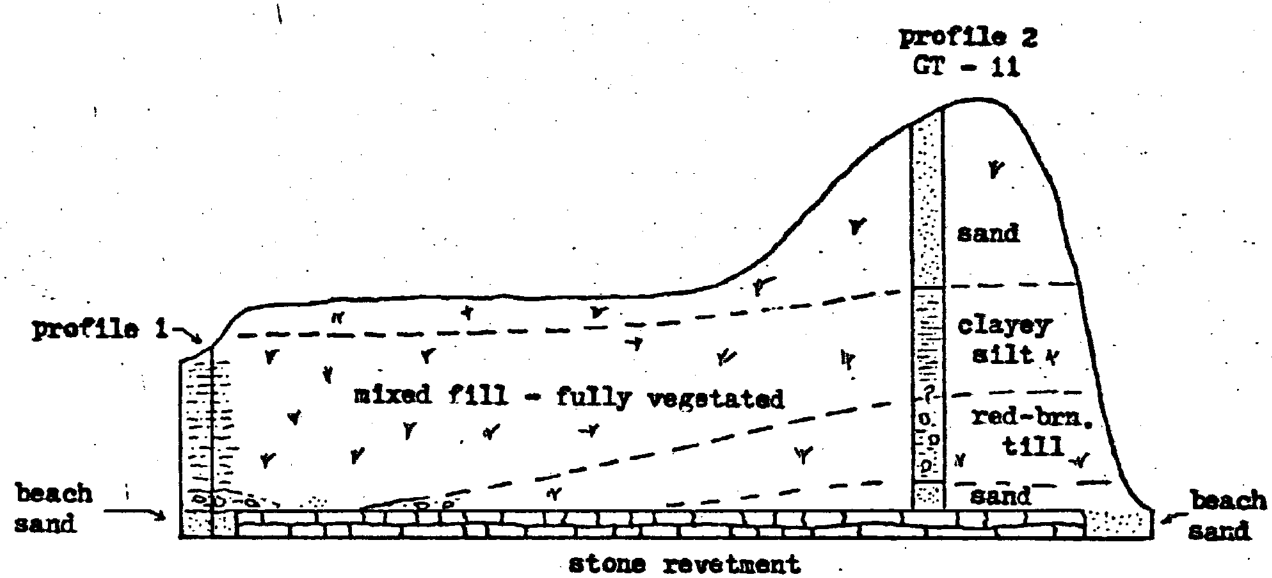


Figure 62. The northern portion of Reach 19 is an area of well-protected high bluffs and is densely populated. (oblique 3,9)



SCALE:

Horizontal: 1 inch = 1000 feet

Vertical: 1 inch = 20 feet

Figure 63. Generalized longitudinal profile of Sec. 35, T. 15 N., R. 23 E., Reach 19.

Casual examination while driving through Reach 20 reveals the shoreline to consist almost entirely of fill, lying behind massive protective structures.

Reach 21

This reach includes the shoreline portions of sections 4, 11, and 2 of T.15N., R.23E., and about the southern two-thirds of section 34 of T.16N., R.23E., It has an overall priority ranking of 25, which gives it the tenth highest priority of those reaches north of Ozaukee County.

Land use within this reach is quite variable, ranging from urban residential in much of the two southernmost sections, to largely agricultural or undeveloped lands to the north where only scattered, small subdivisions indicate the close proximity of Sheboygan.

In its southern sections, the shoreline is composed primarily of granular fill placed behind heavy revetments with a moderately high bluff to the rear. Throughout the urban portions of this reach, study of the stratigraphy of the bluffs is extremely difficult due to the extensive placement of fill on the bluff face as well as a heavy vegetative cover in many areas protected by revetments.

In the less highly developed areas to the north, the shoreline generally has a moderately wide cobble beach, normally ranging between ten and thirty feet in width. In some areas in which till appears in a basal position, however, the beaches are very narrow, or, in some cases, nonexistant. The height of the bluffs throughout the reach is, for the most part, between forty and fifty feet.

Near the southern boundary of the reach bedrock is very shallow or exposed in the nearshore area. This body of dolomite at or near the water surface is known as the "Sheboygan Reef". The promintory, Sheboygan Point, that marks the southern reach boundary is almost certainly due, in part, to the protection provided by this natural breakwater. These features are shown on Figure 64.

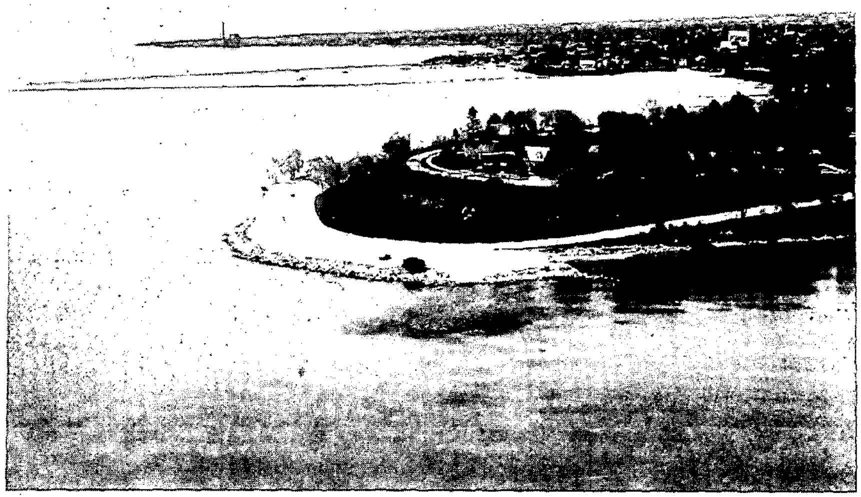


Figure 64. Oblique aerial photograph of Sheboygan Point at the southern boundary of Reach 21. The disturbed water in the foreground is the result of waves breaking on the exposed dolomite of the Sheboygan Reef. (oblique 53,6)

Along most of the shoreline in Reach 21 the bluffs are made up largely of lacustrine sediments. These sediments display a regressive sequence, with silty clay at the base grading upward to sand at the top of the section. A typical shoreline segment with a steep bluff cut in lacustrine sediments is shown on Figures 65,66 In portions of sections 11 and 34, till 3A is exposed in a basal position, and till 3C is exposed at or near the bluff top in section 2. In section 34, till 3C is exposed at the base of the bluffs near the center of the section, where it is seen to rise rapidly to the north. At the northern reach boundary, till 3C is once more at the surface, where it overlies till 3A.

Several types of slope failure were noted along this reach. In those areas in which lacustrine sediments appeared to extend down to the toe of the slope, failure was often in the form of very closely spaced slumps occurring at a steep angle. The slumped fine grained lacustrine material was subsequently greatly modified by flows, especially where a thick sand sequence occurred along the bluff top, leading to extensive ground water seepage. In areas in which the slumped material was removed through wave action, undercutting and subsequent soil falls became important mechanisms for slope failure.

Where tills 3C or 3A were exposed at the base of the bluffs, failures often took the form of very large scale slumps, with the scarp often lying several hundred feet behind the roe of the slope.

Where thick till sequences were exposed at the base of the bluff, and especially where the exposed till was till 3A, failure occurred primarily through undercutting and subsequent soil fall, resulting in near vertical cliffs bordering the beach.

Erosion rates were not determined for the extreme southern regions of Reach 21, probably due to the fact that this area is almost completely protected by revetments.

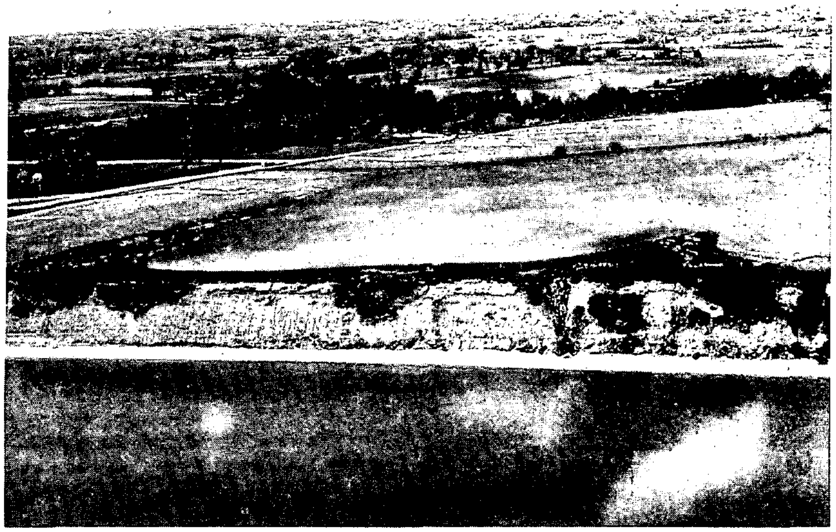


Figure 65. Oblique aerial photograph of a typical shoreline segment in north and central Reach 21. The bluff is composed entirely of lacustrine sediments with silty clay at the base grading through clayey silt to sand at the bluff top. Slope failure here is primarily through undercutting and soil fall with some high angle slumping. (oblique 52,14)

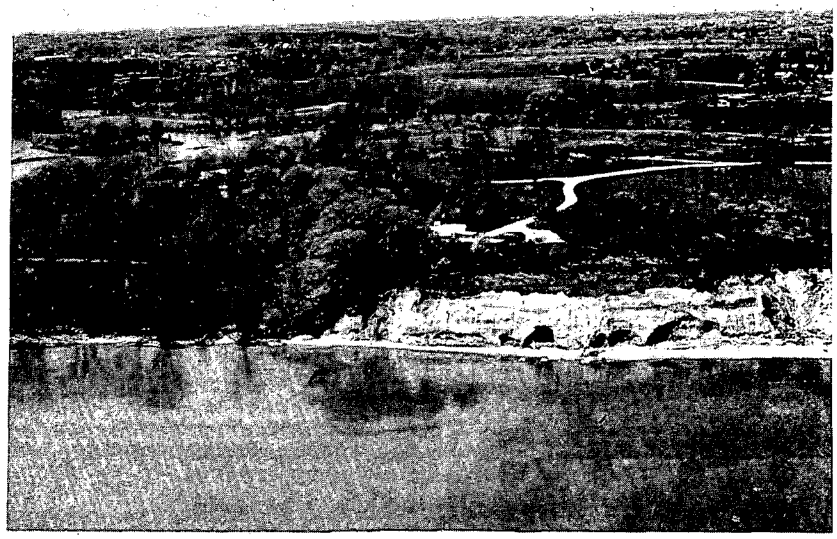


Figure 66. Oblique aerial photograph at the northern valley wall of the Pigeon River in Reach 21. Erosion of a massive silt along the base of the bluff has created a series of "sea caves." (oblique 52,22)

In the central portions of the reach the results are anomolous, with readings of 1.3 feet/year and 1.6 feet/year for the ten year average taken in close proximity to a site that showed a ten year erosion rate of only 0.3 feet/year.

In the northern portion of the reach, near the till hard point that marks its northern terminus, the ten year erosion rate was only 0.1 foot/year, although a one hundred year average of 2.0 feet/year was obtained for the same point.

Reach 22

Reach 22 is made up of the shoreline in the northern quarter of section 34 and all of that along section 27 and 22 in T. 16 N., R. 23 E. The reach has a priority ranking of 22, making it the seventh highest ranking reach in the Sheboygan-Manitowoc study area.

Land use throughout the reach is primarily agricultural, although the Wisconsin Electric Power Company has large holdings in the area and may be planning future development of a nuclear power plant.

Cobble beaches of about 20 to 30 feet are commonly found along the shoreline in this reach, and the bluff height is normally between forty-five and fifty feet.

In the immediate vicinity of the unnamed point that marks the southern boundary of the reach, the bluff is made up almost entirely of till with till 3C lying directly on till 3A . As we move northward, the normal intervening lacustrine sediments once more appear. At the south section line of section 27, twenty feet of lacustrine sediments separate tills 3C and 3A. An additional ten feet of lacustrine sediments overlie till 3C at this point. The same general stratigraphy carries northward throughout Section 27. The shoreline along this part of the coast is a relatively uniform and steep bluff. At about the south section line of section 22, there is a dramatic change in the nature of the shoreline. The steep, bare bluff found immediately to the south gives way to a series of massive slumps, some of which approach a tenth of a mile in length and are more than 100 feet from scarp to toe. This dramatic change in mode of failure appears to coincide with the pinching out of the lacustrine beds between the two tills. A profile at right angles to the bluff in a very similar area in Reach 23 is shown in Figure 67 and the contrasting failure modes are shown on Figures 68 and 69.

At the extreme northern end of the reach, the lacustrine sediments overlying till 3C begin to thin, becoming completely absent at the northern boundary.

Ten year average erosion rates at the southern and northern ends of the reach are 1.7 and 1.2 feet/year respectively. A somewhat anomolous figure of 0.1 feet/year was obtained for a site near the center of the reach. One hundred year average figures of 1 foot/year in the south, 1 foot/year in the center, and 2 feet/year in the northern portions of the reach were also obtained.

Reach 23

Reach 23 lies in Sheboygan and Manitowoc Counties and includes the shoreline in Sections 10, 15, 3 in T. 16 N., R. 23 E., and of Section 34 and a portion of Section 2 in T. 17 N., R. 23 E. This is the area lying between Seven Mile Creek and Centerville Creek. The reach has a priority ranking of 23, and is the eighth most highly ranked reach in the area north of Ozaukee County (Fig. 51,70).

With the exception of the town of Cleveland, which lies at the extreme northern end of the reach, the shoreline is almost exclusively agricultural land. Average density of dwelling within the reach, excluding the Cleveland area, is less than 5 homes per mile. (Fig. 71).

At the southern boundary of the reach, the bluff plunges sharply into the valley of Seven Mile Creek. North of the valley, which is about 1000 feet wide, the bluff once again rises steeply, attaining a height of about 50 feet. The bluff is very uniform north from this point, showing a very slow rise to the north where it reaches a height of almost 60 feet before reaching the valley of Centerville Creek at Cleveland. Throughout the reach, beaches are predominantly of cobbles, and normally 20 to 30 feet in width.

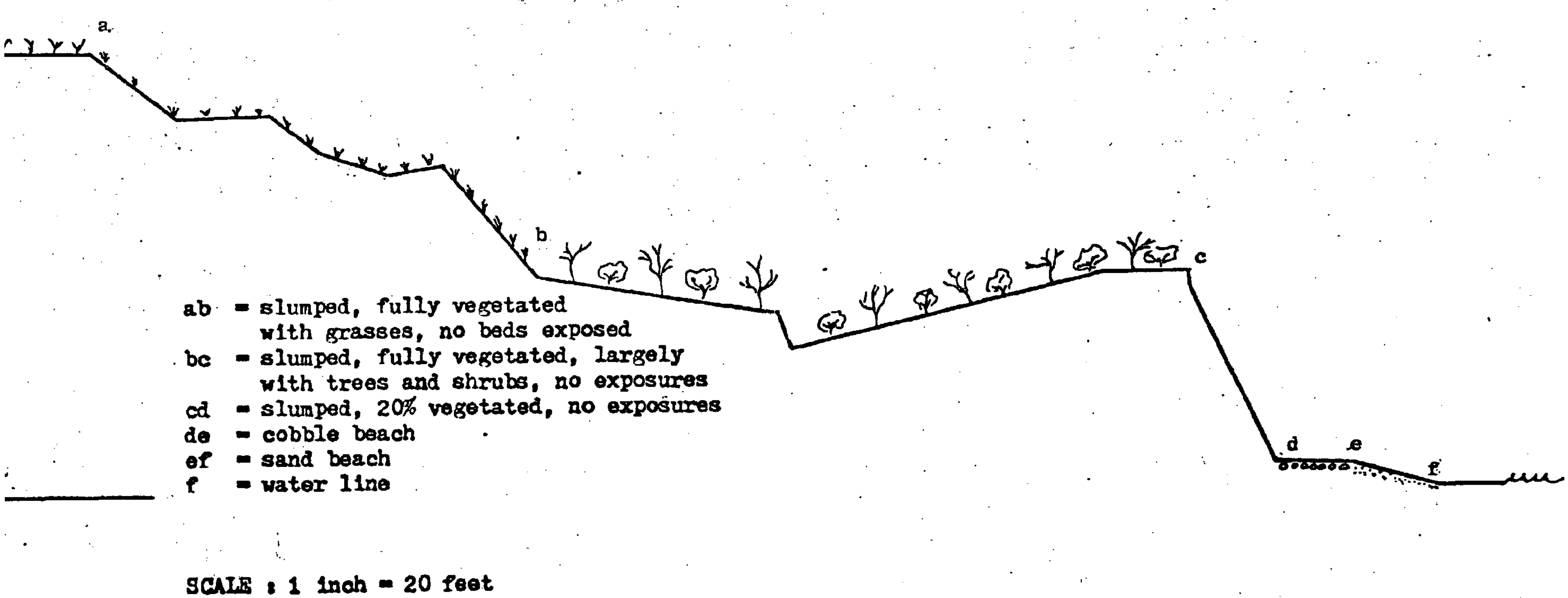


Figure 67. Cross-section through an area of large scale sequential slumping. Slope failures of this type are typical of the northern portions of Reach 22 and most of Reach 23.

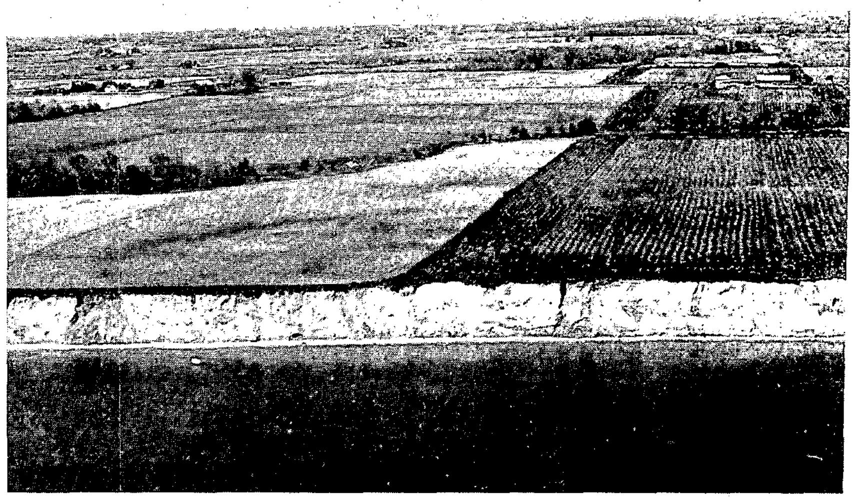


Figure 68. Oblique aerial photograph showing steep, unvegetated bluff typical of the southern portions of Reach 22. (oblique 51,35)

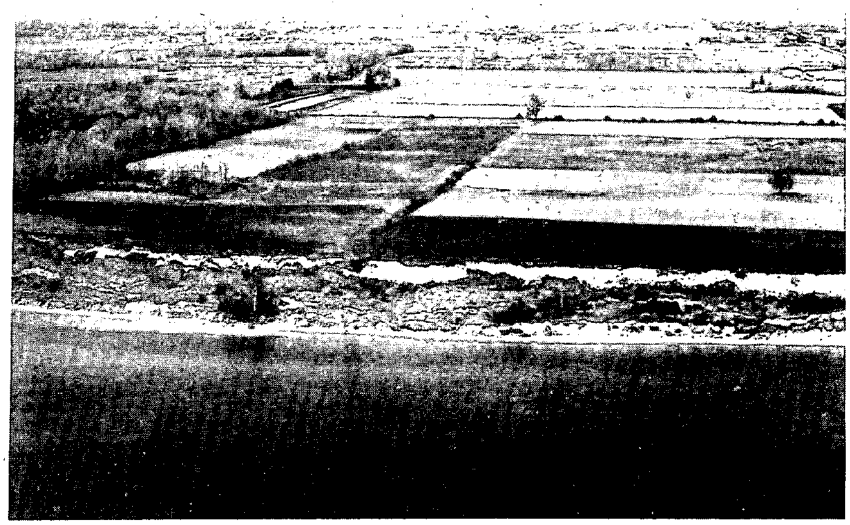


Figure 69. Oblique aerial photograph showing the large scale sequential slumping typical of the northern portions of Reach 22. (oblique 51,25)

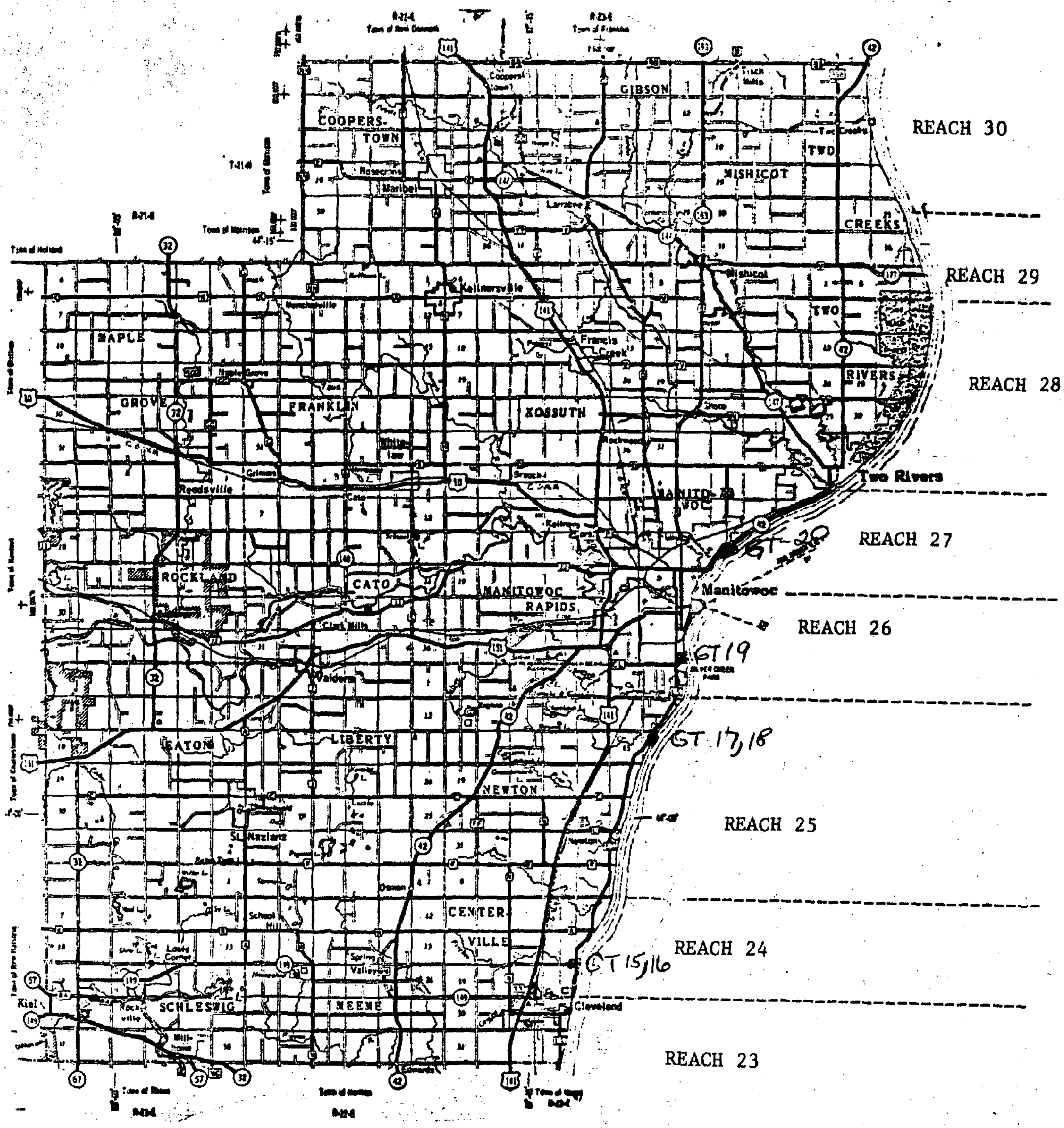


Figure 70 Map of Manitowoc County showing locations of Reaches 23, 24, 25, 26, 27, 28, 29 and 30, and geotechnical sites 15, 16, 17, 18, 19 and 20.

MANITOWOC CO.
DEPARTMENT OF TRANSPORTATION

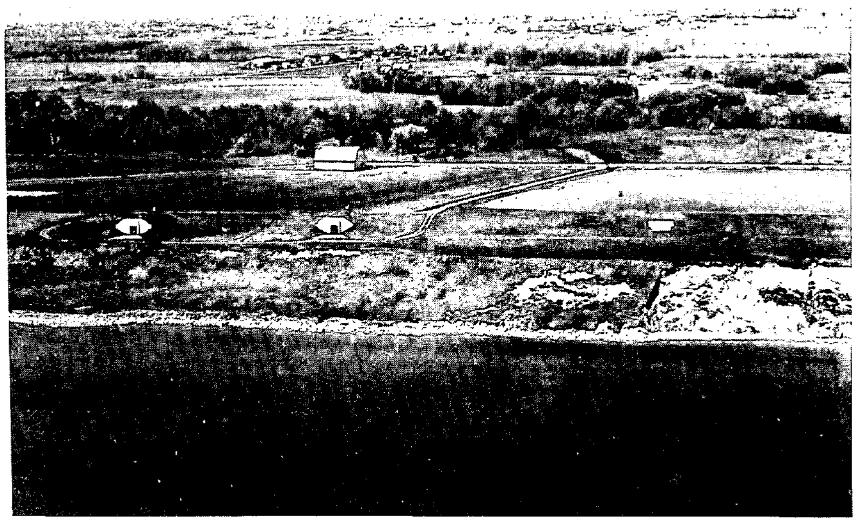


Figure 71. Oblique aerial photograph showing the contrast between the unprotected shoreline shown at the right and the largely stable and erosion free slope lying behind a well designed and constructed stone revetment on the left. Reach 23, Sec. 15, T. 16 N., R. 23 E. (oblique 51,20)

Immediately to the south of the Seven Mile Creek, till 3C is roughly 10 feet thick, and lies directly on the surface of till 3A. Just north of the valley, till 3C is absent and the erosion surface that marks the top of till 3A is within 5 feet of the bluff top under a thin cover of silty and sandy lacustrine deposits. Moving northward, the surface of till 3A makes a slow and irregular descent with the overlying lacustrine sediments showing a commensurate increase in thickness. The contact is, however, extremely irregular throughout the reach.

Till 3C once again appears in Section 10 of T.17N., R.23E. Rather than being present as a persistent bed, it occurs as lenses of till completely surrounded by sandy sediments in the upper portion of the lacustrine sequence. This is thought to be the mode of occurrence of the upper till throughout the remainder of the reach.

Despite the abrupt change in stratigraphy that occurs at the south end of Reach 23, the slope failures along the shoreline continue to be in the form of very large scale slumping with the resulting slump blocks of the type found in the northern portions of Reach 22. This type of failure makes the study of the stratigraphy through this reach extremely difficult, since very little of the stratigraphic sequence is exposed.

Only two ten year recession rate determinations were available for Reach 23 the southernmost of which was 1.7 feet/year, and the other, which was taken in Section 3, was 0.3foot/year. The one hundred year average recession rates for the reach were about 1 foot/year.

Reach 24

Reach 24 includes the area between Centerville Creek at Cleveland and Point Creek, three and one-half miles to the north. The reach includes the shoreline of the northern half of section 27 and that of all of sections 22, 14, and 11, T.17N., R.23E.

Reach 24 has a priority ranking of 17, and is the third highest reach in priority of those reaches lying north of the Ozaukee County line.

The reach includes an area of substantial residential development at its southern end, associated with the town of Cleveland, and large portions of the remainder of the reach are the property of land developers and will probably see substantial residential development in the future.

The shoreline in the extreme southern portion of Reach 24 consists of the remnants of an ancient terrace. This terrace is about two hundred feet wide near the southern reach boundary, and pinches down to the modern bluff line about a mile to the north. Beaches in this terrace area are predominantly of sand, and between thirty and fifty feet wide. Figure 72 is an oblique aerial photograph of a shoreline segment lying on the terrace.

In the area between the terrace and Fischer Creek, which lies about half way up the reach, cobble beaches predominate and beach widths are in the range of 20 to 30 feet in most areas. North of Fischer Creek, the beaches once again become predominantly composed of sand with beach widths normally between 20 and 35 feet.

The bluff height throughout the reach is about 50 feet, except in those areas where the modern ground surface slopes down into the stream valleys.

The backshore area along the terrace in the southern portion of the reach is composed of sands of mixed origin. At the point at which the ancient bluff behind the terrace begins to join the modern bluff line, till 3A once again is exposed. The erosion surface on the till is well developed, and in some areas there is a prominent stone line visible. The till is overlain by 1-3 feet of sand and rises to the north.

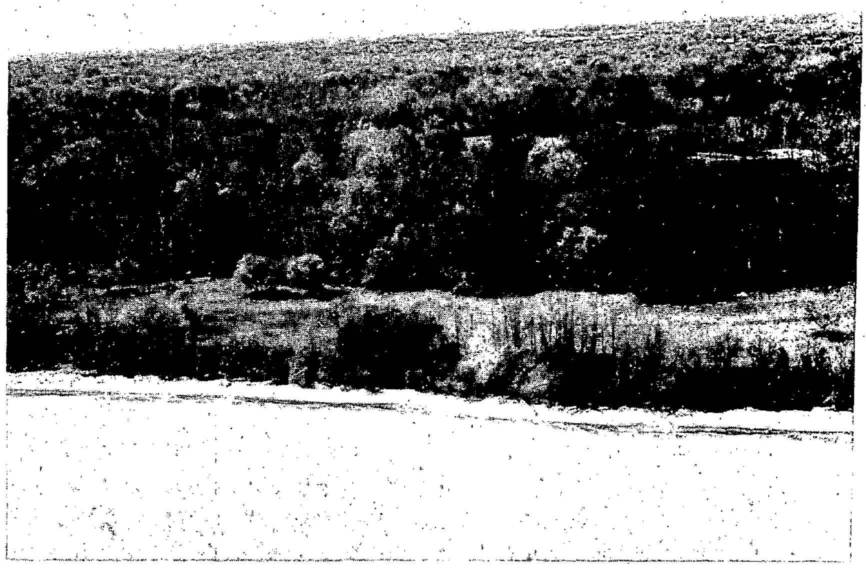


Figure 72. Oblique aerial photograph of a portion of the terrace that lies in southern Reach 24.

At the point where the terrace has fully rejoined the modern bluff line, the till is about twenty feet thick and is overlain by thirty feet of silt and sand. These stratigraphic relationships hold northward for about a half mile at which point the surface of the till plunges into the valley of Fischer Creek. The bedding in the overlying lacustrine sediments conforms to the till surface.

For a distance of about a mile north of Fischer Creek, the section is composed entirely of lacustrine sediments. These sediments are complex and contain many highly contorted beds. In the northernmost section of the reach, till 3A once again emerges from the subsurface. The top of the till is extremely irregular with the contact between the till and the overlying lacustrines dipping below the surface in a number of areas.

Along the terrace, the mechanism of erosion is simply the erosion of the highly vulnerable sand by storm waves. In the area between the terrace and the point at which the full bluff height is obtained, the mechanism of erosion is undercutting of the exposed till through wave action, leading to soil falls. Once full bluff height has been obtained, slumping becomes the predominant mechanism. Slumps in this area are, however, extremely steep and do not normally involve the full face of the bluff. In many areas, slumping is confined to the till and overlying fine grained lacustrines, with the silts and sands that make up the upper portion of the bluff in this area remaining undisturbed under a vegetative cover.

In the area of lacustrine sediments north of Fischer Creek, slumping is once again the predominant mechanism. In this area, slumps are full face with many secondary slumps occurring in those areas in which the sandy sediments have been partially removed through wave action along the toe of the slope. This type of slope failure continues to be most abundant in the northern mile of the reach, especially in those areas in which the basal till is below the beach surface.

No ten year average recession data were available for this reach. One hundred year averages ranged from 0.3 foot/year in the southern portions of the reach to 2 feet/year in the north.

Reach 25

Reach 25 is located in southern Manitowoc County, covering a north-south distance of 5.9 miles. It consists of section 1 of T. 17 N., and sections 36, 25, 24, 18, and 7 of T. 18 N., R. 23 E. Land use is predominantly agricultural with sparsely spaced rural housing. A small amount of sand and gravel extraction occurs in section 24 (Fig. 73). The reach ranks 20th on the overall priority list. Erosion rates vary from 2 feet in the north to between .2 and .3 in the central and southern portions over a 100 year average as computed by the Army Corps of Engineers in their 1952 Shore Damage Survey.

The highest bluffs in the reach are found in the far southern and the far northern portions where they obtain heights of 80 feet and 60 feet respectively. Between these two areas the bluff generally maintains a height of between 40 and 50 feet.

A red/brown silty clay till (till 3A) from 0 to 55 feet thick is found along nearly the entire length of the reach at the base of the bluff. Except in sections 1 and 36, the till is overlain by sand with smaller amounts of gravel. In these two sections silts and clay lie between the sand and the red/brown silty till. A second thin, sandy till (till 3B) lies in several locations above the red/brown silty clay till (sections 1, 7, 18), but it does not form a continuous unit.

Seeps are often noted at the contact of the surficial sand and the silty clay till (3A). The sand is usually dry and holds a nearly vertical face. The steepness of the face of the sand is aided by a vegetative cover and, in places, by compaction. Where sand composes a large portion of the bluff, failure occurs most often by slumping. Masses of clumped sand entangled in roots also slide down the face of the bluff (southern part of section 1, northern part of section 24).

Figure 73. Oblique aerial photograph showing gravel pits in a body of pitted outwash in Sec. 24, T. 18 N., R. 23 E. The floor of the pit in the foreground is at the contact between the outwash and the underlying till 3A. (oblique 48,16)

Vegetation covers large portions of the bluff face in some sections as the result of relatively stable conditions.

Where little or no vegetation is established on the silt, clay, or till, sliding and flow occurs. In places where undercutting occurs, soil fall results in steep cliffs, some measured to be as great as 56 degrees even with a 51 foot high bluff (southern part of section 18). Large slump blocks have also been noted in this reach in the northern portion of Section 18.

Beach width is variable, ranging from 5 to 50 feet. The predominant beach material is sand sized material although gravels do constitute a significant portion in some places, especially at the immediate lakeshore.

The geology and stratigraphy in section 7 of T. 18 N. are probably the most complex encountered in the area north of Ozaukee County. The section is unique in that it is the only place known to the authors in which all of the tills that have been recognized in the area are exposed (Fig. 56).

The southern boundary of the section lies just south of the south valley wall of Calvin Creek. At the section line the stratigraphic section consists of a bed of very sandy till, till 3B, overlying a thick exposure of till 3A. In the immediate vicinity of the south section line, the two tills are often separated by a thin sand bed. On the north side of the valley of Calvin Creek till 3B, rather than occurring as a continuous and well developed unit, is found as prominent lenses of till within a sequence of mixed lacustrine sediments between 5 and 10 feet thick. At several locations, this lacustrine sequence was also found to contain what appeared to be a red-brown till. This material could either be highly oxidized till 3A, till 3C, or a lacustrine clayey silt with a high pebble content. Faint indications of bedding would indicate that the latter possibility is the most likely.

At the north section line, the stratigraphy differs greatly from that in the southern portions of the section. The observed sequence is a thick bed of coarse sand overlying till 3C which in turn overlies a thick unit of sand and gravel. The widely differing stratigraphic sequences that occur at the two section boundaries can each be traced readily towards the central portion of the section. The geologic relationships where these two differing sequences meet are extremely complex and are not yet fully understood. Unfortunately, Section 7 was the last section investigated and the early advent of winter weather conditions, especially the presence of a snow cover on the high, steep bluffs that are found in this area, forced a termination of field activities in mid-December before the geology had been fully worked out.

The authors' preliminary interpretation of the geology in Section 7 is shown graphically on the longitudinal profile. As can be seen from this profile, the authors now believe that till 3A represents the oldest unit exposed and that the very sandy till 3B was deposited upon the erosion surface that marks the top of this till, probably in a shallow lacustrine environment. The sand and gravel that occupied the basal position in the northern portions of the section are believed to lap up on an erosion surface that was cut on both till C and the overlying till B with its accompanying lacustrine beds. Till 3C is believed to have moved across the sand and gravel and up the erosion surface on tills 3B and 3A. The bed of coarse sand that lies over till 3C in the northern portions of the section is thought to be the youngest unit present in the section.

If this interpretation is correct, it would lend support to the view that the sandy till 3B is intermediate in age between the two red-brown tills, tills 3A and 3C.

One investigator has reported the presence of a fourth till unit (till 1A?) in this section. This till was described as being up to 20 feet thick, and was said to occur within the sand and gravel that is the basal unit in the northern portions of the section. The relative stratigraphic position of this till, if present, has not been established.

Reach 26

Reach 26 extends from about ½ mile south of the city limits of Manitowoc at Silver Creek Park to the northern jetty at the Manitowoc Harbor. It includes Section 5 of T. 18 N., R. 24 E. and Sections 32 and 29 of T. 19 N., R. 24 E. This is a north-south distance of 3 miles. The reach has a priority ranking of 26 and is therefore the eleventh most highly ranked reach north of Ozaukee County.

At the southern boundary of the reach land use is primarily agricultural with a scattering of private residences along the shoreline. Within ½ mile, the shoreline is in parkland and at the northern end of Section 5, the shoreline is occupied by the campus of the UW-Manitowoc Center. Moving northward the reach passes through residential areas until reaching about the center of Section 32 at which point it enters Red Arrow Park. From the north end of the park to the end of the reach land usage is primarily industrial.

At the southern end of Section 5 the bluffs are 70 feet high and are made up of 14 feet of coarse sand overlying 10 feet of till 3C which in turn overlies almost 50 feet of sand and gravel. Moving northward from this point both the upland surface and the contact between the stratigraphic units drop rapidly. At the south valley wall of Silver Creek the contact between the lower sand and gravel unit and till 3C, for example, is 40 feet lower than at the south section line, 0.6 miles to the south.

At the south section line of section 32 the bluffs are 18 feet high and are composed entirely of sand. The bluffs rise steeply to the north and at the site of boring GT-19, the bluffs have risen to a height of almost 30 feet and till 3C is now exposed overlying the sand. North of this point the bluffs are heavily vegetated and where exposures are present it is usually found that the surface of the bluff is veneered with fill material that has been pushed over the edge of the bluff.

The surface continues to rise to the north until about the middle of the section at which point the bluffs are about 50 feet high. Northward from this point the bluffs lose height rapidly and by about the north section line have completely given way to a low sand plain along the shoreline.

The beaches along the southern half of Reach 26 are of sand and cobbles and are from 20 to about 40 feet wide. North from here to the north end of Red Arrow Park, sand beaches predominate. Many of them are more than 50 feet wide. North of this point the beaches are either absent or obtain a maximum of about 20 feet.

From the south section line of section 5 to about 0.15, erosion is very rapid and slumping and sliding of the lower sand and gravel in this high bluff area appears to cause quite rapid retreat of the bluffs. From 0.15 to about 0.7 at the mouth of Silver Creek, slope failures occur mainly as slumps which often involve most, if not all, of the face of the bluff. From Silver Creek north to the end of Silver Creek Park at about 0.9 there are no bluffs and shoreline erosion occurs through the action of waves against the low lying shoreline. From this point north to the section line slopes are gentle and completely vegetated with grasses.

Slumping is again common in about the southern 0.2 mile of sec. 32. North of this area, the slopes are veneered with fill, fully vegetated and appear to be largely stable. From Red Arrow Park to the end of sec. 32, there are no bluffs.

As part of a separate investigation, the author inspected the south half of Section 29 (the remainder is Manitowoc Harbor) and photographed the structures lying along the shoreline in this area. It was found that the entire shoreline is armored by heavy revetments or bulkheads and that the bulkheads were backed by sand, some of which is undoubtedly fill. Since this is a fully armored section, Section 29 has been deleted from this investigation.

Two long term recession measurements both gave values of one foot per year.

Reach 27

Reach 27 consists of the area between the northern jetty of the harbor at Manitowoc and the town of Two Rivers. The reach includes the shoreline in portions of Sections 20, 17, 16, 10, 11, and 1 of T. 19 N., R. 24 E. The reach has a priority rating of 16, and is the most highly ranked reach in the Sheboygan-Manitowoc study area.

Over most of this reach, the shoreline consists of a well-constructed revetment with either sand, fill, or both behind. The immediate shore zone is separated from residential, commercial, or park lands by a four lane highway in most of the reach.

A few small, scattered beaches are found in this reach, but many appear to be ephemeral. Some of the beaches present when the reach was inspected were not found to be visible on the air photographs taken earlier in the year, and some beaches shown on the photos were no longer present.

The reach is, with the exception of a single section to be discussed later, protected by heavy structures which over large areas are backed by fill.

Significant exposures of stratigraphy and unprotected shoreline segments are, however, present in section 16. The remainder of this discussion will, therefore, be confined to this section.

The bluffs in section 16 rise to a maximum height of about 30 feet above the beaches. In the southwestern portion of the shoreline in the section, very little stratigraphy is exposed due to heavy vegetative cover and the large amount of slumped silt that covers the greater part of even actively eroding areas. About 3 feet of bluff silt over 2 feet of silty clay was the maximum section observed in the southwestern portion of section 16 (Fig. 74).

In the northeastern portion of the section, several excellent exposures were located from which it was possible to determine the stratigraphy from the top of the bluff to beach level. The section was found to consist of basal lacustrine sands, which were overlain by a one to three foot thick bed of till 3B, which was in turn overlain by roughly 10 feet of the same red silty clay observed to the southwest. The silty clay was in turn overlain by the buff silt found in the equivalent stratigraphic position in the southwestern exposure. The silt was overlain by a highly oxidized till identified as till 3C, and the section was capped with about a foot of sand. A thin greenish-gray sand layer in this unit was found to make an excellent marker bed.

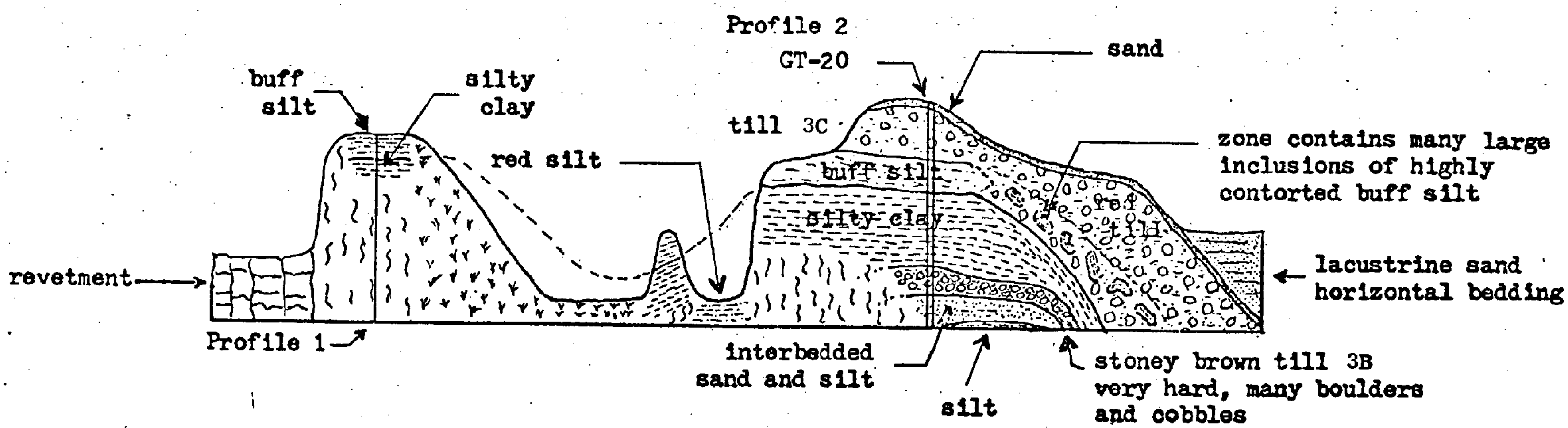
Although essentially flat lying where first observed, all of the units described were found to plunge to the northeast at the wayside on top of the hill in Section 16. The beds were then overlapped by a horizontally bedded sand. The top of the bed of till 3C dipped into the subsurface at the north section line.

Figure 74 is a generalized longitudinal profile of Section 16; figure 75 is an oblique aerial photograph of a portion of the high bluff shoreline in section 16; and figure 76 shows a low-lying and heavily protected area, typical of most of Reach 27.

Lake Superior Reach Descriptions

Reach 1

Reach 1 extends southeasterly 3.4 miles from the Wisconsin-Minnesota state line at Superior Entry to the base of Wisconsin Point (Fig. 77). The reach is located in sections 27, 28, 34, and 35 of township 49 north, range 13 west in Douglas County and is the most northwesterly reach in Wisconsin. The reach is a low-lying sand spit that ranges from 3 to 15 feet above lake level which together with Minnesota Point, to the west, forms a bay mouth bar that is the longest fresh water spit in the world. The spit separated Allouez Bay from Lake Superior. Beaches are made up predominantly of sand and pebbles and range in width from



SCALE:
Horizontal: 1 inch = 1000 feet
Vertical : 1 inch = 20 feet

Figure 74. Generalized longitudinal profile of Sec. 16, T. 19 N., R. 24 E., Reach 27.

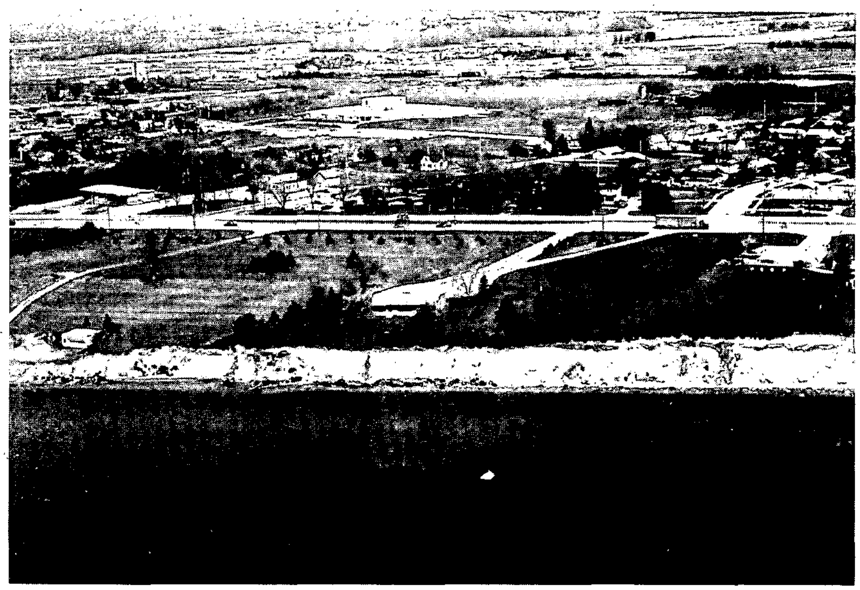


Figure 75. Oblique aerial photograph showing a portion of the high bluff area in Sec. 16, T. 19 N., R. 24 E., Reach 27.

Figure 76. Oblique aerial photograph showing a typical heavily protected segment of the shoreline in Reach 27.

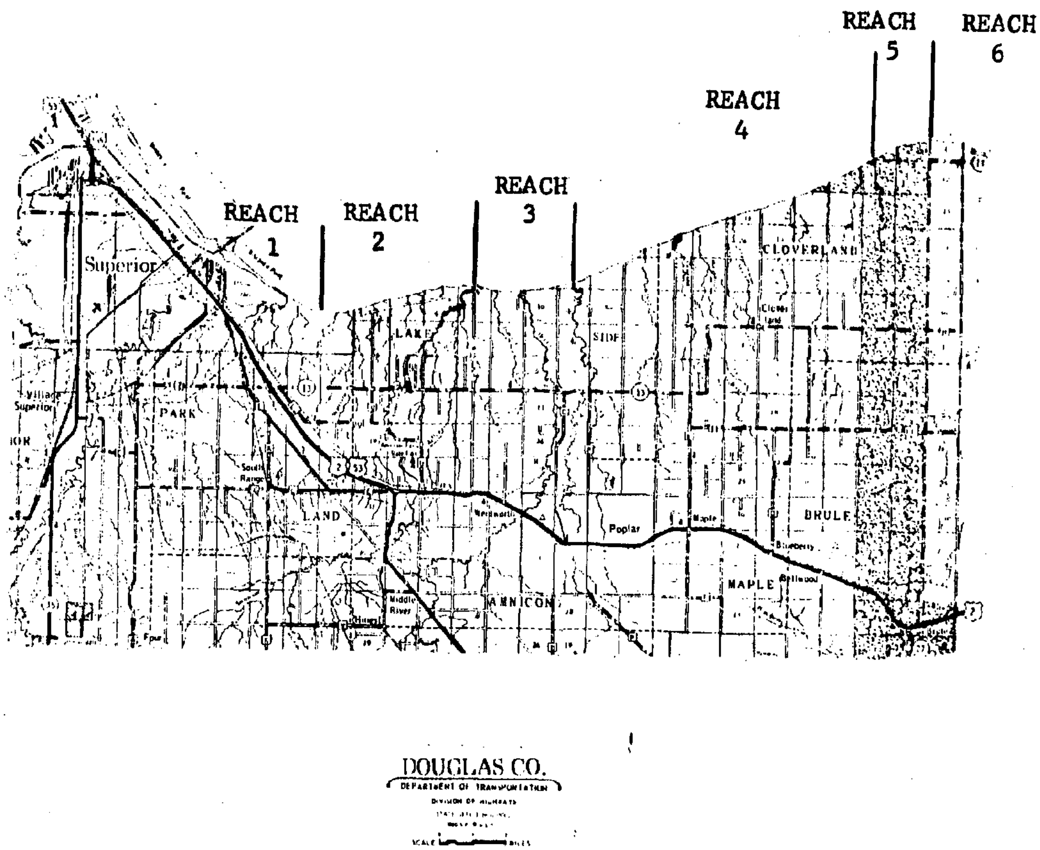


Figure 77. Map of Douglas County.

more than 300 feet on the west to 3 feet on the eastern end of the reach. Although accretion is dominant in this segment of the coast the amount of accretion decreases from a maximum of more than 10 feet/year at Superior Entry to an erosion rate of about two feet/year near the base of the spit. Breaches of the spit have periodically exposed the marshes on the east end of Allouez Bay to direct wave action. The reach is also one of the few shore areas on the western arm of Lake Superior where the sand supply is sufficient to allow the formation of sand dunes.

Much of the reach is a low developed recreational area largely owned by the City of Superior. The abandoned Coast Guard Station adjoining Superior Entry is occupied as a study center by the University of Wisconsin-Superior. The only shore protection or navigational structures in the reach are the jetties protecting Superior Entry and a dock adjacent to the Coast Guard Station.

Reach 2

Reach 2 extends 4.9 miles east from the base of Wisconsin Point to the mouth of the Amnicon River in sections 35 and 36 of township 49 north, range 13 west and sections 31, 32, 33, and 34 of township 49 north, range 12 west in Douglas County (Fig. 77). The reach has an erodible, high bluff ranging from 40 feet to 65 feet above lake level. The bluff is composed predominantly of red clay and silt with occasional sand lenses. The bluff is dissected by Dutchman Creek, Morrison Creek, six unnamed streams and the Amnicon River. Along this shore the rivers emanate from south of the Douglas fault some 6 to 10 miles inland and flow predominantly on bedrock across the intervening coastal plain. The creeks and unnamed streams are still down cutting through the red clay of the coastal plain and are frequently subject to damming by long shore drift during low flow conditions. Beaches in this reach vary from a maximum width of 65 feet to being absent. The widest beaches are almost always in the vicinity of a river or creek mouth and are frequently covered with draftwood, a typical feature of the Lake Superior Coast. The beach is composed of sand and pebbles with occasional boulder erratics. Frequently the beach offers no protection for the bluffs and relatively low waves cross the narrow beaches to act directly on the toe of the bluff. The wave action destroys the stability of the slope subjecting the bluff to almost constant erosion in the form of slides, slumps and earth flows. During rainy seasons the bluff material flows across the narrow beach and the near shore area becomes highly turbid with the fine materials. Spring sapping is also frequent, particularly in areas of the bluff having sand lenses. The erosion rates in this reach range from 8.7 feet/year to 2.7 feet/year. The reach is largely undeveloped with a few seasonal or permanent residences in the vicinity of road ends and stream mouths. There are no shore protection structures or bedrock outcrops in this reach.

Reach 3

Reach 3 extends 3.2 miles east from the mouth of the Amnicon River to the mouth of the Poplar River and is located in sections 34, 35, and 36 of township 49 north, range 12 west, and section 30 of township 49 north, range 11 west in Douglas County (Fig. 77). The height of the bluff in this reach ranges from 55 feet to 65 feet and the bluff is composed predominantly of red clay and silt. The bluff is dissected by Hanson Creek, Middle River and three unnamed streams in addition to the Amnicon and Poplar Rivers.

Beach width in this reach varies from about 30 feet at the mouth of the Amnicon River to nothing at intermediate points between stream mouths. The beach is composed of sand and pebbles, occasional cobbles and frequently driftwood. With the narrow beaches the waves frequently impact directly on the bluff instigating slope failures such as slides, slumps and earth flows.

The reach is mostly undeveloped and the only access is by three town roads. The only shore protection structures in the reach are located on the east side of the Amnicon River. A timber groin and a sunken barge were placed at that point to protect a now abandoned sand and gravel operation. These structures are almost completely destroyed and offer little shore protection.

Reach 4

This Reach 4 extends 9.7 miles east from the mouth of the Poplar River to the mouth of the Bois Brule River in Douglas County, and is located in sections 13, 14, 21, 22, 23, 28, 29, and 30 of township 49 north, range 11 west, and sections 8, 9, 10, 17 and 18 of township 49 north, range 10 west (Fig. 77). The reach has an erodible, high bluff ranging from 40 feet to 75 feet above lake level. The bluffs decrease in height from west to east. The bluffs are primarily red clay and silt with occasional sand lenses. Beaches are composed of sand, pebbles and driftwood. The beaches vary in width from about 100 feet at the mouth of the Bois Brule River to nothing at many locations. Waves consistently cross the narrow beaches to cause massive slides, slumps and earth flows. Frequent slide scars indicate the movement of large trees from the bluff crest to the water's edge.

The bluff through this reach is highly dissected by Bardon, Pearson, Haukkala, Nelson, Fisher and SMith Creeks, and sixteen unnamed streams as well as the Poplar and Brule Rivers. An unusual feature in this reach is the very long spit that frequently develops at the mouth of the Bois Brule River. The spit extends westward from the east bank of the river mouth and may at times attain a length of over one-half mile, sometimes adding a neighboring stream as a tributary of the Brule by extending across that stream entrance. The reach is relatively undeveloped except near the mouth of the creeks and rivers. Access is generally restricted to the section line roads except at the mouth of the Bois Brule River which is served by a state forest road. There is a precast concrete groin immediately west of Bardon Creek that is in excellent condition and a beach has formed on its easterly side. There are no other structures in the reach except for a boat ramp near the mouth of the Bois Brule. Erosion rates in this reach range from nearly six feet per year to about two feet per year. Minimum erosion along the western arm of Lake Superior coincides with the entrance of rivers into the lake because maximum beach widths also occur at the mouth of the rivers. There are no bedrock outcrops in this reach.

Reach 5

This reach extends 2.0 miles northeast from the mouth of the Bois Brule River to Brule Point in Douglas County. The reach is located in sections 2, 3, and 10 of township 49 north, range 10 west (Fig. 77). Bluff height in this reach varies from 10 feet to 40 feet and averages about 35 feet. The bluff is primarily made up of red clay and silt except in the lower portions where the sand content increases. Beach widths range from absent to 30 feet and the beach is composed of sand and pebbles. Bedrock outcrops are not readily visible in this reach but sandstone outcrops do occur in the immediate near shore zone near Brule Point and may control the location of that promintory. The reach is largely state owned and undeveloped except near the mouth of the Brule. Cleared fields near Brule Point are evidence that some cultivation has been tried and abandoned. Access to the area is limited to the western end of the reach and five trails near the east end. There are no shore protection structures in this reach, but there is a boat ramp on the Bois Brule near its mouth. Erosion processes are similar to other segments of this "Red Clay" shore, waves cross the narrow beaches to directly attack the base of the high erodible bluffs. This action keeps the bluffs' slopes unstable and promotes various forms of mass movement such as slides, slumps and earth flows.

Reach 6

This reach extends 4.4 miles easterly from Brule Point to a rock prominence 700 feet west of the mouth of the Iron River and is located in sections 1 and 2 of township 49 north, range 10 west; sections 4, 5, and 6 of township 49 north, range 9 west; and section 33 of township 50 north, range 9 west (Fig. 78). The western 1.1 miles of this reach are in Douglas County and the balance is in Bayfield County. The bluff height ranges from 20 feet to 40 feet and the bluff is predominantly red clay with some interbedded sands. The bluff is dissected by Fish Creek, Reefer Creek and two unnamed streams. Erosion rates in this reach vary from a high of about 10 feet/year to a low of about 7 feet/year. Beach

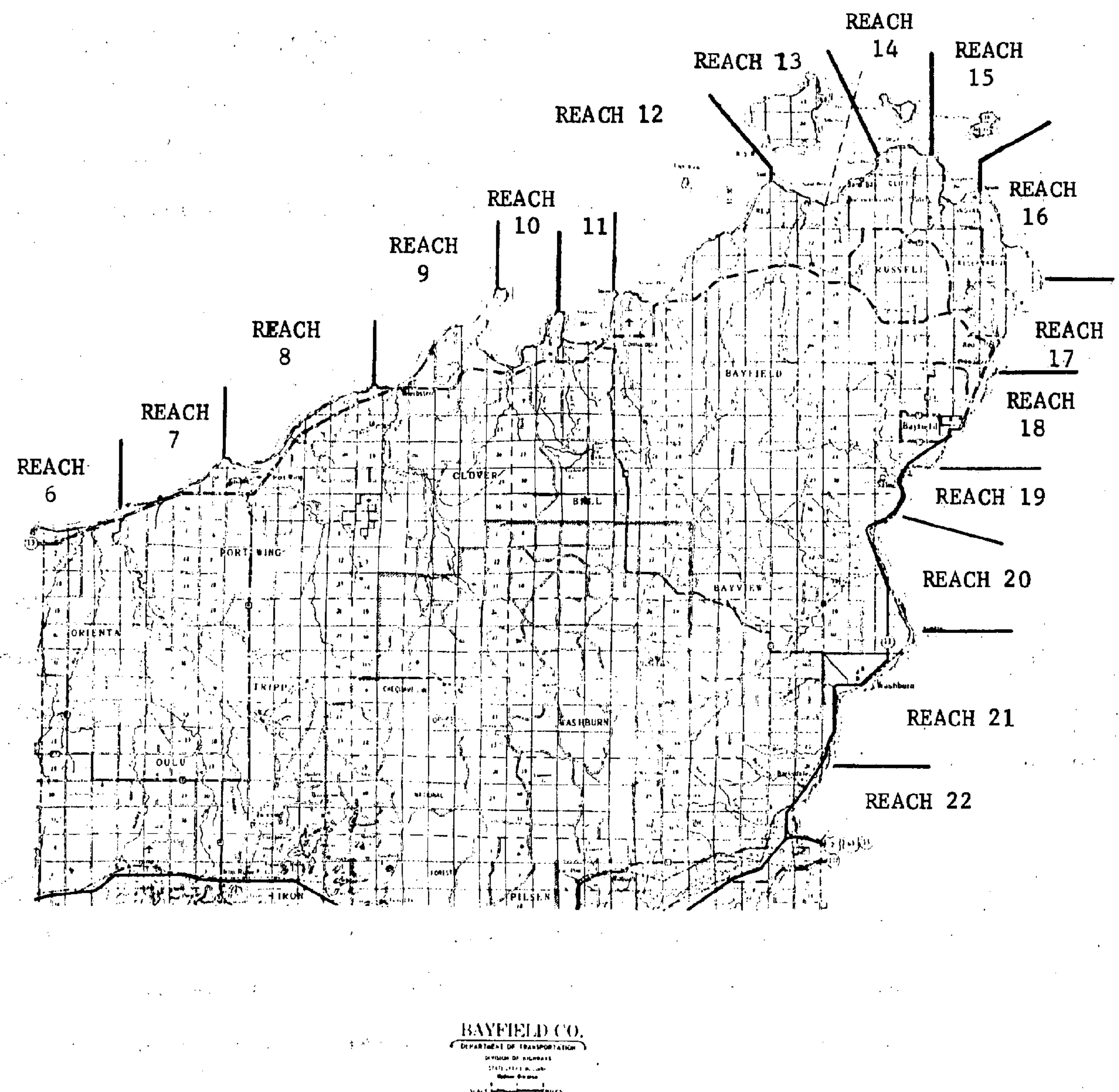


Figure 78. Map of Bayfield County.

widths in the reach vary from 30 feet to nothing and are composed mostly of sand and pebbles although an increasing number of boulder erratics are also present. The westernmost bedrock outcrops along the south shore occur in this reach in the form of flat-bedded sandstone about 1000 feet west of the Iron River. This outcrop is visible near the level of the lake. Erosion processes are visibly similar to other "red clay reaches" with wave action causing direct erosion of the bluff in areas with narrow beaches and also causing bluff failures such as slides, slumps and earth flows. The evidence of these failures is not as spectacular as it is farther west in the areas of higher bluff.

Reach 6 is highly developed with primarily seasonal residences between the shore and state highway 13. There are no shore protection structures in this reach of the Lake Superior Coast.

Reach 7

Reach 7 extends five miles northeasterly from a point 700 feet west of the mouth of the Iron River to Quarry Point in Bayfield County. The reach is located in sections 33, 34, 35, and 25 of township 50 north, range 9 west; and sections 30 and 19 of township 50 north, range 8 west. The reach is a medium to high bluff (average 25 feet) shore. The bluff is composed mainly of red clay and silt. The bluffs are dissected by the Iron River, Jardine Creek and two unnamed streams in this reach. The beach varies in width from 110 feet on the west bank of the Iron River to absent at other locations. Where present, it is composed of sand and pebbles, some boulders, and localized sandstone shingle and cobble. One frequently finds clay balls formed by wave action on pieces of clay from the bluff. The erosion rates in this reach range from 4.4 feet/year to 1.0 foot/year and average about 2.0 feet/year. The erosion processes are dominated by wave action on the bluffs and the resulting slope failures in the form of slumps, slides, and flows.

One of the unusual features in this reach is a shingle-cobble spit damming the mouth of Jardine Creek. The material is well rounded sandstone that is a deep reddish brown. The source of the material may be a sandstone outcrop on the west side of the creek mouth or other outcrops in the near shore zone. A major sandstone outcrop occurs at Quarry Point, west of Port Wing. This outcrop was quarried, as the name would imply, for building stone used in Superior and Duluth near the turn of the century.

There is a boat ramp on the Iron River near its mouth but no shore protection structures in this reach. The reach is sparsely developed with seasonal and permanent residences located between the shore and Highway 13.

Reach 8

This reach extends from Quarry Point 7.1 miles east and northeast to a rocky promontory 1.1 miles west of the mouth of the Cranberry River and includes the harbor entrance at Port Wing in Bayfield County. The reach is located in sections 11, 12, 14, 15, 19, 20, 21, and 22 of township 50 north, range 8 west; and sections 6 and 7 of township 50 north, range 7 west (Fig. 78). This reach is marked by highly contrasting shore types. At each end of the reach low sandstone cliffs are present, the westernmost two miles of the reach are low-lying sand spits forming a bay mouth bar at the mouth of the Flag River, and the remainder of the reach has the highest (over 200 feet above lake level) bluffs on Wisconsin's Great Lakes Coast. Sin unnamed streams dissect this extremely high bluff segment of the reach. Quarry Point averages only about 10 feet in height while the Port Wing spit is generally less than 10 feet above the present lake level. One of the highest shore recession rates occurred west of the entrance to Port Wing when the spit was completely eroded following the extension of the jetties at the harbor entrance. This shore retreat amounted to almost 2000 feet and occurred in about a 10 year period during and after World War II. The spit has since been rebuilt, with the aid of the westerly long shore drift, although it remains narrower than the spit to the east of the harbor entrance.

The extremely high bluffs to the east of Port Wing are very different in appearance and composition from the high bluffs to the west. The bluffs appear to be either reworked glacial till or outwash and take on a "flat iron" appearance when viewed from the lake. The bluffs are composed of interbedded sand, silt, and clay with abundant gravels and cobbles. This bluff is undoubtedly the source of most of the beach material at Port Wing because of the much higher percentage of coarse material than the "red clay bluffs." Although recession rates are lower than many other areas, 2.0 feet to 6 feet per year, the volume of material eroded probably exceeds any other segments of Wisconsin's Lake Superior shore of similar length, because of the greater bluff height. Beach widths vary from about 50 feet at Port Wing to absent at the rocky points. Beach widths along the high bluff segment average less than 10 feet inwidth because of the steep near shore slope. The high bluff area is undeveloped in contrast to the Port Wing area where the harbor was developed in the latter part of the 19th Century in connection with a saw mill operated in that area. There is good public access at Port Wing but the high bluff shoreline is totally inaccessible by road. The only shore protection structures in this reach are the steel sheet pile jetties protecting the entrance to the Flag River and Port Wing.

Reach 9

This reach extends from the rocky prominence one mile east of Herbster northeast 6.9 miles to Bark Point and is located in sections 4, 5, and 6 of township 50 north, range 7 west; and sections 24, 26, 27, 33, and 34 of township 51 north, range 7 west in Bayfield County (Fig. 78). The bluff in this reach is quite variable ranging in height from 150 feet to 10 feet and averaging about 40 feet above the level of the lake. The low bluff areas are a sand spit at the mouth of the Cranberry River. This area also has greater beach widths than the rest of the reach (about 70 feet) and the only structure. The structure was originally a jetty or pier at the mouth of the Cranberry River but all that remain are a few timber pilings in very poor condition and nonfunctional. The bluff is composed of sand, clay, and gravel while the beach is mostly sand and pebbles.

Beach widths along the higher bluff areas are generally less than 10 feet wide. Sandstone bedrock outcrops at each end of the reach and its height in the bluffs is usually higher to the east. The reach is moderately developed with seasonal and permanent residences. Public access is excellent at Herbster where the village maintains a public park on the lake front. Bark Point is a mixture of residential, recreational and agricultural development.

Reach 22D

This reach is located on the east side of the City of Ashland and extends 2.1 miles east from the west boundary of Lake Park to a road end two miles east of the city limits. It is located in sections 27, 23, 24, and 19 of township 48 north, range 4 west. The top of the bluff in this segment ranges from 20 feet to 40 feet above the lake level and much of the bluff is composed primarily of red clay and silt. Beaches are composed of sand and pebbles but are relatively rare in this reach.

The reach is largely residential except for the city park and there are many shore protection structures in the reach of highly variable construction. The most common structural form is rock-filled timber cribs used as groins or revetments. Some of the most interesting and substantial structures are "home made" from salvaged timbers of the old ore docks in Ashland that float ashore after heavy storms. The most serious erosion problems occur in those properties that have not constructed shore protection structures. This also creates a major problem for those property owners that have protective structures because of the difficulty of protecting the existing structures from flanking (wave attack on the unprotected sides of the structure). Shore recession rates in the unprotected segments of this reach have averaged as high as five feet per year, even though this reach is semi-protected by the offshore breakwater in Ashland and the arm of Chequamegon Point and Long Island. These sand spits protect the reach from the open lake and decrease the effective fetch of waves approaching this shore.

Reach 27

Reach 27 extends from the base of Chequamegon Point eastward 4.8 miles to Marble Point, in sections 26, 27, 35, and 36 of township 48 north, range 2 west; section 1 of township 47 north, range 2 west; sections 5 and 6 of township 47 north, range 1 west and section 32 of township 48 north, range 1 west (Fig. 79, 80). The western 2.6 miles are in Ashland County and the eastern 2.2 miles are in Iron County. Bluff heights range from 20 feet to 80 feet above lake level, but average bluff height is about 60 feet above the lake. Although this reach is in the "red clay" area, samples of the bluff material indicate that these materials are primarily coarse silt and very fine sand with little if any clay size material. The composition of these bluffs is however highly variable.

The beaches, composed of sand and pebbles, range from 30 feet to 10 feet in width and are particularly susceptible to rapid changes in dimension because of their openness to large northeast storms off Lake Superior. There are no shore protection structures in this reach, but a demonstration site using various patterns of Longard tubes is to be constructed in this reach in 1977. The reach is generally undeveloped except for a recreational site on the west end of the reach and a picnic ground at Madigan Beach. Erosion rates in this reach average about one to two feet per year. This reach is entirely within the Bad River Indian Reservation.

Reach 28

This reach extends 4.4 miles from Marble Point easterly to the Wisconsin-Michigan state line at the mouth of the Montreal River. It is located in sections 3, 4, 10, 11, and 12 of township 47 north, range 1 west; and section 7 of township 47 north, range 1 east in Iron County (Fig. 80). The westernmost mile of the

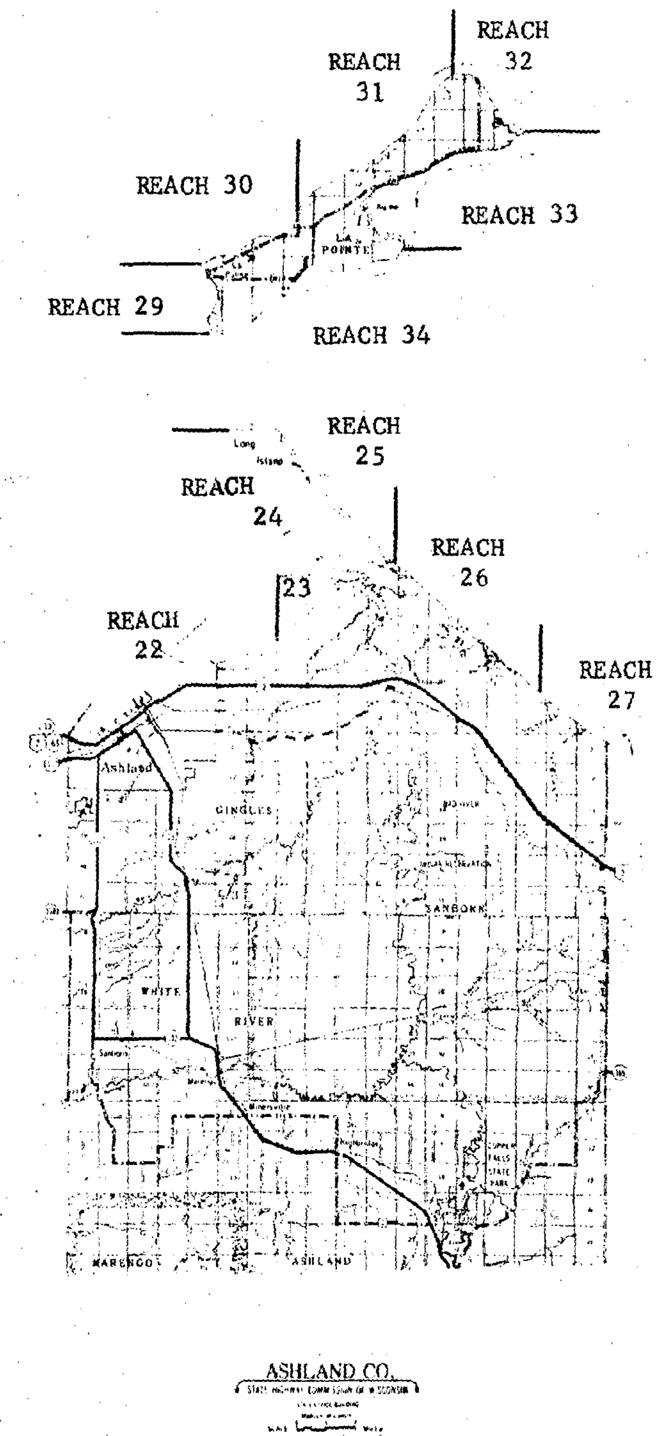


Figure 79. Map of Ashland County.

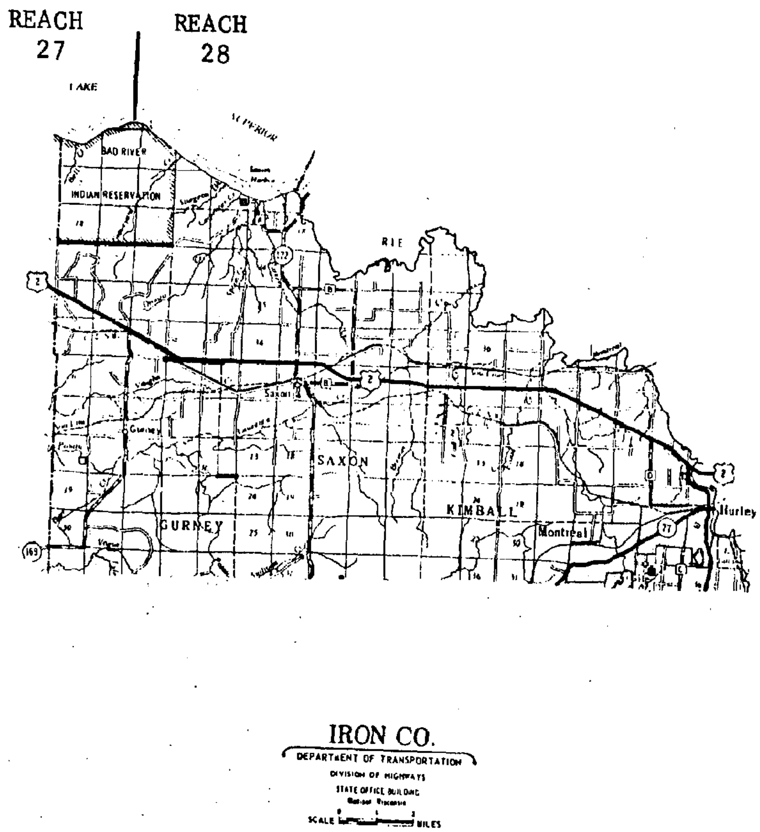


Figure 80. Map of Iron County.

reach is in the Bad River Indian Reservation. The reach has a high bluff (10-80 feet) shore with narrow beaches and several bedrock outcrops. Most of the bluff is composed of interbedded sands and silts with a clay cap in the upper 10 feet. Sandstone bedrock outcrops at Marble Point and as steeply dipping strata in the vicinity of the Montreal River. Slumps, slides and earth flows are promoted by the eroding waves that cross the narrow beaches to attack the toe of the bluffs. The bluff is dissected by Graveyard Creek, Sturgeon Branch, Carpenter Creek, Parker-Oronto Creek and the Montreal River.

The reach forms a large open embayment known as Oronto Bay. At the apex of the bay a small boat marina, Saxon Harbor, is located adjacent to the mouth of Parker-Oronto Creek. Beaches in the reach are narrow varying from 30 feet to nothing and are composed primarily of sand and pebbles with increasing amounts of well-rounded pebbles and cobbles to the east. The only shore protection structure in this reach is a riprap revetment immediately west of the entrance to Saxon Harbor. The revetment has not been adequate to protect this site from further erosion. The harbor entrance is protected by a sheet pile nozzle and a caisson arm. The mouth of Oronto-Parker Creek is also protected by sheet piling in an effort to prevent the damming of the stream by long shore drift.

Reach 33

This reach extends from Big Bay Point easterly 5.6 miles to Amnicon Point on Madeline Island in Ashland County in sections 12, and 13 of township 50 north, range 3 west; sections 19, 7, 8, 5, 4, 3, and 2 of township 50 north, range 2 west; and sections 35 and 36 of township 51 north, range 2 west (Fig. 79). Bluff heights in this reach range from 5 feet to 20 feet above the level of the lake. The bluff material is highly variable and includes red clay, till, sand and sandstone. The sandstone bedrock outcrops at Big Bay Point, Amnicon Point and on both sides of Big Bay. Big Bay has a spit forming a bay mouth bar on its western side that forms Big Bay Lagoon. Beach widths range from more than 60 feet to absent. The beaches are composed of sand and pebbles and occasionally sandstone cobbles and erratic boulders in the near shore area. The reach is lightly developed on the western end of the reach on Big Bay where the use is primarily recreational in state and county parks. From Big Bay east to the vicinity of Amnicon Point the reach is primarily residential although there are also several fishing camps. The easternmost end of the reach, at Amnicon Point, is in theBad River Indian Reservation. There are many shore protection structures associated with the residential area bordering County Highway H. The structures are quite variable but the most common form is rock filled oak cribs used as piers, groins and revetments. The structures are economical and usually functional. A portion of Highway "H" in section 8 of township 50 north, range 2 west has been repeatedly threatened by erosion damage creating a major problem in this reach.

SUMMARY AND CONCLUSIONS

Material Properties

A really intensive investigation of the material properties of the soiles along the shoreline and especially their statistical variations and interdependencies, was not undertaken in this study. However, several general observations can be made through an interpretation of the laboratory results obtained.

Standard Penetration numbers for the sand deposits indicate in most instances relatively dense sands. A plot of all the triaxial test results on sands and silts shows a strong relationship between the dry density of the sands and their drained angle of internal friction (see Fig. 81). For most of the sands, maximum and minimum void ratios were not determined, so that a comparison based on relative density is not possible; however, with respect to their absolute density, there is still a reasonable dependence of ϕ' on γ_d, with the points falling in a fairly narrow range of values. Maximum and minimum ϕ' angles are 34.7 and 41.0° respectively, with the angle of internal friction at any given density falling within a range of values varying by less than 4.5°. The values for the silts tested as a dry powder in triaxial tests indicate a lesser angle of internal friction for the same density, while the cohesion, obviously could not be measured.

For clayey soils, the values of the Liquid and Plastic Limits for all the samples tested have been plotted on a plasticity chart, Fig. 82. This chart shows the relatively narrow range in the classifications of these materials; all samples tested were either low-plasticity silts or clays. The grain size distribution of the tills is shown in Figures 83, 84 and 85.

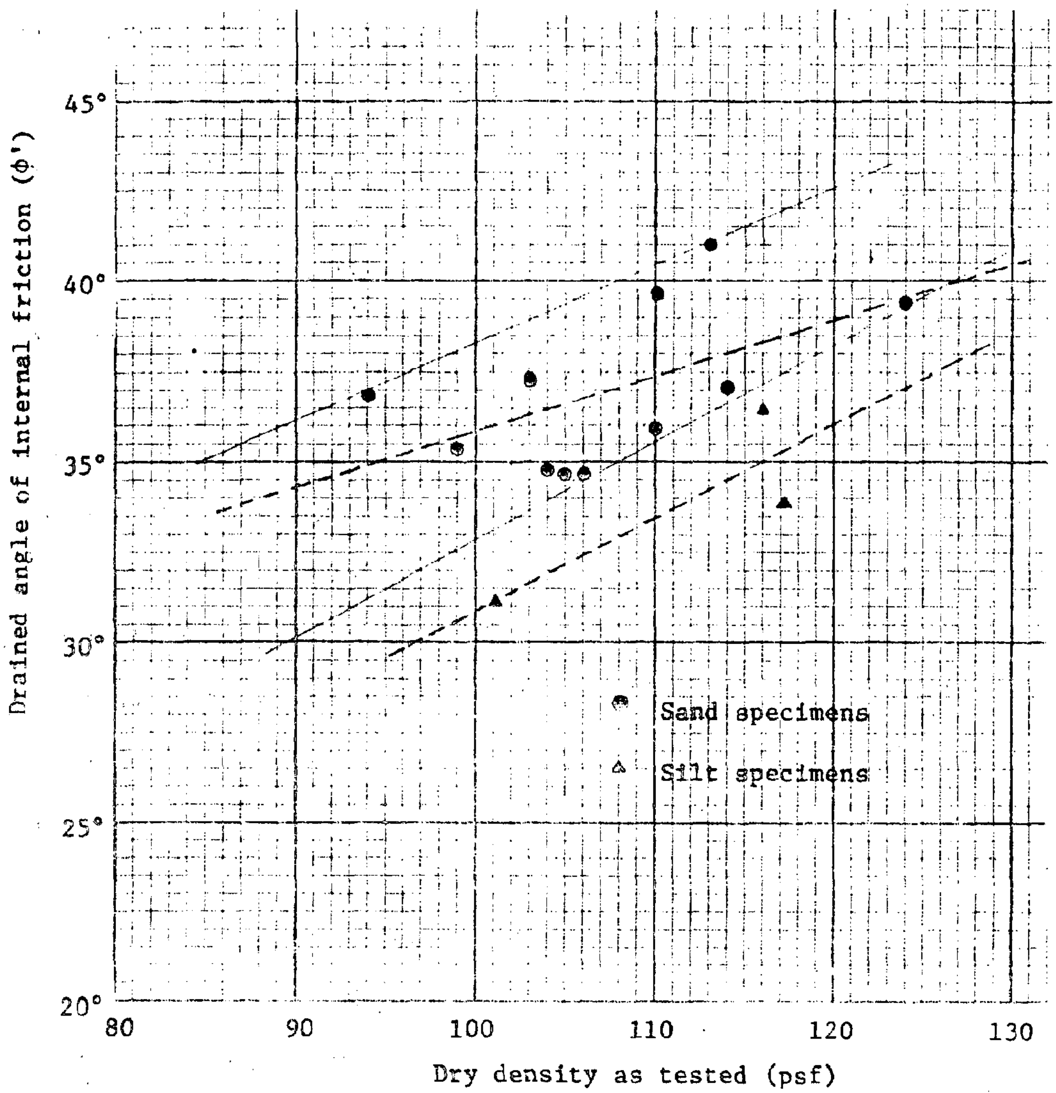


Figure 81. Drained angle of internal friction vs. dry density for sand and silt specimens.

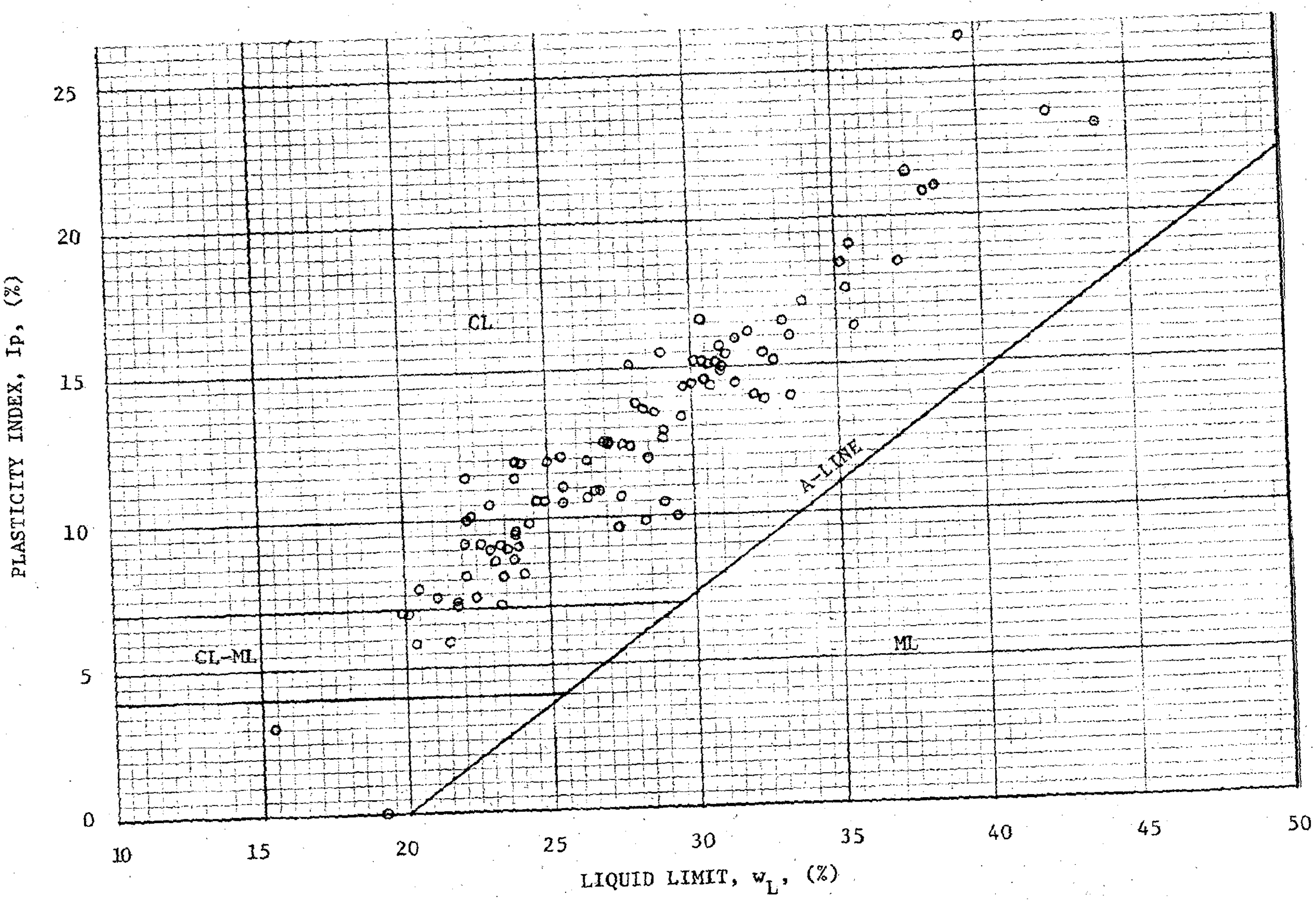


Figure 82. Plasticity chart for all soils tested.

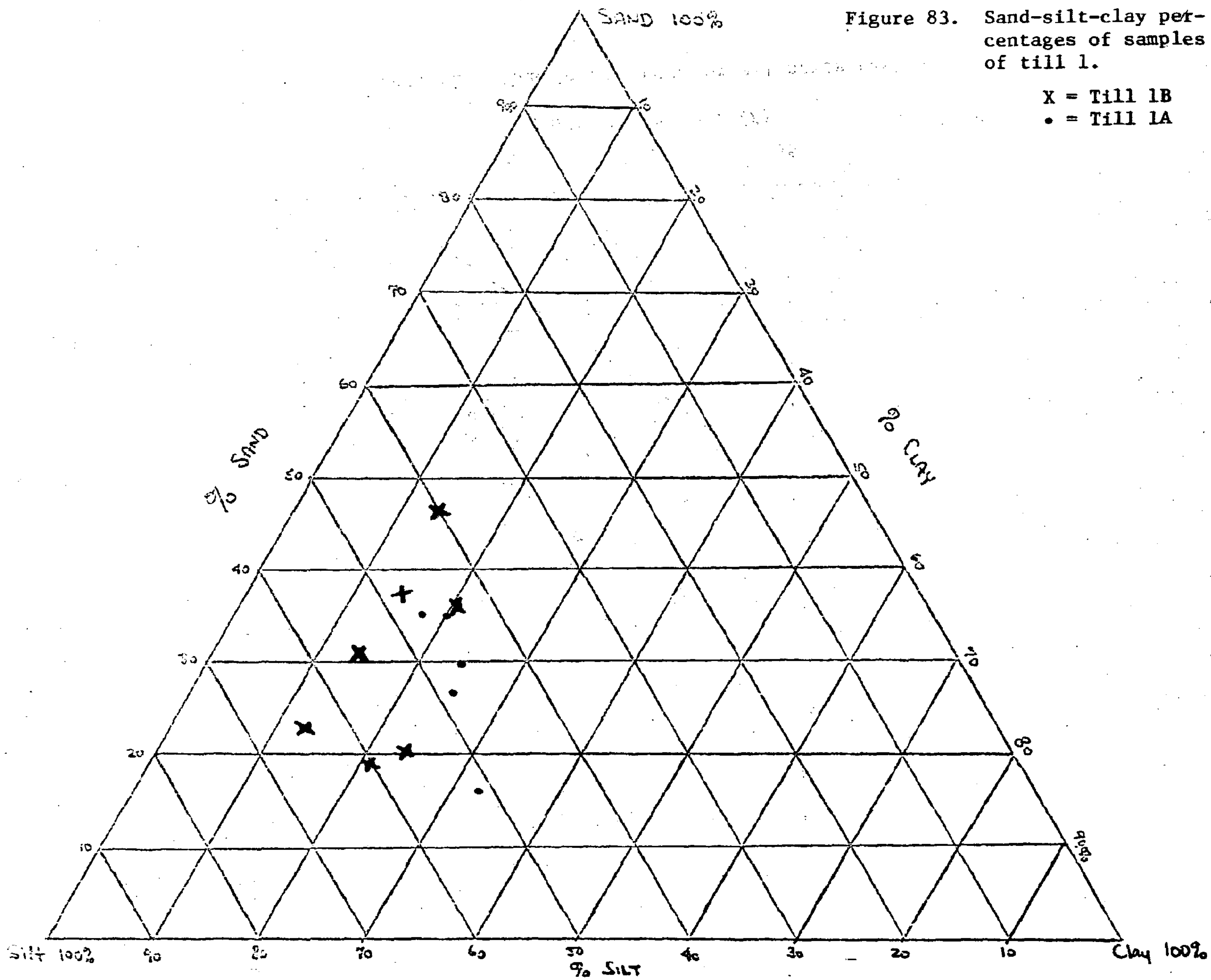


Figure 83. Sand-silt-clay percentages of samples of till 1.

X = Till 1B
• = Till 1A

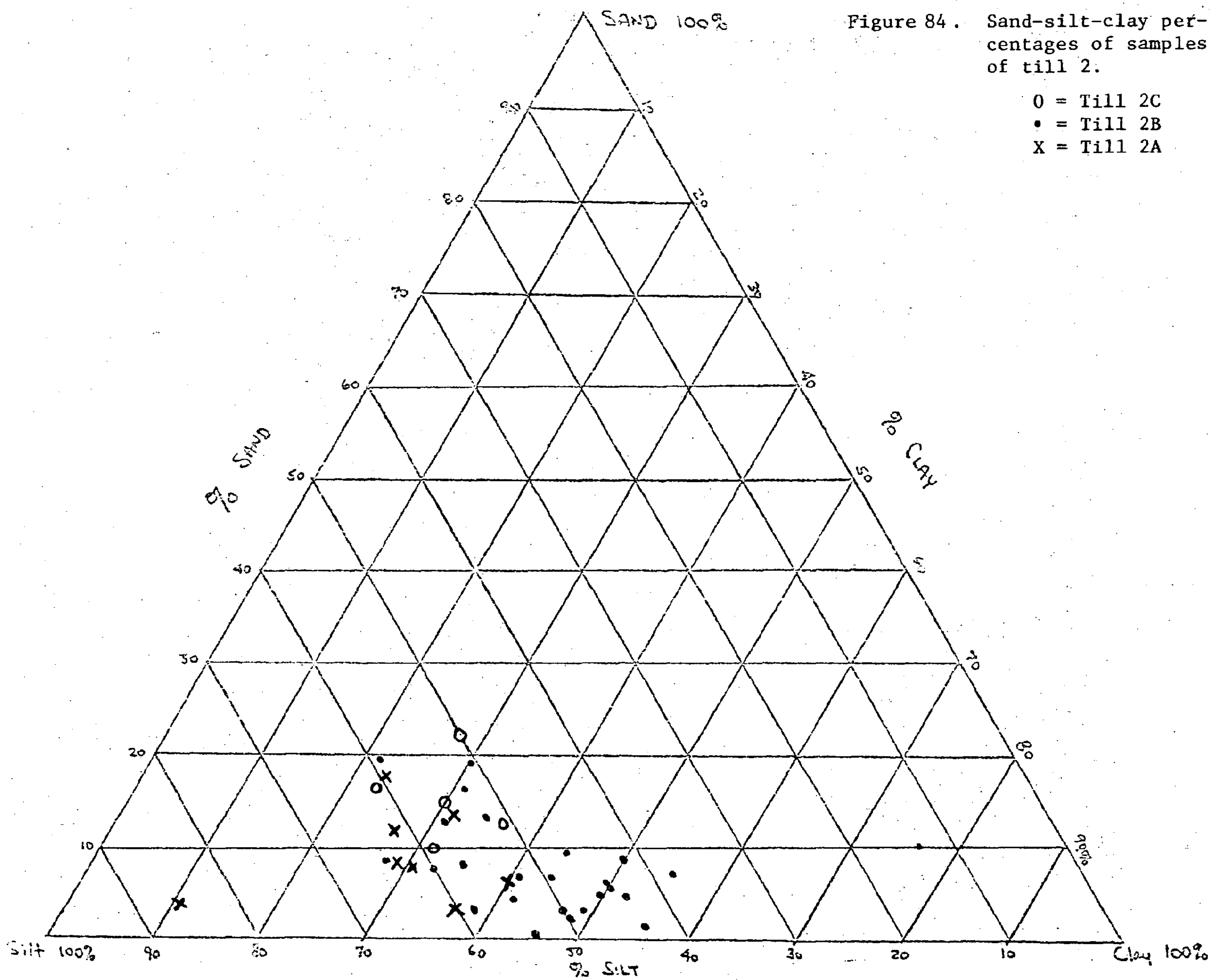
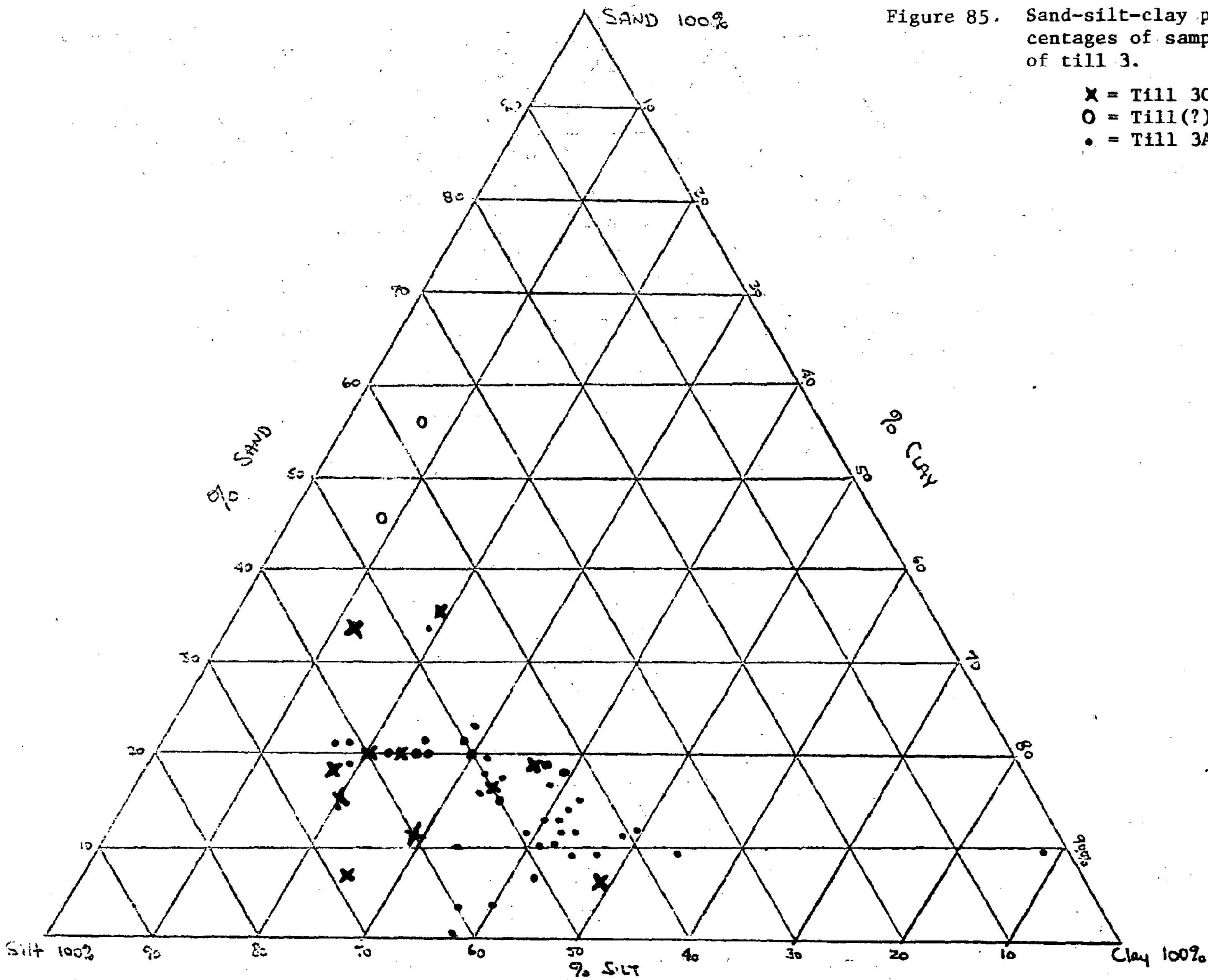


Figure 84. Sand-silt-clay percentages of samples of till 2.

0 = Till 2C
• = Till 2B
X = Till 2A

Figure 85. Sand-silt-clay percentages of samples of till 3.

X = Till 3C
O = Till(?)3B
• = Till 3A



Inspection of the Atterberg limits, and strength characteristics of the clayey soils, leads to a distinct differentiation of the tills and lacustrine deposits. A summary of these properties based on the averages of all of the samples tested within a given layer or unit at each borehole is shown in Table 2,3. The till layers have been grouped according to their geologic similarities, and their properties statistically correlated. The results are tabulated in Table 4, and drawn on a plasticity chart, Fig. 86. Difference in the material properties within a particular unit arise in the fact that local chemistry may alter the clay characteristics, source material from the same glacial unit may vary somewhat with location, and the local stress history at any particular site (e.g. glacial overburden, overlying lake deposits, etc.) may change the strength parameters significantly.

With reference to the above correlations, the following generalizations or observations can be made:

1. The entire range of the Atterberg limits of all the specimens tested is relatively small, comprising mostly low-plasticity clays and clayey silts. This is even more striking when the average values for the till units is observed--practically all of the averages have Liquid Limits between 22 and 32 per cent, with corresponding Plasticity Indices between 9 and 15 per cent.

2. A correlation cannot be made between the Atterberg limits of a particular sample and its drained strength parameters. The southern grey till unit (2A,B) in Racine and southern Milwaukee Counties has drained strength parameters approximately equal to those of the red till unit (3A) of northern Milwaukee and Ozaukee counties; but the averages of their Atterberg limits (w_L = 24.1 & 30.7%; Ip = 10.1 & 14.1%, respectively)

South | North

	GT-9	GT-10	GT-5	GT-4	GT-1	GT-8	GT-6	GT-7
	Sand ϕ'=36.8 γ=94	Sand ?	?	Tan, Sandy Silty Clay ϕ'=29° W_L: 17.6 I_p: 5.0 ϕ'=27°	Gray Silty Clay Till Till 2B ϕ'=31.4 c'=0 γ=117 W_n=15.4 W_L: 21.8-29.0 (25.1) I_p: 7.2-12.8 (10.06)	Red-Brown Silty Clay Till Till 3A ϕ'=32.5 c'=0 γ=113 W_n=17.7 W_L: 28.3-31.0 (29.8) I_p: 9.8-15.2 (12.6)	Red-Brown Silty Clay Till Till 3A ϕ'=30.5 c'=0 γ=112 W_n=19.3 W_L: 30.4-32.5 (31.3) I_p: 14.6-15.4 (15.0)	Red-Brown Till (3A) ϕ'=31.3 c'=0 γ=113.8 W_n=17.4 W_L: 28.1-33.2 (31.0) I_p: 13.7-16.5 (14.7)
	Gray Silt ϕ'=36.4 c'=0 γ=116	Gray Silt ϕ'=31.1 γ=101	Gray Lacustrine Clay ϕ'=28 c'=318 γ=120 W_n=14.8 W_L: 21.2-28.5 (25.7) I_p: 8.3-11.9 (10.3)	Gray Clayey Till Till 2A ϕ'=31.2 c'=0 γ=120 W_n=13.7 W_L: 22.2-24.9 (23.2) I_p: 8.1-10.6 (9.45)	Gray Lacustrine Clay ϕ'=25.6 c'=1187 γ=110 W_n=19.6 W_L: 26.6-30.6 (28.9) I_p: 10-15.1 (12.0)	Sand ϕ'=41 γ=113	Sand ϕ'=34.7 γ=106	Sand ϕ'=34.8 γ=104
	Gray Silty Clay Till Till 2 ϕ' unknown W_L: 29.6-31.3 (30.0) I_p: 13.4-13.5 (13.5)	Gray Silty Clay Till Till 2 ϕ' unknown W_L: 22.1-26.8 (24.4) I_p: 8.7-10.7 (9.66)			Gray Silty Clay Till 2A ϕ'=31.0 W_n=17.2 γ=114 W_L: 23.8-27.7 (25.8) I_p: 9.8-12.4 (10.9)	Gray Clayey Silt Till 2 ϕ' unknown W_L: 20.5-25.0 (22.8) I_p: 7.7-11.8 (10.0)	Gray-Clay Till(2) γ=119 W_n=16.7 W_L: (24.5) I_p: (9.9)	Silt ϕ'=33.7 γ=117 ϕ'=35.9 γ=114
							Silt ?	Rd-Brown Lacustrine Clay ϕ'=29.6 c'=82 γ=112 W_n=18.8 W_L: 25.4-32.8 (29.5) I_p: 12.1-15.2 (14.2)
							Gray Clay Till (1B) W_L: 23.0 I_p: 10.7	

Table 2. Summary of borehole information (see also Table 3).

South — North

GT-11	GT-12	GT-14	GT-13	GT-15	GT-17	GT-19	GT-20
Tan Sand $\phi'=39.7$ $\gamma=110$	Yellow Sand $\phi'=39.4$ $\gamma=124$	Red-Brown Till (3C) $\phi'=29.9$ $c'=471$ $\gamma=116.5$ $W_n=15.5$ W_L: 23.8-35.5 (29.2) I_p: 11.8-19.1 (14.7)	Sand $\gamma=94$	Sand $\phi'=34.7$ $\gamma=105$	Sand $\phi'=35.4$ $\gamma=99$	Till C ? no record	Till A Red Till $\phi'=29.3$ $c'=792$ $\gamma=111$ $W_n=15.8$ $W_L=(27.4)$ $I_p=(10.3)$
Red-Brown Silty Clay Till(3A) ϕ' unknown W_L: 31.5-43.8 (37.9) I_p: 15.8-23.2 (20.0)	Silty Sand $\gamma=124$	Gray Clayey Sand	Clayey Silt (Till) (Till 3C) $\phi'=29.8$ $c'=471$ $\gamma=119$ $W_L=(21.2)(9.1)$	Silt $\gamma=123$	Sandy Gravel ?	Yellow Sand $\phi'=37.3$ $\gamma=103$	Brown Lac. Clay $\phi'=35.9$ $c'=0$ $\gamma=103$ $W_n=24.3$ $W_L=(36.8)$ $I_p=(19.2)$
Sand ?	Brown Silty Clay Till(3C) $\phi'=28.7$ $c'=511$ $\gamma=106$ $W_n=22.4$ W_L: 24.2-35.6 (31.7) I_p: 8.2-16.3 (13.6)	Gray Clayey Silt ϕ' unknown $\gamma=130$ $W_n=15.8$ W_L: 21.4-25.6 (23.5) I_p: (9.2)	Sand ?	Red-Brown Clayey Silt Till $\phi'=31.3$ $c'=530$ $\gamma=118$ $W_n=17.3$ W_L: 19.9-30.1 (24.2) I_p: 5.8-15.2 (9.45) (Till 3A)	Red-Brown Clayey Silt Till $\phi'=31.5$ $c'=380$ $\gamma=120.5$ $W_n=15.5$ W_L: 26.3-34.4 (29.7) I_p: 11.9-17.6 (14.2) (Till 3A)	Silt ?	Sand $\phi'=35.9$ $\gamma=110$
	Red Clay Till (3A) $\phi'=30$ $c'=696$ $\gamma=116$ W_L: 29.0-30.6 (29.8) I_p: 12.6-14.3 (13.5)	Red Brown Clay Till 3A $\phi'=22.3$ $c'=1023$ $\gamma=102$ $W_n=25.3$ W_L: (36.4) I_p: (19.6)	Clay Till(3A) $\phi'=31.3$ $c'=530$ $\gamma=109$ $W_n=20.3$ W_L: 23.3-42.3 (33.6) I_p: 7.1-23.4 (17.1)			Sand $\phi'=37.1$ $\gamma=114$	

Table 3. Summary of borehole information (see also Table 2).

Table 4

Summary and Correlation of
Laboratory Results on Glacial Till Units

Grey till. Racine and Milwaukee Counties. (Till 2)

Strength: (GT-4) $\phi' = 31.2°$, $c' = 0$ (GT-1) $\phi' = 31.4°$, $c' = 0$ (GT-1) $\phi' = 31.0°$, $c' = 0$

Average-- $\phi' = 31.2 \pm .2°$
$c' = 0$

Atterberg Limits: (GT-10) $w_L = 24.4$, $I_p = 9.66$ (GT-4) $w_L = 23.2$, $I_p = 9.45$ (GT-1) $w_L = 25.1$, $I_p = 10.06$

(GT-1) $w_L = 25.8$, $I_p = 10.9$ (GT-8) $w_L = 22.8$, $I_p = 10.0$ (GT-6) $w_L = 23.0$, $I_p = 10.7$

Average-- $w_L = 24.05 \pm 1.13\%$
$I_p = 10.13 \pm .52\%$

Red-brown till. North Milwaukee and Ozaukee Counties. (Till 3A)

Strength: (GT-8) $\phi' = 32.5°$, $c' = 0$ (GT-6) $\phi' = 30.5°$, $c' = 0$ (GT-7) $\phi' = 31.3°$, $c' = 0$

Average-- $\phi' = 31.4 \pm .8°$
$c' = 0$

Atterberg Limits: (GT-8) $w_L = 29.8$, $I_p = 12.6$ (GT-6) $w_L = 31.3$, $I_p = 15.0$ (GT-7) $w_L = 31.0$, $I_p = 14.7$

Average-- $w_L = 30.7 \pm .65\%$
$I_p = 14.1 \pm 1.07\%$

Lower Red-brown till. Sheboygan and Manitowoc counties. (Till 3A)

Strength: (GT-12) $\phi' = 28.7°$, $c' = 511$ psf (GT-12) $\phi' = 30.0°$, $c' = 696$ psf (GT-17) $\phi' = 31.5°$, $c' = 380$ psf

(GT-14) $\phi' = 22.3°$, $c' = 1023$ psf (GT-13) $\phi' = 31.3°$, $c' = 530$ psf (GT-15) $\phi' = 31.3°$, $c' = 530$ psf

Average-- $\phi' = 29.18 \pm 3.2°$, $c' = 612 \pm 206$ psf; $\phi' = 30.56 \pm 1.07°$, $c' = 529 \pm 100$ psf (if GT-14 ignored)

Atterberg Limits:
Average-- $w_L = 30.93 \pm 3.97\%$, $I_p = 14.53 \pm 3.24\%$ (all samples of till unit, including boreholes GT-8,6,& 7)

$w_L = 29.8$ 3.1%, $I_p = 13.6$ 2.4% (lower till unit in Sheboygan & Manitowoc)

Upper red till. Sheboygan and Manitowoc counties. (Till 3C)

Strength:
Average-- $\phi' = 29.55 \pm .39°$, $c' = 578 \pm 151$ psf (GT-14&13) $\phi' = 29.83°$, $c' = 471$ psf (GT-20) $\phi' = 29.0°$, $c' = 792$ psf

Atterberg Limits:
Average-- $w_L = 27.34 \pm 4.08\%$, $I_p = 12.7 \pm 1.76\%$ (all samples of till unit)

Note: Averages are mean values of the average properties assigned to each till layer at each borehole, with the standard deviation indicated.

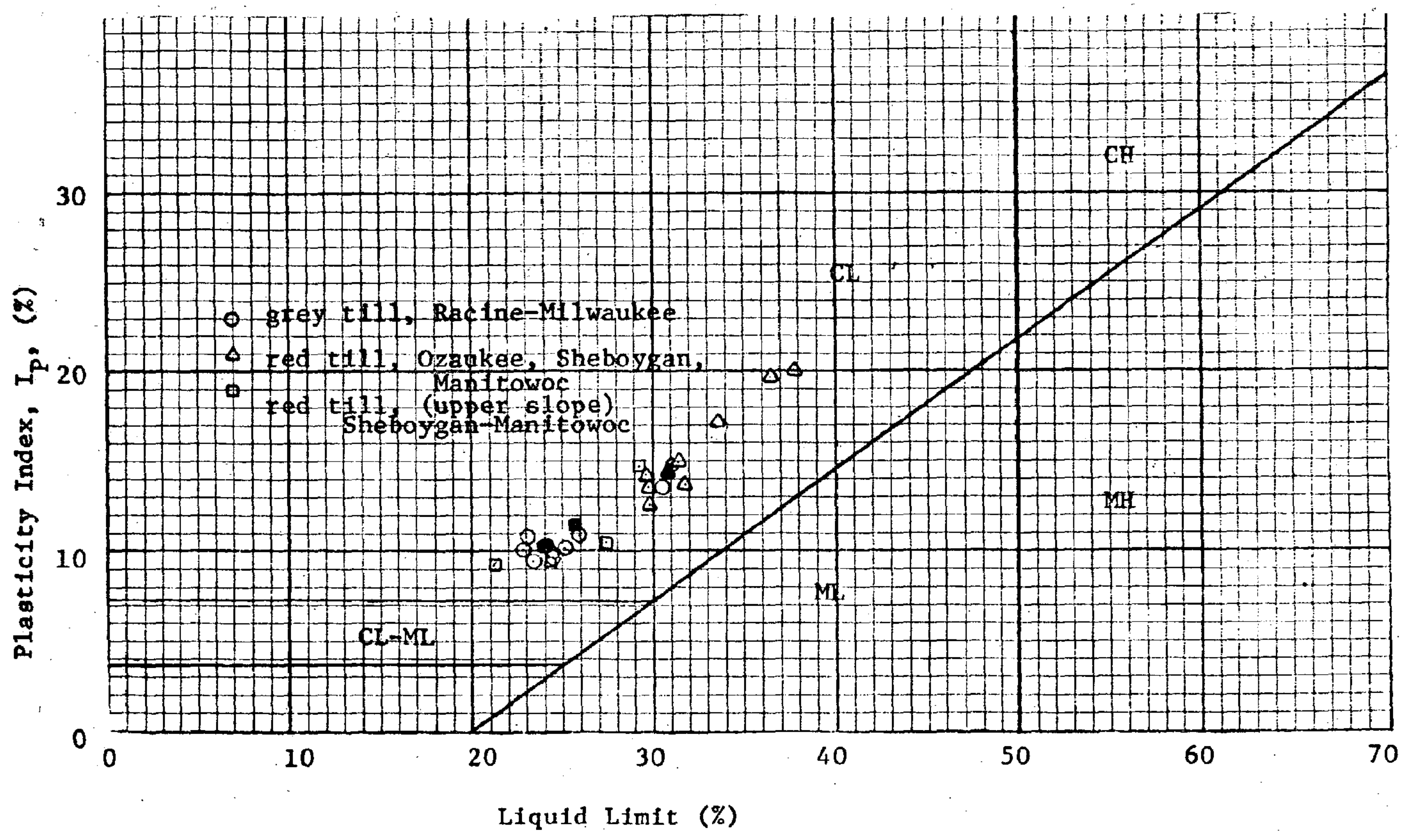


Figure 86. Plasticity Chart for averages of till units. (average for unit in solid color)

do not agree well with one another. Conversely, the Atterberg limits for the red till of Ozaukee County (3A) compare closely to the averages of several samples of the same till unit exposed in the lower bluff reaches of Sheboygan and Manitowoc counties; but their drained strength parameters vary considerably (ϕ' = 31.4° & 30.6°, c' = 0.0 and 530 psf, respectively). Therefore, no "rule-of-thumb" simplification is possible.

3. This is not to say that there is complete scatter in the results obtained. In fact, the geotechnical properties are relatively constant for samples of a given glacial unit under similar conditions, i.e. in a similar geographic location. The drained angle of internal friction for all samples of the Racine-Milwaukee grey till unit (2A,B) vary by only 0.2 degrees, while their average Liquid Limits vary by only 1.13 per cent, and their Plasticity Indices vary by only 0.52 per cent. Also, the red, upper till (3A) of Ozaukee County has a variation in ϕ' of only 0.8°, and in Atterberg limits of 1.07 and 0.65% for w_L and I_P, respectively. Even the somewhat more variable lower red till unit (3A) of Sheboygan and Manitowoc counties has drained strength parameters varying by only 1.07 degrees for ϕ', and 100 psf for c', which is relatively small in comparison with the lab inaccuracies. The upper red till unit (3C) of Sheboygan-Manitowoc varies by only 0.39° in ϕ', and by only 151 psf in c'.

4. Lacustrine deposits follow no set trend in their properties, so that their drained strength parameters cannot be predicted. As a casual observation, the drained angles of internal friction of lacustrine clays are generally smaller, the cohesion generally larger than those of the till units in the same area, but this is not true in every case. The clay of GT-5, it may be noted, has Atterberg limits very close to those

of the grey till of Racine-Milwaukee (2A,B) which lies on either side of it; likewise, in GT-7, the lower red-brown lacustrine clay has limits very similar to those of the upper red till in Ozaukee county. In other instances, the limits of neighboring till and lacustrine deposits may vary considerably, as in GT-1 and GT-20.

In summary, it can be stated that the Atterberg limits of the till deposits along the Lake Michigan shoreline do, in many cases, exhibit significant similarities, when they are of the same glacial unit, and are subjected to similar influences. The drained strength parameters can be roughly predicted for the southernmost tills (2, 3A in Racine, Milwaukee and Ozaukee counties) within relatively narrow limits at about 31° for ϕ', and $c' = 0$. The northenmost tills show greater variability, but all have considerably more cohesion (c' = 300-700 psf), while their drained angles of internal friction are slightly lower (ϕ' = 29-30°). Atterberg limits alone cannot be used to estimate ϕ' and c'.

There are a number of problems and inaccuracies that have arisen in the sampling and lab testing of the samples reported. First, insufficient equipment and experience in the field made proper sampling techniques impossible, and therefore, proper geotechnical identification and testing erroneous or incomplete. Too many boreholes were drilled where the only samples obtained were disturbed samples off the auger flights, or Shelby tubes filled with sand of questionably intact relative density. Often tubes were filled with slump, or only enough "undisturbed" sample to run one triaxial test, thus giving a poor estimation of the actual strength. In the lab, there were major differences in the results obtained by direct shear and triaxial tests on sand specimens, so that direct shear results had to be disregarded. Hand carving and trimming of silt specimens was found to be too difficult for the technicians, so the silts were too often disturbed, dried, and tested as sands, thus losing any assessment of their cohesive strength. Finally, vane shear tests provided an unreliable measure of the unconfined compressive strength of cohesive materials, since the values obtained on the surface of just one Shelby tube sample were found to vary by more than 100 per cent.

Stability Analysis

The stability analysis of the bluffs covered in this study yielded a number of distinct types of failure processes, which are shown schematically in Fig. 87. These failure types shall be referred to as follows:

1. Toe failure. This is the most common type of failure encountered, in which the failure circle indicates a shallow slip failure at the toe of the bluff.
2. Face failure. Analysis on many bluffs resulted in broad, shallow zones of failure, indicating a trend slope wash or translational failure of the slope, which itself could not be analyzed by the particular computer program used.
3. Erosion of the top of the bluff face. Shallow back-cutting of the top of the bluff was often indicated, however, was not always the most critical condition for the bluff, nor investigated in every case.
4. Removal of toe material. In mostly stable bluff, where slope debris (slump blocks) were accumulated at the toe of the bluff, the failure circle indicated the removal of this toe material, while not affecting the stability of the bluff as a whole.
5. Stable slopes. Minimum Safety Factors for stable bluffs were either for shallow or deep-seated circles, but indicated no tendency to fail.

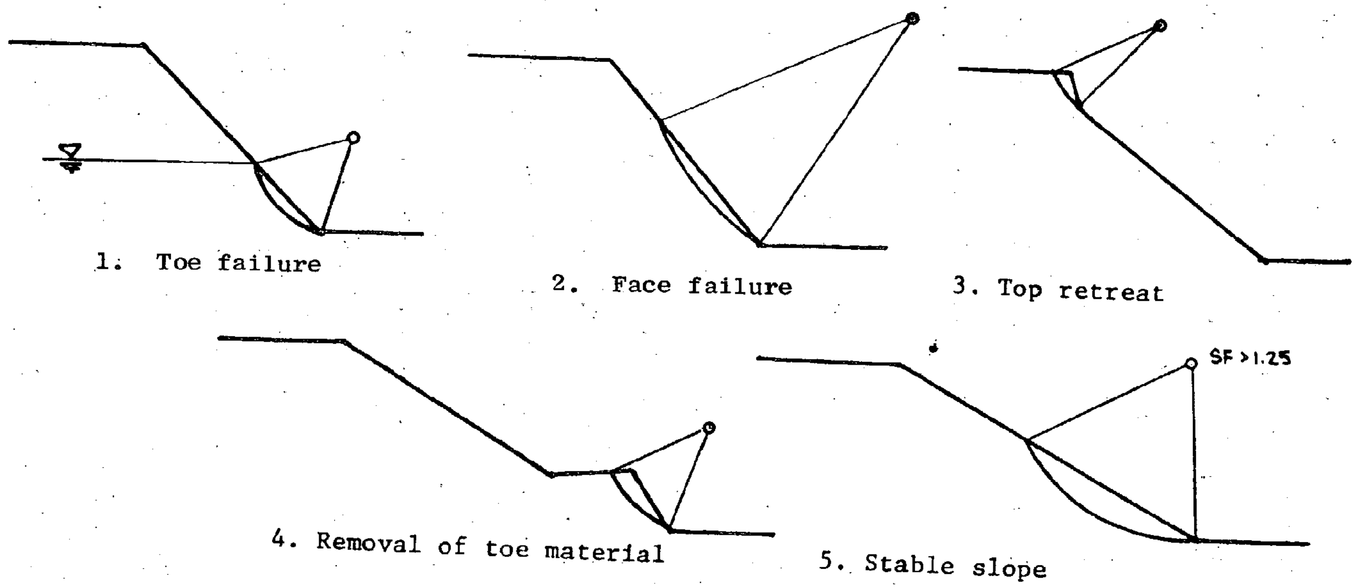


Figure 87. Types of slope failure and face configuration.

Computer analysis resulted in almost all cases in computing a minimum Factor of Safety for a circle indicating a small, surficial slump. This is due mainly to the fact that the cohesion was relatively small for many of the materials encountered. Thus, the slope material behaved like a sand; the Safety Factor decreases as the inclination of the failure plane increases, giving a small, steep failure circle. As the cohesion increases, the depth of the failure circle increases, as does the value of the Safety Factor itself. The term "deep slip" shall be used in describing the failure of natural bluffs that result in failure zones that are deeper than the small surficial slumps described above. In many instances, the two act together.

The "critical circle" shall be defined as that failure circle having the lowest factor of safety, as calculated by the computer. This indicates the most unstable surface of sliding, or the smallest ratio of the assumed shear strength of the material to the shear stresses. However, any trial failure circle may be considered "unstable" if its safety factor is less than one. This results in two criteria, or explanations, of the progressive failure of the bluffs.

1. Critical circle criterion. According to this criterion, the process of failure of the bluffs is seen to follow a succession of small, rotational slides which progress from the toe to the top of the bluff. (Edil & Vallejo, 1977). An example of this was investigated at borehole GT-6, and outlined in Fig. 88. Each time a critical circle with a Safety Factor of less than one was obtained, failure was assumed to occur, and the slumped material was assumed to be removed by waves and surface erosion. The resulting profile was re-analyzed, and each consecutive failure allowed to occur. This sequence of successive failures showed a pro-

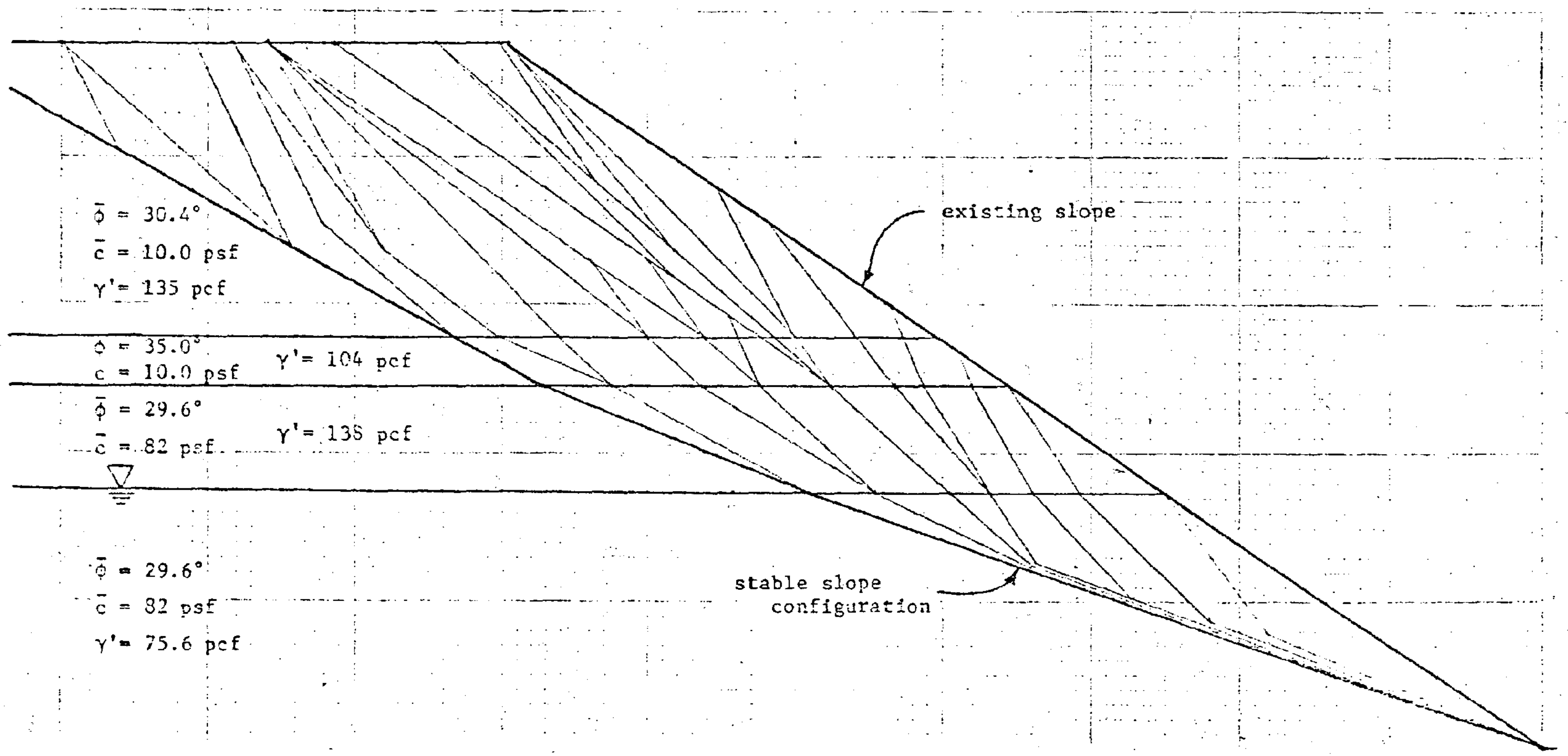


Figure 88. Slope evolution example showing sequence of successive failures at Profile 2, Section 28, T9N.

gression of small, surficial slides which progressed up the face of the bluff, continuing until a Safety Factor greater than unity was encountered, and a stable slope configuration was reached.

2. Unstable circle criterion. An example of the unstable circle criterion was studied for a slope in Reach 13; Profile 2, Sec. 33, T10N, and is outlined in Fig. 89. Failure was assumed to occur throughout the zone where the computer analysis indicated a Safety Factor less than unity, for each failure circle try. This zone was bounded by the largest failure circle with a Safety Factor less than one, which was then assumed to rotate, but not to be completely removed. This criterion resulted in failures which also progressed up the slope, but each failure was of much larger extent, and a stable slope configuration was reached after just three failures.

It is believed that the actual erosion of the bluffs involves both of these criteria. The critical circle indicates the particular surface where incipient failure is likely, and will probably occur first. Where subsequent failures occur, and if they occur, depends on the local variations of the soil, weather influences, groundwater conditions, vegetation cover, surface wash, and other factors. There is a danger of failure whenever the Safety Factor is less than one, but only when assumed conditions prevail in the field at the time of failure. Also, an absolute time scale is not available for the events described above. The unstable circle criterion may be thought of as a culmination of smaller criterion circles that fail at approximately the same time. In other words, the entire failure zone may be undergoing internal failures and deformations, so that failure occurs everywhere within the unstable zone, not just on the largest failure surface.

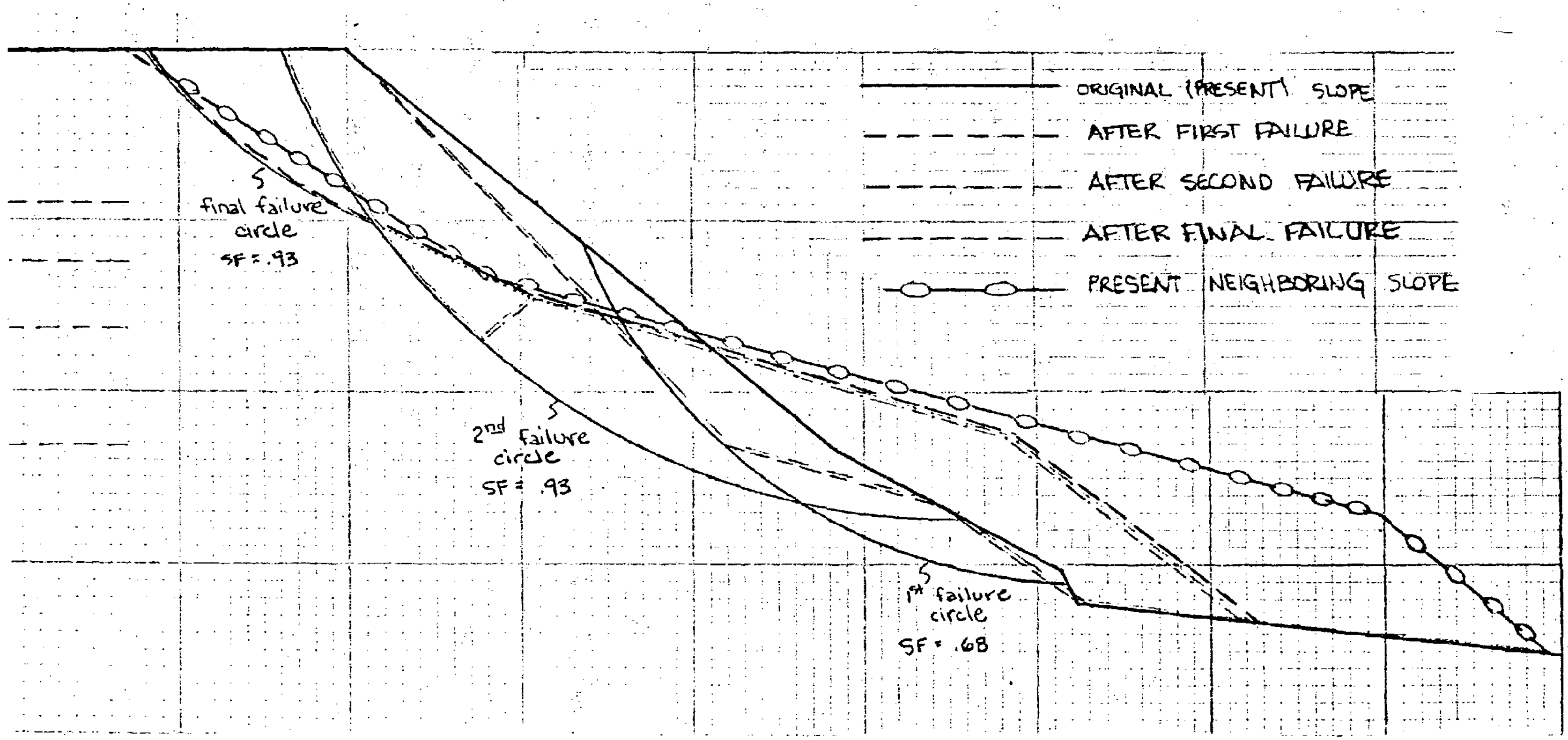


Figure 89. Slope evolution model showing series of progressive failures using the "unstable circle" criterion (profiles 1 and 2, Section 33, T10N.

In addition, solifluction, surface wash, mudflow, or other forms of mass wasting may be occurring in conjunction with the processes above. The undrained failure of the bluffs, that is, a stability analysis using total stresses and the undrained strength parameters of the soil, was not investigated in this study, but may be of major importance in many instances.

The ultimate angle of repose for a stable slope was determined by assuming a long-range equilibrium condition of the bluff whereby the cohesion reduces to zero due to weathering, and the angle of repose is then the angle of internal friction of the soil. Below the groundwater table, the stable slope angle is reduced due to the effects of water pressure, so the stable angle, β, can be computed by the equation

$$\tan = \frac{\gamma_{SAT}}{\gamma_{BOUY}} \tan\phi' \cong 1/2\tan\phi'$$

and results in a slope angle about half that of the angle of internal friction. Artesian pressures and excess hydrostatic pressures due to seepage effects tend to decrease this stable slope angle even more; however, these conditions are not prevalent in this study.

Where the cohesion of a slope is high, it is not necessarily logical to assume that the cohesion will weather to zero causing shallow slides until a low-angle stable slope is reached. Instead, higher stable angles may be maintained safely; these were determined by using charts presented by Edil & Vallejo (1976) which related the stable slope angle to the cohesion for $\phi' = 30°$ and for various bluff heights with varying water table.

The ultimate stable angle of a bluff, and the corresponding amount of regrading required, depend on a number of assumptions and influences. If wave action is prevented, face degradation will flatten the slope to an angle corresponding to the zero cohesion condition described above due to weathering of the surface, and other slope processes. Stabilization measures for slopes of higher cohesion and consequently higher slope angles, require that the Safety Factors using both drained and undrained strength parameters be greater than 1.3 to 1.5, and also that proper drainage of the surface and sufficient vegetation cover is provided to prevent face degradation. Protection of the toe from wave action is imperative.

Case studies

Evaluation of the results of the stability analysis permits a number of observations and comments to be made. Example profiles to be used as case studies are made reference to in an attempt to explain the various phenomena occurring in the erosion of the shoreline. These profiles are drawn in Figs. 90-94, with their assumed strength parameters and critical failure circles.

Effect of lowering the lake level.

The lowering of the lake level will by itself cause no change in the stability of the bluff, but may induce an indirect change in the stability by affecting other factors in the bluff, such as the height of the bluff, the groundwater conditions, or the wave action. As is evident in practically all of the bluff profiles of Figs. 90-94, the critical failure circle does not intersect the bluff beyond the toe; thus, the bluff above

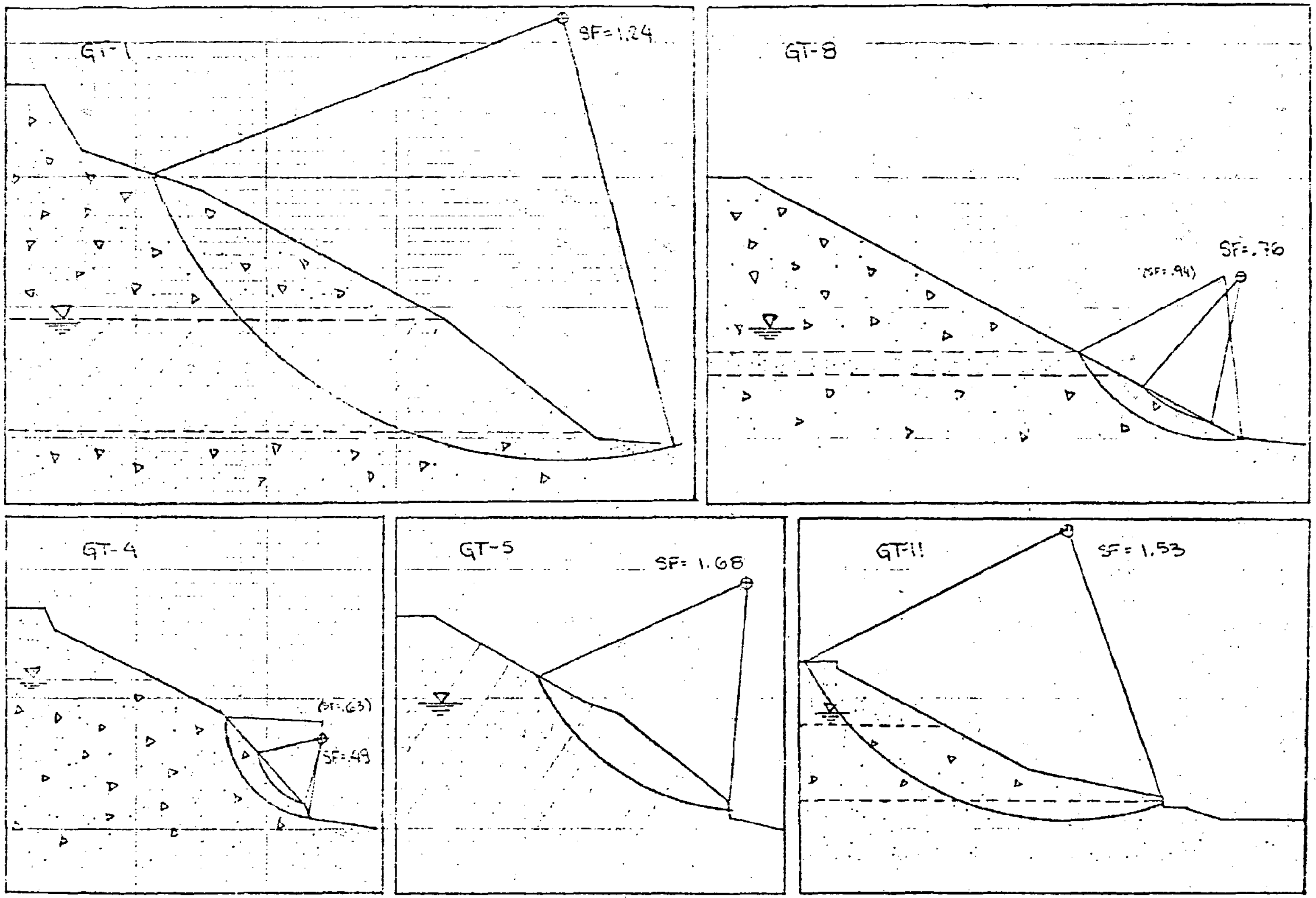


Figure 90. Profiles at geotechnical sites showing critical failure circles. See Fig. 94 for meaning of symbols.

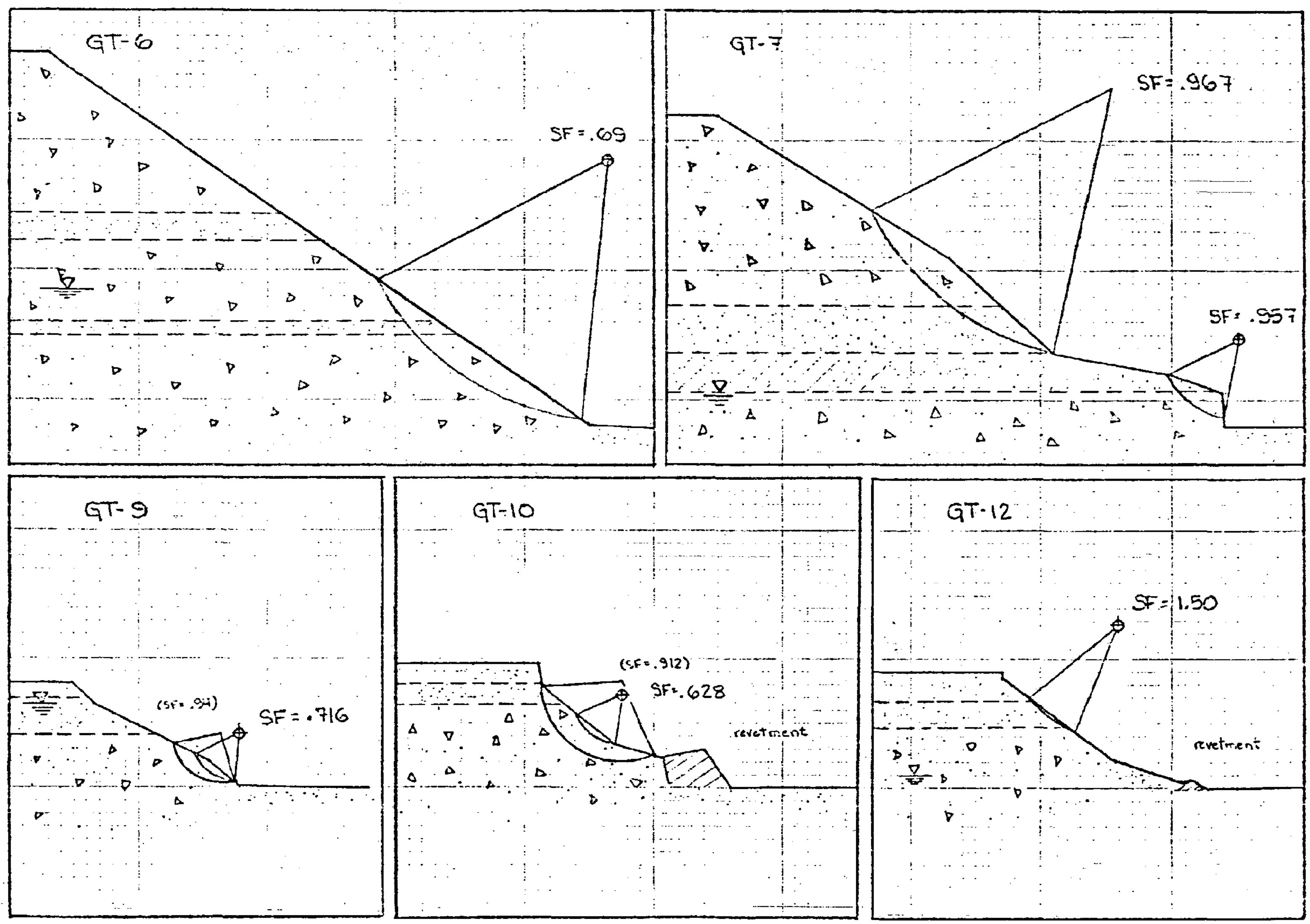


Figure 91. Profiles at geotechnical sites showing critical failure circles. See Fig. 94 for meaning of symbols.

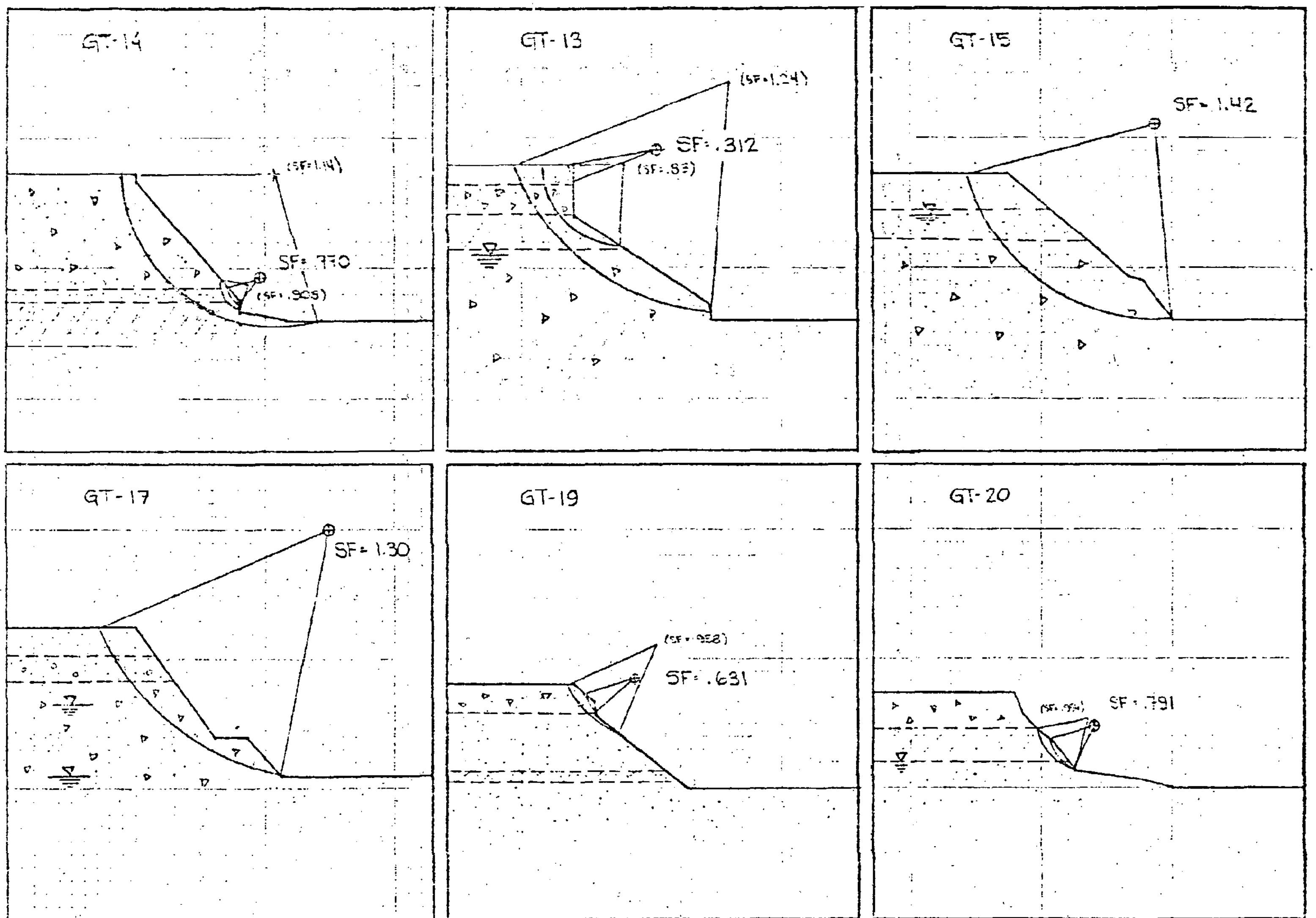


Figure 92. Profiles at geotechnical sites showing critical failure circles. See Fig. 94 for meaning of symbols.

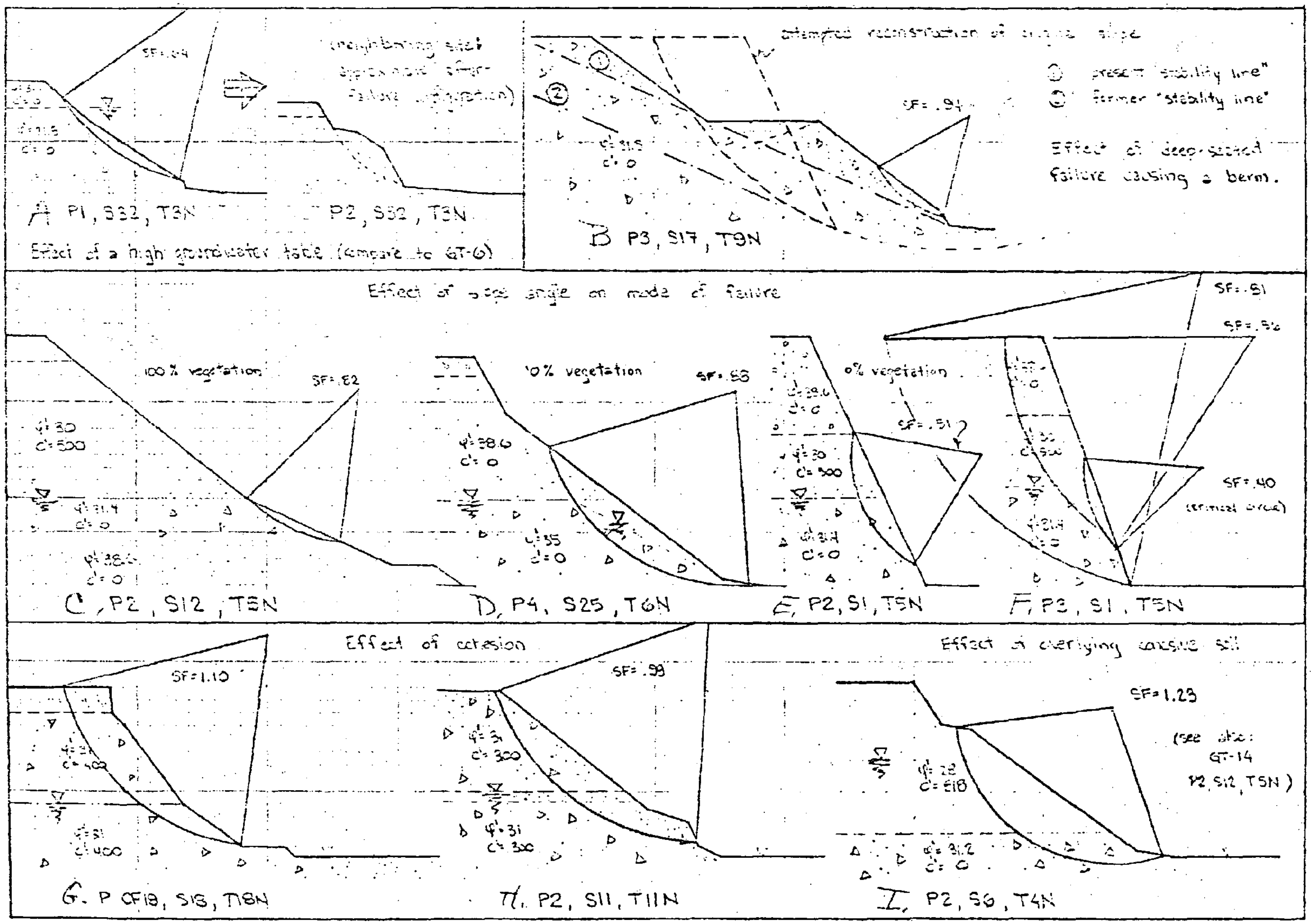
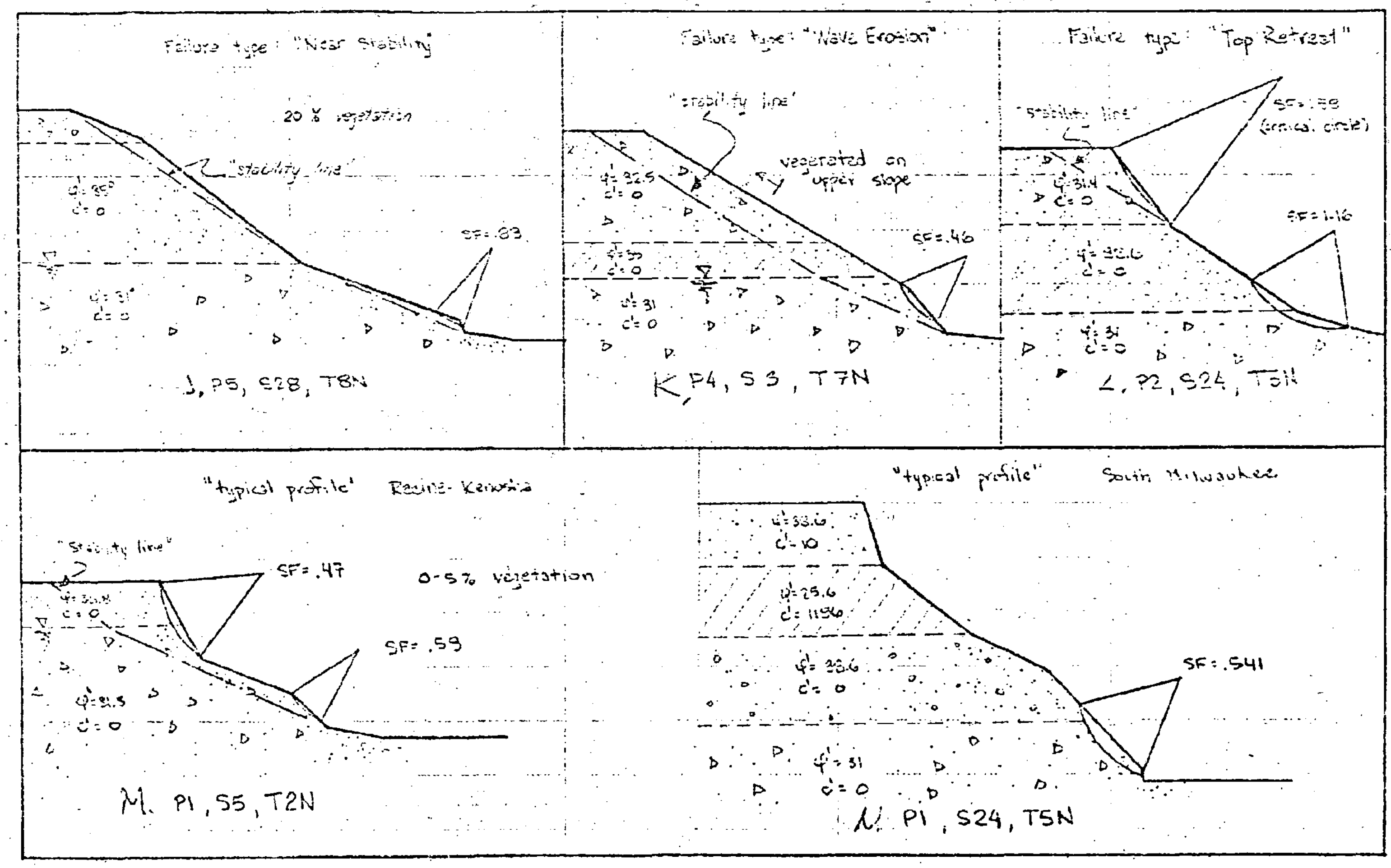


Figure 93. Profiles illustrating effects of groundwater, berm, vegetation, cohesion and overlying cohesive soil. See Fig. 94 for meaning of symbols.



Key to symbols for soil types: sand, gravel; silt; clay, silty clay; till

Figure 94. Illustration of failure types and "typical profiles".

the beach acts as a separate unit since the slope of the beach is so low. Should the waves begin to encroach on the base of the bluff by eroding the beach, the effect will be to increase the height of the bluff in the long run, and thereby decrease its stability. If the initial beach is very steep, porepressures may remain high in the bluff, while the relative height is increased rapidly; thus, the lowering of the lake level may have a direct affect on the stability of the bluff. Porepressures are often kept high for extended periods due to the stratigraphy of the bluff and the forced position of the groundwater table. Also, as the groundwater table decreases, and the height of the bluff is increased due to the lowering of the lake level, some weak layers which were originally below the bluff base may now become part of the bluff face and may induce failure.

Effect of high groundwater table.

Raising the groundwater table decreases the stability of the bluff, while increasing the size of the failure circle in proportion to the increase in the height of the groundwater table. The profile at borehole GT-6 (Fig. 91) shows the water level at about one-third of the height of the bluff, with a Safety Factor of 0.69; Profile A in Fig. 93, with approximately the same slope angle, and a slightly higher ϕ', has a groundwater level at about $\frac{3}{4}$ H, with a Safety Factor of only 0.64.

It is typical for the failure surface on straight bluffs with no cohesion to intersect the bluff at the toe of the slope, and just above the level of the groundwater. This can be seen in the two profiles discussed above as well as many other bluffs along the shoreline. The net result is to slough away the saturated material at the toe, thus decreasing the stability of the overall bluff, and initiating a progressive failure sequence, as investigated at borehole GT-6.

Effect of slope angle.

(Fig. 93, Profiles C, D, E, & F) Increasing the slope angle decreases the Safety Factor of the critical circle, as can be seen in the above profiles each with similar stratigraphy, and cohesion equal to zero. The amount of vegetation also gives an indication of their relative stability, and decreases with an increasing slope angle.

The profile at borehole GT-6 (Fig. 91), and Profile C (Fig. 93) both have low-angle slopes with 100% vegetation. At this angle, the critical criterion is of greatest concern, and the effects of the vegetation, and actual groundwater levels must be taken into account to assess the ultimate stability of the bluff. A series of progressive shallow slides may be expected.

As the slope angle increases, the critical circle criterion becomes of less interest than the largest unstable failure circle criterion. Profile D (Fig. 93) shows the limiting case where the critical circle is also the largest unstable circle; note that the slope angle is approximately equal to ϕ'. At this slope angle, also, the vegetation has decreased substantially, and the critical failure circle is much deeper than for slopes of a lesser angle.

In Profiles E & F (Fig. 93), the slope angle is so large, that the largest unsafe circle criterion controls, indicating a deep-seated failure mode for the bluff. This condition would suggest that failure, when it occurs, will progress very rapidly up the slope, causing a net failure of the entire slope.

Effect of a berm-type post-failure slope.

If we try to reconstruct the pre-failure shape of the given profile, we find that the maximum amount of regrading required is much greater than that which would now be estimated from the present slope configuration. The reason for this descrepancy is that as the slope fails, and the "berm" is created, the slope toe actually extends further into the lake. Thus, the amount of regrading required may be estimated from a point further lakeward, and the net loss of the top of the bluff is calculated less. It can be seen from Profile B (Fig.93), that there is 100% vegetation at the top of the berm, and on the slope above the berm, but that the face of the slope below the top of the berm has little or no vegetation, suggesting a lower stability. The critical failure circle does indicate an unsafe condition at the toe of the berm, and is an example of the removal of slump material at the toe of the bluff. The berm will be eroded back until evidence of it has disappeared; thus, the effect of the berm is not to stabilize the slope, for the ultimate angle of stability will not change, but rather, the presence of the berm shifts the stability line, so that a lesser amount of regrading required is likely. With a greater amount of cohesion, however, the berm will tend to stabilize the slope somewhat, since the berm will act as a separate unit of lower total height, and the ultimate angle of stability for this height will be greater.

Effect of stratigraphy.

A greater amount of cohesion of the soil making up a bluff will correspondingly increase the Safety Factor and the size of the critical failure circle. The critical circle becomes most important in the stability of the bluff, but Safety Factors may often exceed unity, as can be seen in Profile G (Fig. 93). Profiles A and H have approximately the same slope angles, and drained angles of internal friction, but their

Safety Factors vary considerably. The profiles at boreholes GT-5 and GT-1 (Fig. 90) both have lacustrine clay deposits over a significant portion of the slope, and the safety factor is high in both cases. Higher cohesion may, however, make undrained failure critical, particularly where artesian pressures are present.

When a cohesive layer in the upper part of a slope overlies a non-cohesive layer, there is little effect on the critical failure circle in the lower part of the bluff. Therefore, sloughing of the lower material is likely, undercutting the toe of the bluff. The stability of the whole bluff is, however, much greater, so that typical failure circles are deep-seated with higher Safety Factors, as shown in Profiles I (Fig. 93) and GT-14 (Fig. 92).

The effect of the presence of a cohesive material overlain by a cohesionless material, is common in many of the northern profiles (see boreholes GT-13, GT-15, GT-12). Characteristically, these bluffs are stable or questionably safe, with no slumping at the toe; but rather, a considerable amount of top retreat. Overall Safety Factors are higher, with a deep-seated failure mode indicated.

<u>Near-stability</u>.

Very often a critical failure circle less than one will be calculated for a slope that will undergo no top retreat to achieve a stable slope configuration. Erosion of the face of the slope involves a "smoothening-out" of certain unstable features, without affecting the overall shape of the bluff. An example of this can be seen readily in Profile J (Fig. 94), where there is little vegetation, and a low Safety Factor, but a slope angle very close to the stable configuration. Another example of this type is the process of the removal of slumped material from the toe of the bluff.

False instability.

When a Safety Factor less than one is calculated for a uniform slope having 100% vegetation and where the ultimate angle of stability parallels the slope face, the failure mode indicated is often misleading. The critical failure circle must be interpreted as an indication of barren slope-forming processes. If the failure indicated is a shallow slide, then the vegetation will retain the slope in its present configuration. If, on the other hand, an unstable circle involves a deep slip, then the vegetation may give a false sense of security, and the slope may be in danger of incipient failure. An example of the former case is the profile at borehole GT-6 (Fig. 91), and of the latter case of false security, is Profile K (Fig. 94).

Wave Erosion.

A former stable bluff configuration may be subjected to the forces of wave erosion, and subsequently become unstable, as in Profile K. The Safety Factor indicates an unsafe critical circle causing a shallow slide near the base, which will initiate a progressive failure of the bluff.

Top Retreat.

Top retreat may be caused by two different conditions, either a difference in the material properties at the top of the bluff, or the final stages in a progressive failure of the slope. Profile L (Fig. 94) is an example of a cohesionless bluff which is stable at its toe, but unstable at the top, the critical failure circle indicating shallow slides at the top of the slope.

Typical slope profiles.

The term "typical slope profile" is actually a misnomer, for every slope is in itself unique; subjected to different environmental influences, shape-forming processes, stratigraphic variations, material properties, groundwater conditions, and vegetation cover. However, some very generalized shapes or failure modes appear more frequently than others for different segments of the shoreline.

Profile M (Fig. 94) is more-or-less typical of many of the bluffs of Racine and Kenosha counties. Where the stratigraphy consists of cohesionless till, sands, or silts, there is often a stepped slope undergoing both toe erosion and top retreat. The groundwater table is typically high. Where the bluffs are either uniform, or straight, they are either stable, or undergoing some undercutting at the toe. The bluffs are low in height, so that the net retreat of the top of the bluff for a stable angle is small to negligible. Lacustrine clay deposits have high cohesion, and generally add significanly to the stability of the slope.

Lower Milwaukee county may be typified by Profile N (Fig. 94). The bluffs are of cohesionless materials with lower angle slopes that are actively undergoing progressive failure sequences. Slumping at the toe is common, with moderate setback of the top to achieve a stable slope angle. Interspersed lacustrine clays of high cohesion allow stable slopes at higher angles. Wave erosion and subsequent slumping at the toe is typical.

Further north, the slope angles become very steep, danger of deep-seated failures by the unstable circle criterion is evident; also failure by an undrained analysis is possible. Interbedded lacustrine deposits vary from high-cohesion clays to dense sands which retain surprisingly high-angle slopes with a considerable amount of surface sloughing. Profiles D, E, and F (Fig. 93) may be common.

Northern Milwaukee and Ozaukee counties are typified by profiles at boreholes GT-6 and GT-7 (Fig. 91), and GT-8 (Fig. 90), where thick deposits of cohesionless tills are subjected to progressive failures of shallow slides, according to the critical circle criterion. Bluffs are generally high, with angles varying between safe slopes to steep, highly complex, and slumped surfaces.

The bluffs in Sheboygan and Manitowoc counties consist generally of tills with higher cohesion overlain by cohesionless sands and silts. Top retreat is active in many areas, but the slopes as a whole are able to maintain high angles at moderate heights, with relatively high Safety Factors. Face degredation and wave action are prevalent. (see GT-14 to GT-17, Fig. 92)

Conclusion

The Factor of Safety analysis for the natural bluff slopes along the coastline indicates the most critical conditions affecting the stability of the slopes. The presence of a shallow slide at the toe of a slope suggests sloughing of saturated, cohesionless material below the groundwater table when the groundwater is at a high level during the spring. The failure of this lower toe material alters the stress conditions affecting the rest of the slope, and subsequent erosional failures, either shallow or deep-seated may result, which progress up the slope. This cycle may repeat year after year if the slumped material is removed by the waves, or undercutting of the toe by waves is allowed.

Critical failure circles showing shallow surface slides may indicate surface wash or a parallel retreat of the slope face. In high-angle slopes, these may be of lesser importance than the larger, deep-seated failure circles, as characterized by the unstable circle criterion. Cohesion tends to deepen the critical failure circles, and increase the Safegy Factor for a given value of the drained friction angle.

The slope-forming processes assumed take into account a number of conservative assumptions and observations. Therefore, the Safety Factors and the stability line values are reflective of the worst possible conditions thought probable for the given slope. The two most important considerations of any given profile are the engineering properties governing the type of failure suspected, and the porepressure within the bluff. One cannot accurately assess the "true" Safety Factor of a slope, but can only try to get a handle on the type of failure mode probable, and the relative chance of this failure occurring. This can only be done by properly interpreting the Safety Factor.

Not all failure modes have been investigated for every profile. Thus, top retreat or the largest unsafe failure circle may not be drawn for a particular profile, but still may be of major importance. The interpreter must look at other similar profiles, or compare the given slope with the failure processes described herein to determine if the slope has modes of failure other than those drawn, or originally calculated.

The stability line is generally a conservative estimate of the maximum retreat of the bluff top probable to insure a Safety Factor greater than one. However, the vegetation cover, beach protection, drainage controls, lakeward advance of the toe of the bluff, or the presence of a greater amount of cohesion than assumed will reduce the amount of regrading required.

All of the engineering properties have been averaged, assumed homogenous and consistent throughout any given profile, and the stratigraphy has been assumed horizontal and continuous. These conditions may not prevail at a particular site, but may be drastically different from those in the near vicinity. Thus, the extrapolation of data is precarious, and the assignment of Unsafe or Safe slope designations must be viewed with a certain degree of scepticism. These extrapolations are to be used as a guideline or an indication of general conditions along the shoreline, but should not exclude detailed geotechnical subsurface investigations at any particular site to assess its slope stability.

Finally, the methods used in analyzing the stability of the slopes do not account for surface sloughing, solifluction, mass flows, slope wash, or wave erosion which must also be considered in determining the ultimate stability of the slope, or the ultimate retreat of the bluff top. Nor has the Safety Factor against an undrained failure been analyzed which may be critical in many cases.

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GLOSSARY

BREAKWATER - A protective structure built off shore and parallel to the shoreline. Incoming waves crash against the breakwater instead of directly on the beach; this lowers their erosive power.

CALUMET STAGE - Stage of Glacial Lake Chicago which is recorded by beaches at an elevation of 620 feet above sea level (40 feet above the present lake surface) throughout most of the Lake Michigan Basin.

CLAY - Very fine grained sediment. In this report clay refers to the less than .002 millimeter fraction.

FETCH - The distance over open water which the wind blows. The fetch is a partial determinate of wave height.

FLOW - A type of downslope movement where the soil mass, saturated with water, moves like a viscous liquid under the influence of gravity.

GLACIAL LAKE CHICAGO - The lake which existed at several different stages (elevations) in the southern part of the Lake Michigan basin during late glacial time.

GLENWOOD STAGE - A stage of Lake Chicago which is recorded by beaches at an elevation of 640 feet above sea level (60 feet above the present lake surface). This is highest level of glacial Lake Chicago and is in part responsible for the lacustrine sediment high in the bluff.

GROIN - A structure built of concrete, steel pilings, rocks or other materials which extend into the water perpendicular to the beach. Groins trap the sediment moved by the longshore drift forming beaches on the updrift side.

GROUNDWATER DISCHARGE - The flow of water from the ground as springs onto the ground surface or into water bodies. Also referred to as seeps.

LACUSTRINE SEDIMENT - Sediment deposited in a lake. Usually refers to fairly fine grained (sandy silt and clay) sediment.

LONGSHORE DRIFT - The transport of sediment (usually sand) along the beach and just off shore by the prevailing currents and oblique waves.

NIPISSING STAGE - One of several fairly long-lived stages of Lake Michigan at an elevation of 605 feet above sea level. Many of the terraces and sand areas along Lake Michigan 20 to 25 feet above present lake level represent wave action during the Nipissing stage. These stages occurred after glacier ice had left the Lake Michigan basin.

PIEZOMETER - A small observation well open to the groundwater system at some depth which is used to measure the depth to the water table.

REACH - A segment of shoreline which has somewhat uniform characteristics and orientation. Reaches of any length can be defined.

REVETMENT - A shore parallel erosion control structure generally built at the base of the bluff and top of the beach. It differs from a sea wall in that it is usually made of rip rap (large chunks of rock) and its surface is generally inclined in the direction of the water as opposed to a sea wall which is generally vertical.

SAFETY FACTOR - The engineering factor of safety as used in this report refers to the likelihood of slope failure by slumping. A discussion of how safety factor is calculated is given in the text.

SAND - Sediment with a grain size between .0625 and 2 millimeters.

SAPPING - The removal of sediment (generally undercutting) by discharging groundwater.

SEA WALL - A wall generally of concrete or sheet piling. It generally has a vertical face, although in some cases, the faces are stepped on the beach side.

SHELBY TUBE - Thin walled steel tube which is forced into soft sediment to collect relatively undisturbed samples.

SILT - Sediment with a grain size between .002 millimeters and .0625 millimeters. This material is intermediate in size between clay and sand.

SLIDE - A type of downslope movement which takes place along a definable, relatively flat surface of failure. Usually the sliding mass is not deformed as it is in flow.

SLUMP - A type of slide where failure takes place along a curved surface and the moving mass rotates backwards in the upslope direction. It leaves a scalloped bluff top of amphitheater shaped scars. This is a very common type of failure along the bluffs of Lake Michigan and Lake Superior.

SOIL CREEP - A very slow movement of unconsolidated material downslope. Very often this is measured in millimeters per year and is not observable to the naked eye. When this process is occurring, however, trees, fence posts, telephone poles etc. become tilted, and making the effect of soil creep is observable.

SPLIT-SPOON SAMPLER - A tubular sample collecter which is attached to the end of a drill rod and pushed or driven into the sediment. This is generally used on harder sediment than the shelby tube.

STRATIGRAPHY In its classical use refers to the study of the formation, composition, sequence and correlation of sedimentary materials. In this report it refers to sequence of materials making up the bluff.

TILL - Poorly sorted, poorly stratified material deposited directly by glacier ice.