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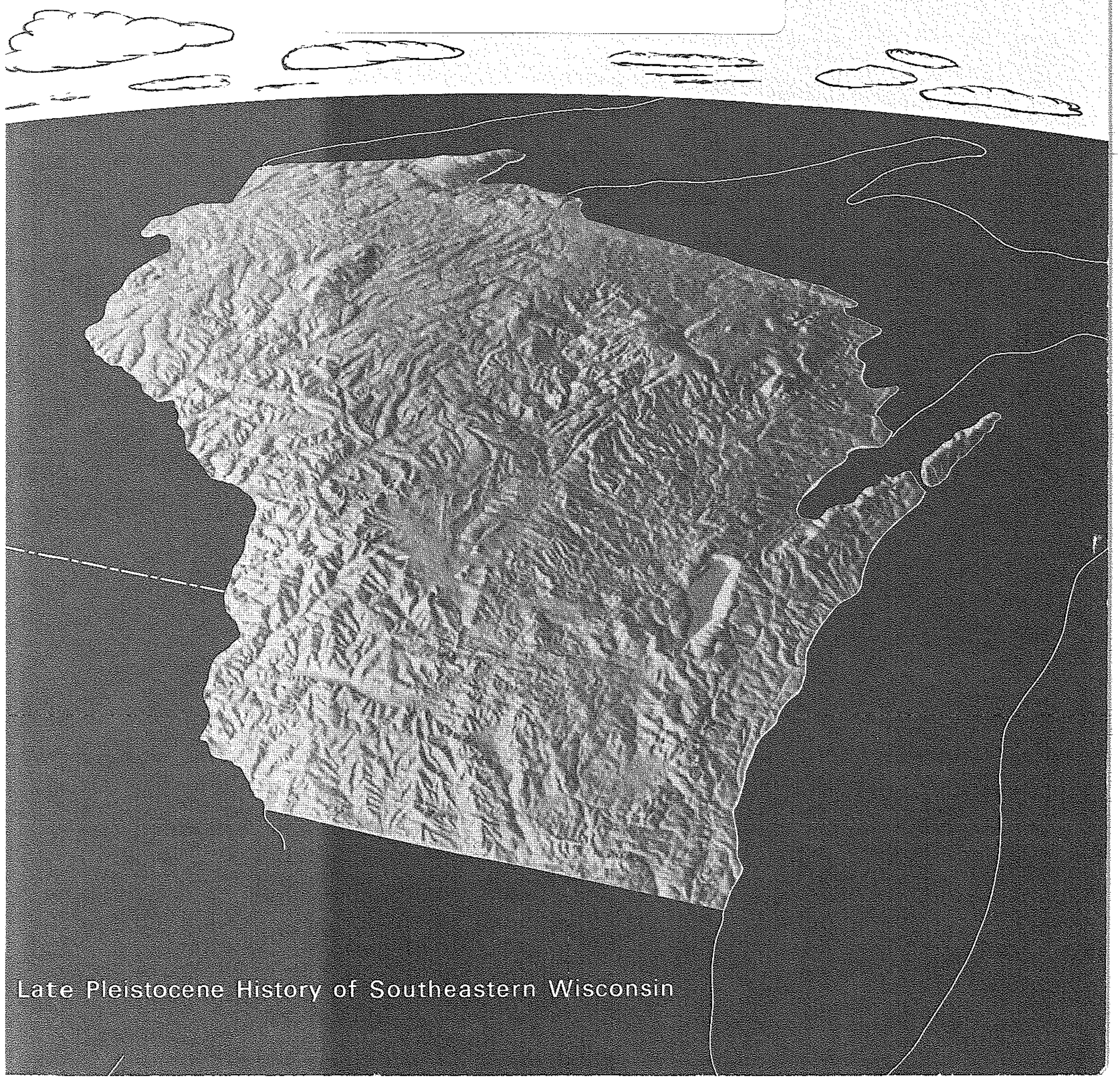

Late Pleistocene History of Southeastern Wisconsin

Cover: An oblique photograph of a plastic raised relief map of Wisconsin by Hans J. Stolle a graduate student in the Geography Department, University of Wisconsin - Madison.

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LATE PLEISTOCENE HISTORY OF SOUTHEASTERN WISCONSIN

edited by
David M. Mickelson and Lee Clayton

with contributions from
Leon R. Follmer, Ardith K. Hansel, N.P. Lasca,
E.A. Need, Christopher S. Peters,
Allan F. Schneider, and Scott D. Stanford

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PREFACE

"Geoscience Wisconsin" is a serial that addresses itself to the geology of Wisconsin--geology in the broadest sense to include rocks and rocks as related to soils, water, climate, environment, and so forth. It is intended to present timely information from knowledgeable sources and make it accessible with minimal time in review and production to the benefit of private citizens, government, scientists, and industry.

Manuscripts are invited from scientists in academic, government, and industrial fields. Once a manuscript has been reviewed and accepted, the authors will submit a revised copy of the paper, and the Geological and Natural History Survey will publish the paper as funds permit, distribute copies at nominal cost, and maintain the publication as a part of the Survey list of publications. This will help to insure that results of research are not lost in the archival systems of large libraries, or lost in the musty drawers of an open-file.

In conjunction with the Seventeenth Annual Meeting of the North-Central Section of the Geological Society of America in Madison in late April and early May of 1983, Tim Kemmis and Lee Clayton coordinated a symposium on recognition of till facies. A round robin excursion to examine the Quaternary record of southeastern Wisconsin was organized by Dave Mickelson. The proceedings of this multi-faceted symposium include Wisconsin Geological and Natural History Survey Field Trip Guide Book Number 7 on the Late Glacial History and Environmental Geology of Southeastern Wisconsin, and Geoscience Wisconsin Volume 7. David M. Mickelson of the University of Wisconsin--Madison and Lee Clayton of the Wisconsin Geological and Natural History Survey coordinated the field excursion and its relations to the seven papers presented in this volume, which they edited.

Preparation of final copy was arranged by David Mickelson through facilities at the Department of Geology and Geophysics, University of Wisconsin--Madison.

Submission of manuscripts relating to Wisconsin geology is encouraged. Special consideration will be given papers which deal with timely topics, present new ideas, and have regional or statewide implications.

M.G. Mudrey, Jr.
Editor--Geoscience Wisconsin
Wisconsin Geological and Natural
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FOREWORD

The late Pleistocene history of southeastern Wisconsin was first studied by T.C. Chamberlin and William C. Alden during the late 1800s and early 1900s. Their pioneering work provided the basis for more detailed studies of recent years. The meeting of the North-Central Section of the Geological Society of America in the spring of 1983 provided an opportunity to review results of some of these recent studies. This volume, which was distributed in preliminary form at the meeting, contains seven papers on the Pleistocene geology of southeastern Wisconsin. Ardith K. Hansel, N.P. Lasca, E.A. Need, and Allan F. Schneider, in four separate papers, describe the stratigraphy of till and associated deposits. Allan F. Schneider and Leon R. Follmer describe an occurrence of the Sangamon soil. Scott D. Stanford outlines his recent work on drumlins, and Christopher S. Peters discusses present-day erosion of the Lake Michigan bluffs.

A companion volume, Field Trip Guide Book 7, Late Glacial History and Environmental Geology of Southeastern Wisconsin, was prepared by David M. Mickelson, Allan F. Schneider, Scott D. Stanford, Leon R. Folmer, and Norman P. Lasca. The Guide Book, which is published by the Wisconsin Geological and Natural History Survey, contains detailed descriptions of outcrops that illustrate points discussed in the following pages.

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THE WADSWORTH TILL MEMBER OF ILLINOIS AND THE EQUIVALENT OAK CREEK FORMATION OF WISCONSIN

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ABSTRACT

The Wadsworth Till Member of the Wedron Formation is the youngest till unit in Illinois and was deposited during the last advance of the Lake Michigan Lobe to reach the southern part of the lake basin. The equivalent unit in Wisconsin is called the Oak Creek Formation (Mickelson and others, 1983).* Around the southern margin of the lake the Wadsworth till is found at the surface in the Valparaiso, Tinley, and Lake Border Moraines. In the subsurface it lies beneath the Lake Chicago plain and beneath nontill sediments under Lake Michigan. The composition and texture of the gray, clayey illitic Wadsworth till reflects incorporation of Paleozoic rock and lacustrine sediment from the Lake Michigan basin. Variation in composition is present in vertical profile and in lateral distribution. Whereas some variation is clearly associated with separate depositional events (Valparaiso and Lake Border), other variation appears to reflect differences in length of flow path in the Lake Michigan basin. On the basis of the available data in the study area, the Wadsworth till is a clearly distinguishable stratigraphic unit that can be subdivided further on textural and compositional characteristics related to geographic and stratigraphic positions.

INTRODUCTION

The tradition of Pleistocene stratigraphy in Illinois has been to distinguish rock-stratigraphic units by their physical characteristics and stratigraphic position. Many till units, including the Wadsworth Till Member of the Wedron Formation, first became a part of the stratigraphic nomenclature in 1970 when Willman and Frye presented their classification scheme for Quaternary depostis in Pleistocene Stratigraphy of Illinois. At that time Willman and Frye saw no need to define groups consisting of several formations, but they recognized (p. 45) that future work might distinguish additional subdivisions and groupings.

At the present time, Quaternary researchers in Illinois are considering further revision of the Wedron Formation based on material characteristics. As presently defined, the Wedron Formation consists of those deposits of till and outwash that extend upward from the contact with the top of the Morton Loess to the top of the till below the Two Creeks deposits in Wisconsin, thereby including all till deposits of Woodfordian age. Among the revisions being considered are (1) elevation of the Wedron in rank to group status, (2) differentiation of formations within the group, and (3) differentiation of members within these formations wherever there is a lithologic basis to do so. These revisions have been proposed because the American Code of Stratigraphic Nomenclature recognizes the formation as the working field unit and the Wedron Formation is not a working field unit in this sense. Instead, the working field units in northeastern Illinois are distinguished within the

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* To avoid unnecessary use of names and to reduce confusion, Wadsworth till is used in this paper to include the same unit in Wisconsin (Oak Creek Formation) unless reference is made specifically to the Wisconsin unit.

Wedron Formation at the member rank (the Tiskilwa, Malden, Yorkville, Haeger, and Wadsworth Till Members). Elevating these till members to formation rank would be in compliance with the Code guidelines and would at the same time allow for more flexibility at lower levels of classification.

Inasmuch as the Wadsworth till was originally defined as a member of the Wedron, an evaluation of its appropriateness as a formation in the proposed group is required. At least two clay-mineral subdivisions within the Wadsworth till have been recognized and it is important to decide whether or not these clay-mineral subdivisions are accompanied by other lithostratigraphic parameters and therefore merit distinction as separate members of the Wadsworth unit. The present research was initiated in order to respond to such questions and to improve understanding of the deglaciation history of retreating Woodfordian ice in the Lake Michigan basin.

The primary objectives of the paper are to (1) evaluate the status of the Wadsworth till in the rock-stratigraphic hierarchy of Illinois, (2) determine prospects for its subdivision, and (3) discuss the genesis and depositional history of the unit. The study area does not include the entire extent of the Wadsworth till; it covers only northern Illinois and southern Wisconsin as shown in figure 1.

METHODS AND DATA

Sample data were obtained from approximately 75 water-well and 60 test-boring sites. Samples collected from surface exposures and the lake bluffs in Wisconsin and Illinois were another important data source. Other samples used in this study were contributed by A. F. Schneider and D. M. Mickelson.

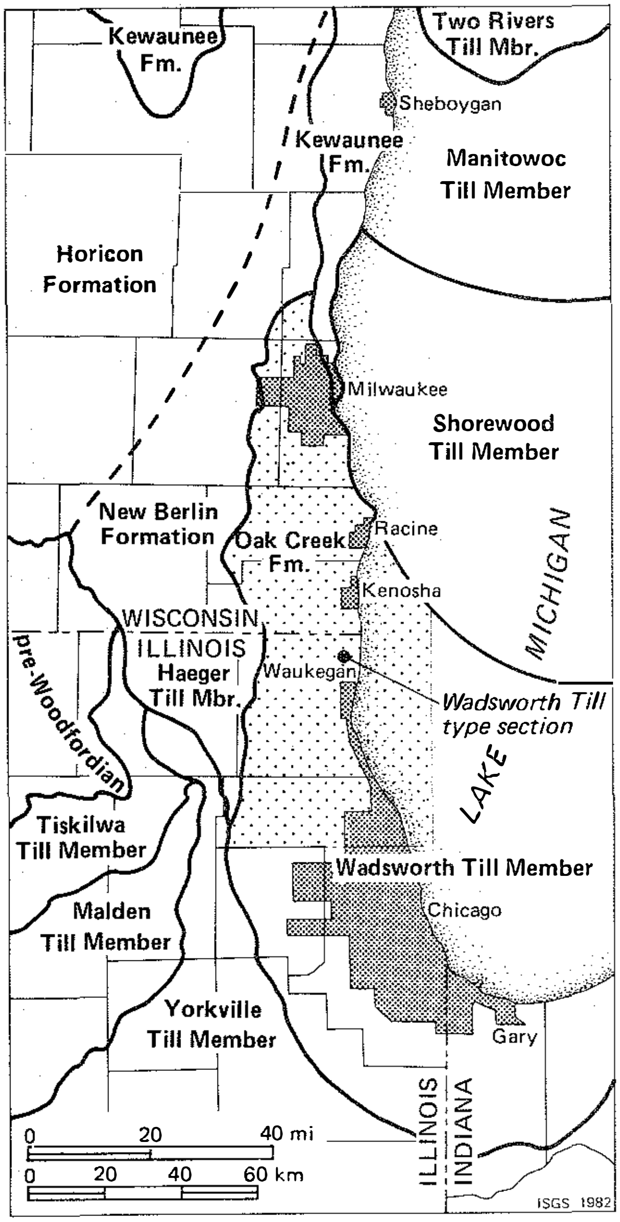


FIGURE 1.--Study area and surficial till units in eastern Wisconsin and northeastern Illinois. (Wadsworth Till Member of Illinois equivalent to the Oak Creek Formation of Wisconsin; Haeger Till Member to the New Berlin Formation; Manitowoc Till Member to part of the Kewaunee Formation.) (Study area stippled.)

Samples were described and analyzed for texture and clay-mineral composition. Textural analysis was determined by R. Bianchini of the Illinois State Geological Survey (ISGS), who used sieve and hydrometer methods to fractionate and determine the weight percentage of gravel (larger than 2.00 mm) in the whole sample and the weight percentages of sand (0.062 to 2.00 mm), silt (0.004 to 0.062 mm), and clay (smaller than 0.004 mm) in the matrix (smaller than 2.00 mm).

Clay mineral identification was done by H. D. Glass (ISGS) from x-ray diffraction data by using oriented aggregate techniques on the smaller-than-0.002 mm material. The clay minerals are separated into three groups, and the percentages of each group are calculated using peak height intensities. The percentage of illite was used to demonstrate variability in clay-mineral content. The calculated value represents a relative index of the amount of illite present. Although relative, the percentage serves as a sensitive measure for discriminating change in clay composition. Other characteristics of the clay-mineral diffraction analyses were also used to help evaluate the clay-mineral composition of weathered samples.

HISTORY OF THE INVESTIGATION OF THE WADSWORTH TILL

The distinct morainic character and trough-shaped configuration of the topography bordering Lake Michigan were noted by Chamberlin in 1878. In 1882 he referred to these deposits as "moraine of the Lake Michigan Glacier." Leverett (1899) was likewise impressed by the striking parallelism of the moraine configuration to the Lake Michigan shore. On the basis of the topography and distribution of the deposits around the lake, he differentiated two morainic systems: the Valparaiso and the Lake Border. Alden's detailed work (1904, 1918) extended Leverett's mapping of the Valparaiso and Lake Border Morainic Systems into Wisconsin.

The glacial deposits of the moraines in the study area have been described by many (Leverett, 1897, 1899; Alden, 1904, 1918; Powers and Ekhlaw, 1940; Bretz, 1955; Willman and Frye, 1970; Willman, 1971; Lineback and others, 1974; Mickelson and others, 1977; and Acomb and others, 1982), but it was not until 1970 that the term "Wadsworth Till Member" was applied to these deposits. At that time, Willman and Frye differentiated the Woodfordian moraines and their related drifts in Illinois and, on the basis of observable physical characteristics, classified materials into rock-stratigraphic units of the Wedron Formation. The exceedingly clayey, gray tills of the Valparaiso Morainic System, the Tinley Moraine, and the Lake Border Morainic System were included in the Wadsworth Till Member of the Wedron Formation.

In 1974 Lineback and others differentiated four till units under Lake Michigan on the basis of core sampling and seismic profiling. The three oldest units were assigned to the Wedron Formation of the Woodfordian Substage and the youngest till was assigned to an unnamed formation of the Valderan Substage. The oldest of these units was the gray, illitic Wadsworth Till Member found in the southern portion of the lake. Two new till members were defined in the central portion of the lake: the Shorewood Till Member and the Manitowoc Till Member. The post-Twocreekan Two Rivers Till of Evenson (1973) was identified in thin patches on the lake floor north of Sheboygan. Analytical data from x-ray diffraction studies of clay minerals and carbonates provided the basis for separating these tills. Their distribution and stratigraphy were determined primarily from seismic profiles. Figure 1 shows the distribution of these four tills in the western part of Lake Michigan.

Shore erosion studies along Lake Michigan in Wisconsin (Mickelson and others, 1977) and Illinois (unpublished reports) have examined the lithology and stratigraphy of the materials that constitute the lake bluffs. In Wisconsin three pre-Twocreekan till units were differentiated along the Lake Michigan bluffs: Unit 1, coarse-textured bouldery till; Unit 2, gray, clayey till; and Unit 3, red, clayey till. In some places these units were further subdivided on the basis of stratigraphic breaks. The Wadsworth till is the only till unit exposed in the lake bluffs in Illinois.

STRATIGRAPHIC RELATIONS OF THE WADSWORTH TILL

Stratigraphic Nomenclature

The Wadsworth Till Member of the Wedron Formation was named for Wadsworth, Lake County, Illinois (Willman and Frye, 1970). The type section is a roadcut exposure at the intersection of Illinois Highway 131 and Wadsworth Road, 2 miles east of Wadsworth (fig. 1). In Wisconsin the equivalent unit is being defined as the Oak Creek Formation (Mickelson and others, 1983).

A stratigraphic column for the study area is shown in figure 2. Because the study area includes portions of both states, both Illinois and Wisconsin nomenclature are given. The placement of Units 1, 2, and 3 of the Wisconsin shore erosion study (Mickelson and others, 1977) in the rock-stratigraphic framework is also indicated. The Illinois nomenclature is used in this paper except where reference is made to units studied by Wisconsin researchers.

Distribution and Topography

In the southwestern Lake Michigan area the Wadsworth till occurs at the surface in the Valparaiso Morainic System, the Tinley Moraine, and the Lake Border Morainic System, at the surface or beneath lacustrine sediment in the Lake Chicago plain, and in the subsurface beneath nontill sediment in southern Lake Michigan (fig. 3). Till samples that have been analyzed from the Valparaiso and Lake Border Moraines outside the study area in Illinois, Indiana, and Michigan are similar in composition to samples from the Wadsworth Till Member in the study area.

In 1970 Willman and Frye identified 13 separate morphostratigraphic units, called "drifts," on the basis of moraines in the area of the Wadsworth till in Illinois. They did not differentiate the Valparaiso Morainic System into separate ridges in Lake and northern Cook Counties, Illinois, where the morainic area is about 15 km wide and is characterized by numerous knobs, kettles, and lakes. To the south where lakes are much less common, the Valparaiso Morainic System can be separated into seven recognizable ridges or crests.

The first moraine younger than the Valparaiso Morainic System is the Tinley Moraine. It has a hummocky surface similar in topography to that of the Valparaiso but it is only 5 to 7 km wide. Extending from Wisconsin to Indiana, it adjoins the next younger morainic system (Lake Border) in the northern half of the study area.

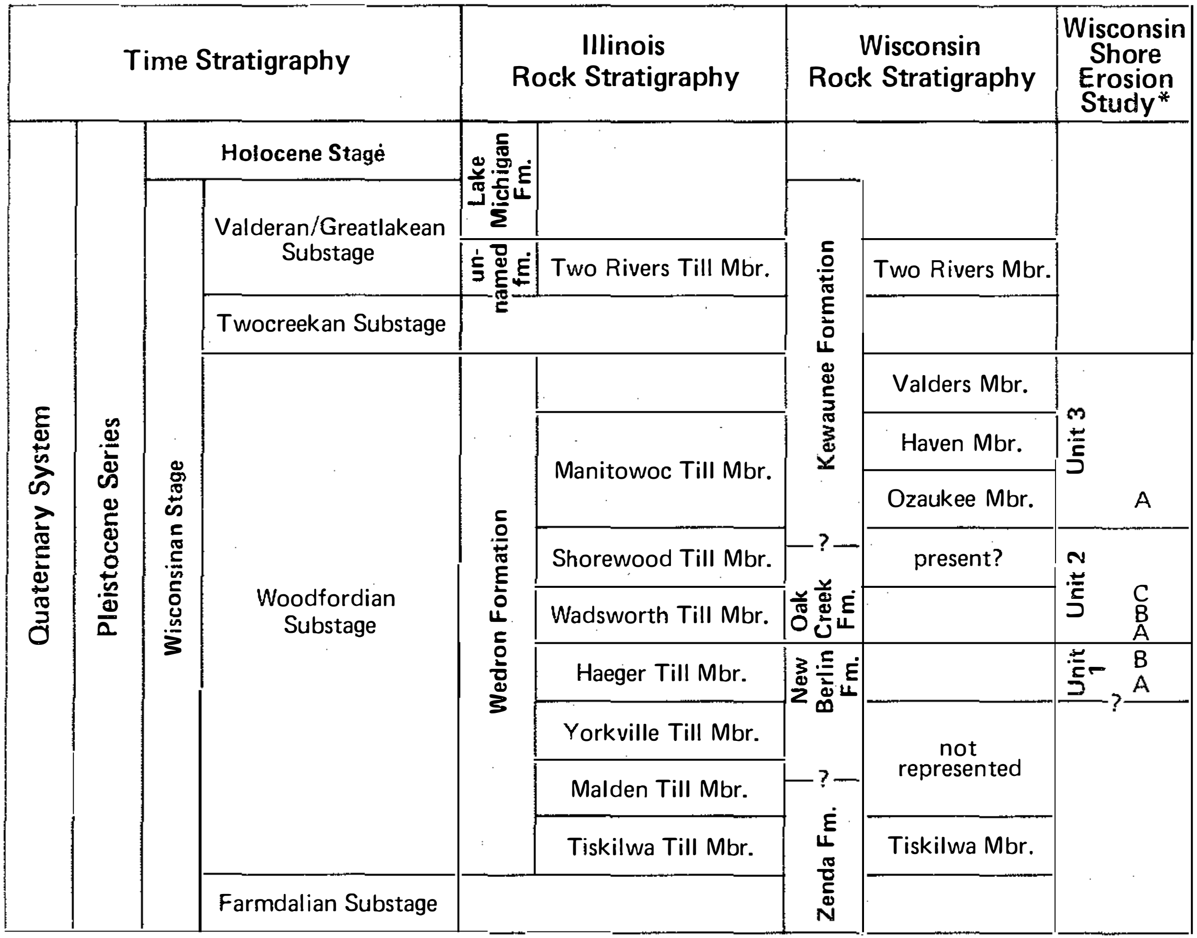
The Lake Border Morainic System consists of five ridges, each a mile or so wide, that rise 10 to 15 m above narrow valleys. The ridges are generally smooth and lack the hummocky topography characteristic of the Valparaiso and Tinley Moraines. In the vicinity of Chicago the Lake Border Moraines are buried by lacustrine sediment of the Lake Chicago plain, an exceptionally flat surface that was formerly the floor of glacial Lake Chicago (fig. 3). In Cook County, Illinois, where the Lake Chicago plain is scoured of lake sediment, the Wadsworth till occurs at the surface.

Lineback and others (1974) found that the Wadsworth till forms a relatively smooth surface in the southern end of Lake Michigan and is generally overlain by thin gravel and sand. No submerged moraines related to the Wadsworth till were found.

Thickness

The thickness of the Wadsworth till in Illinois ranges from a few meters to more than 50 m. The western margin of the Wadsworth till lies east of the Fox Lake Moraine, the western margin of the area mapped as Valparaiso (undifferentiated) by Willman and Frye (1970); the Wadsworth till was not found to extend into the Chain O'Lakes lowland (fig. 3 and 4). In the area east of the Chain O'Lakes the thickness of the Wadsworth till increases from a few meters to more than 45 m in the distance of a few kilometers. In the hummocky topography of northern Lake County, lacustrine sequences are common and occur in close proximity to thick till sequences. The average thickness of the Wadsworth till in the Valparaiso Morainic System of Lake and northern Cook Counties, Illinois, is 22 m.

Average thicknesses of the Wadsworth till in the Lake Border Moraines, in the Lake Chicago plain, and beneath Lake Michigan have not been estimated



*Mickelson and others, 1977.

FIGURE 2.--Time and rock stratigraphy for till units in the study area. (Illinois rock stratigraphy from Lineback and others, 1974; Wisconsin rock stratigraphy from Mickelson and others, 1983.)

because of a lack of data. Along the Wisconsin portion of the lake bluffs, 30 m of Wadsworth till and interbedded lacustrine sediment has been found. Thicknesses of up to 50 m occur in the Lake Border Moraines and up to 23 m in the Lake Chicago plain. Up to 18 m of Wadsworth till have been reported in the southwest corner of Lake Michigan (Lineback and others, 1974).

Stratigraphic Position

In Illinois the Wadsworth till lies older Woodfordian tills of the Wedron Formation (fig. 1 and 2). In Wisconsin the Wadsworth till (Oak Creek Formation) overlies the Haeger till (New Berlin Formation). The contact between the Oak Creek Formation of the Valparaiso Moraines and the New Berlin Formation can be seen in quarry exposures in Racine and Waukesha Counties, Wisconsin (Mickelson and others, 1983). Along the lake bluffs south of Milwaukee, the Wadsworth till overlies Unit 1 of Mickelson and others (1977), the bouldery coarse-textured till they suggest may be correlative with the Haeger Till Member of Illinois.

In Illinois, Wadsworth till is not known to overlie Haeger till. Examination of test-boring and water-well samples from Lake and Cook Counties failed to produce a stratigraphic relationship between these tills, but Wadsworth till was found to overlie outwash of Haeger composition in Cook County. Subsurface data show that the Wadsworth till of northeastern Illinois is usually underlain by a reddish-gray, silty till containing 70 percent illite that is known to occur above peat. The silty till also occurs above Tiskilwa till. Peat occurring below Tiskilwa till in northern Cook County is dated at 23 000 radiocarbon B.P. (Kempton and Gross, 1971); hence, the reddish-gray till

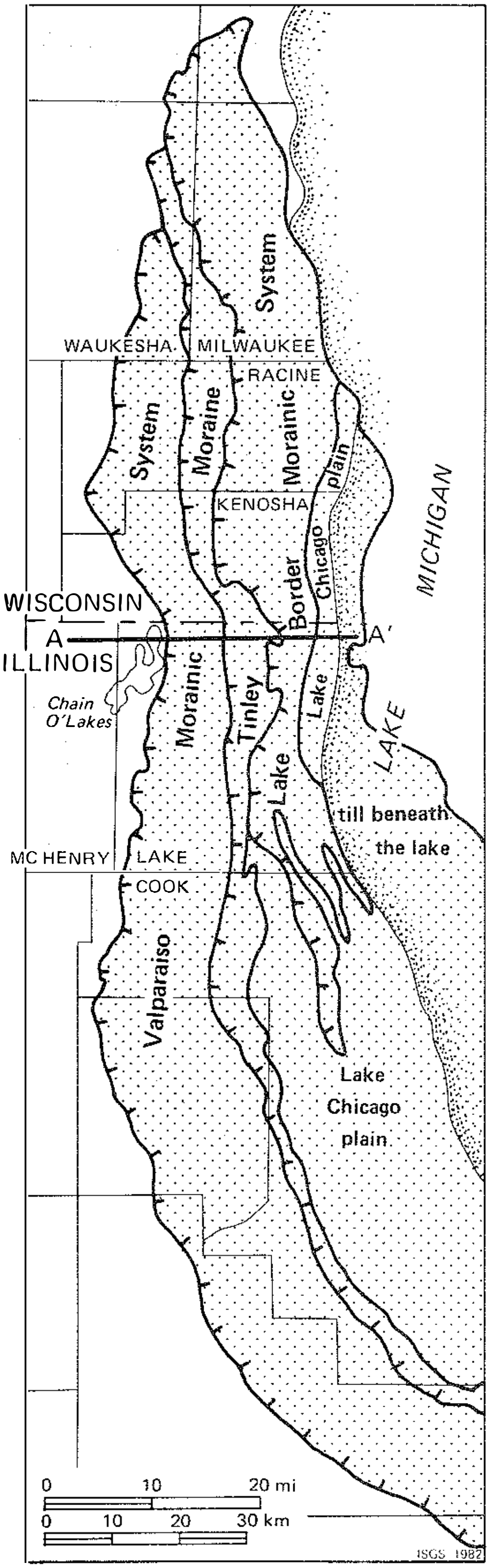


FIGURE 3.--Distribution of the Wadsworth Till Member in the southwestern Lake Michigan area.

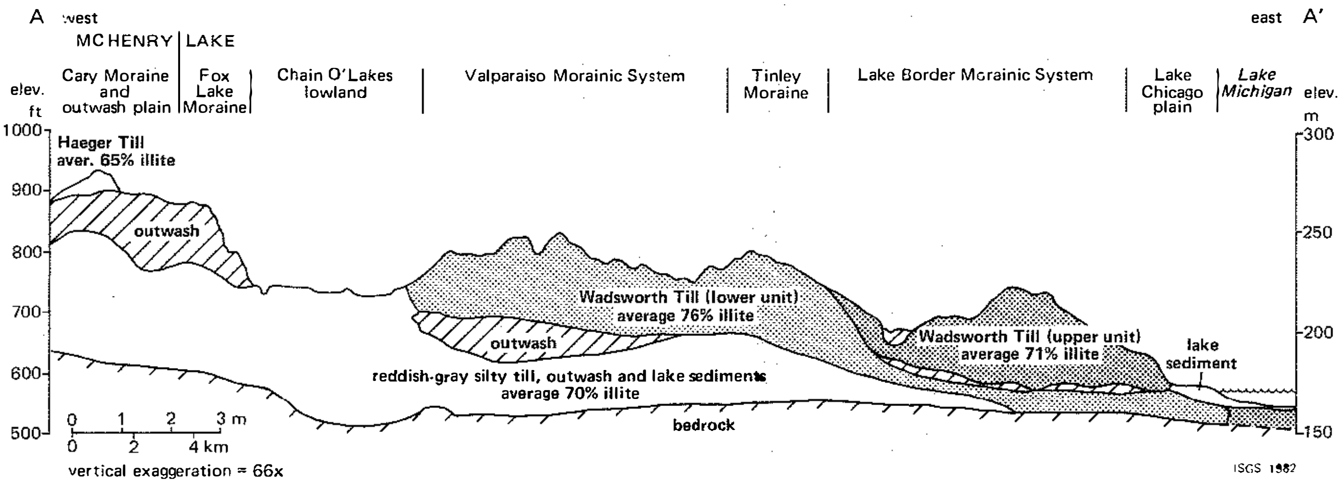


FIGURE 4.--Typical cross section west-east across northern Illinois. Line of section (A-A') is shown in figure 3.

found beneath the Wadsworth till is of Woodfordian age. This same till occurs in the Chain O'Lakes lowland and beneath Haeger till and outwash in McHenry County, Illinois, west of the Chain O'Lakes (fig. 4); it is redder and finer textured than the Haeger till. Although the reddish-gray, silty till is thought to be equivalent to older Wedron units that occur at the surface west and south of the study area (fig. 1) no definite correlation has been established. In the southern part of this study area the Wadsworth till is underlain by either the clayey Yorkville Till Member or the sandy Lemont drift, which Bogner (1974) has correlated to the Malden Till Member.

The stratigraphic relationship of the Wadsworth till and the next younger till is not clear. Lineback and others (1974) state that the Shorewood Till Member overlies the Wadsworth Till Member along the mid-lake high in Lake Michigan. This relationship is based on interpretation of a north-south seismic profile in which a subsurface boundary between the Wadsworth and the Shorewood units can be traced for several miles north of a prominent moraine front in southern Lake Michigan. No samples of the two tills in stratigraphic position have been recovered from the lake. Neither has the Shorewood till been traced on land at the surface in Wisconsin (fig. 1). Unit 2C of the shore erosion study (fig. 2) occurs at the surface along the bluffs south of Milwaukee and has been suggested as a possible equivalent of the Shorewood till (Acomb and others, 1982); however, it contains more illite (usually 70 percent or more) and is less red than the Shorewood till (63 percent illite) as defined by Lineback and others (1974). In the bluffs north of Milwaukee, the Oak Creek Formation which here has the clay-mineral composition of the Shorewood till, is overlain by the red-brown Ozaukee Member of the Kewaunee Formation (Acomb and others, 1982; Mickelson and others, 1983). Surface samples of Wadsworth till from the area mapped as Tinley Moraine west of Milwaukee are compositionally similar to the Shorewood till, but the Tinley morainic ridge appears to mark an ice margin position that is clearly traceable from Wisconsin to Indiana.

This discrepancy between the stratigraphy in the lake basin and the stratigraphy on land remains to be resolved. The Shorewood till is not considered a separate unit in Wisconsin as it is in Lake Michigan. Tills of Shorewood and Wadsworth composition (as defined by Lineback and others, 1974) have not been found in stratigraphic contact.

Stratigraphic unit	Average matrix texture (%)				Average Illite (%)	N
	Sand	Silt	Clay	N		
Shorewood Till Member						
Wickham and others, 1978	--[a]	--	--	--	63	4
Wadsworth Till Member						
Wickham and others, 1978	--	--	--	--	72	15
Willman and Frye, 1970	11	38	51	--	67	--
	12	37	51	--	77	--
This study[b]	11	43	46	98	70	83
Haeger Till Member						
Wickham, 1975	45	39	16	32	62	35
Willman and Frye, 1970	39	39	22	--	63	--
Yorkville Till Member						
Killey, 1982						
upper (Dwight mineral zone)	10	43	47	48	76	49
lower	13	43	44	132	81	141
Wickham, 1975	15	42	43	84	77	94
Willman and Frye, 1970	12	38	50	--	78	--
Malden Till Member						
Wickham, 1975	32	46	22	28	76	33
Willman and Frye, 1970	22	44	34	--	77	--
Tiskilwa Till Member						
Wickham, 1975	35	39	26	850	66	918
Willman and Frye, 1970	31	37	32	--	65	--

N = Number of samples

[a] No data

[b] Includes all data from area mapped as Wadsworth Till Member and Oak Creek Formation in Figure 1.

TABLE 1.--Characteristics of the Wadsworth and adjacent till members of the Wedron Formation.

TEXTURE AND COMPOSITION

Mean values for texture and clay mineral composition for the Wadsworth till are given in table 1. Typical values of these parameters cited by other researchers who have studied the Wadsworth and adjacent tills of the Wedron Formation are also shown.

The Wadsworth till of Illinois is characterized by its gray color, clayey texture, high illite content (generally greater than 70 percent) and low percentage of larger-than-2-mm clasts (average 3 percent). It can be distinguished from the "overlying" Shorewood till in Lake Michigan by its higher illite content and grayer color. The Wadsworth till is readily differentiated from the adjacent and subjacent Haeger till by its finer texture and grayer color. The clayey Yorkville till is very similar to the Wadsworth till; these tills are not easily distinguishable, but the Wadsworth till is sandier at its western margin. Although the lower Yorkville till of Killey (1982) has more illite (80 percent) than the Wadsworth, her upper Yorkville (Dwight mineral zone) is nearly identical in clay mineral composition (76 percent illite) to that of the lower part of the Wadsworth. The Malden till is generally sandier and more often oxidized than is the Wadsworth Till; the Tiskilwa has a distinctive red-brown color and a sandy texture, and it is lower in illite.

Location	Sand (%)			Silt (%)			Clay (%)			Illite (%)[a]		
	X	S	N	X	S	N	X	S	N	X	S	N
Lake Border Moraines	8	3.6	36	43	5.4	36	49	7.0	36	71	2.2	30
Inner	8	3.7	25	45	4.8	25	47	6.8	25	71	2.2	22
Outer	7	3.3	11	39	5.0	11	54	4.8	11	71	2.1	8
Tinley Moraine	8	3.0	21	38	5.3	21	54	6.0	21	74	2.4	24
Valparaiso Moraine	15	4.2	41	45	3.8	41	40	5.2	41	76	1.9	55
Lake Chicago plain	--[b]	--	--	--	--	--	--	--	--	75	1.4	12
Lake Michigan	--	--	--	--	--	--	--	--	--	72	0.8	4

X = mean; S = standard deviation; N = number of samples

[a] Data from Ozaukee, Washington and part of Waukesha Counties, Wisconsin, not included

[b] No data

TABLE 2.--Characteristics of the Wadsworth Till Member in the Lake Border, Tinley, and Valparaiso Moraines, the Lake Chicago plain, and Lake Michigan.

LATERAL VARIATION

The character of the Wadsworth till of the study area varies along lines perpendicular to ice margin positions and along lines parallel to ice margin positions. Both types of variation show distinct patterns. Lateral variations in the characteristics of the Wadsworth till are reported in table 2.

Figure 5 shows lateral variation in percentage of illite in the clay-size fraction over the study area. The illite values are from unoxidized surface samples or the unoxidized portions of the top till unit from test-boring and water-well samples. In Illinois and the southern portion of the Wisconsin study area (Kenosha and Racine Counties), a fairly distinct change in illite content occurs between the Wadsworth till of the Valparaiso Morainic System and the Wadsworth till of the Lake Border Morainic System. The average illite content in the Valparaiso is 76 percent whereas the average in the Lake Border is 71 percent. The small standard deviations associated with the averages (around 2.0) (table 2) suggest that little overlap in percent illite occurs between the tills of the two morainic systems. The average percent illite in the Tinley Moraine is intermediate between the two--in some areas the clay-mineral content is similar to that of the Valparaiso, in other areas, to that of the Lake Border. The Lake Chicago plain is underlain by Wadsworth till similar in illite content (75 percent) to that in the Valparaiso Moraines (76 percent) while that in Lake Michigan is lower (72 percent) and more like that of the Lake Border (71 percent).

North of the border between Racine and Waukesha Counties in Wisconsin the percentage of illite in samples of Wadsworth till from the Valparaiso Morainic System is less than to the south. In Waukesha County the Wadsworth till appears to thin, and in some places the moraine truncates the Waukesha drumlin field (fig. 5). In these places the Wadsworth till is lower in illite and sandier, and thus--where oxidized--dificult to differentiate from the Haeger (New Berlin) till of the drumlin field.

The till of the Tinley and outer Lake Border Moraines becomes redder and progressively lower in illite northward from the vicinity of south Milwaukee. Illite in samples ranges from 72 percent in the south to 52 percent to the north in Washington County; such wide variation in illite is most uncommon within the Wadsworth Till Member and other till units in Illinois.

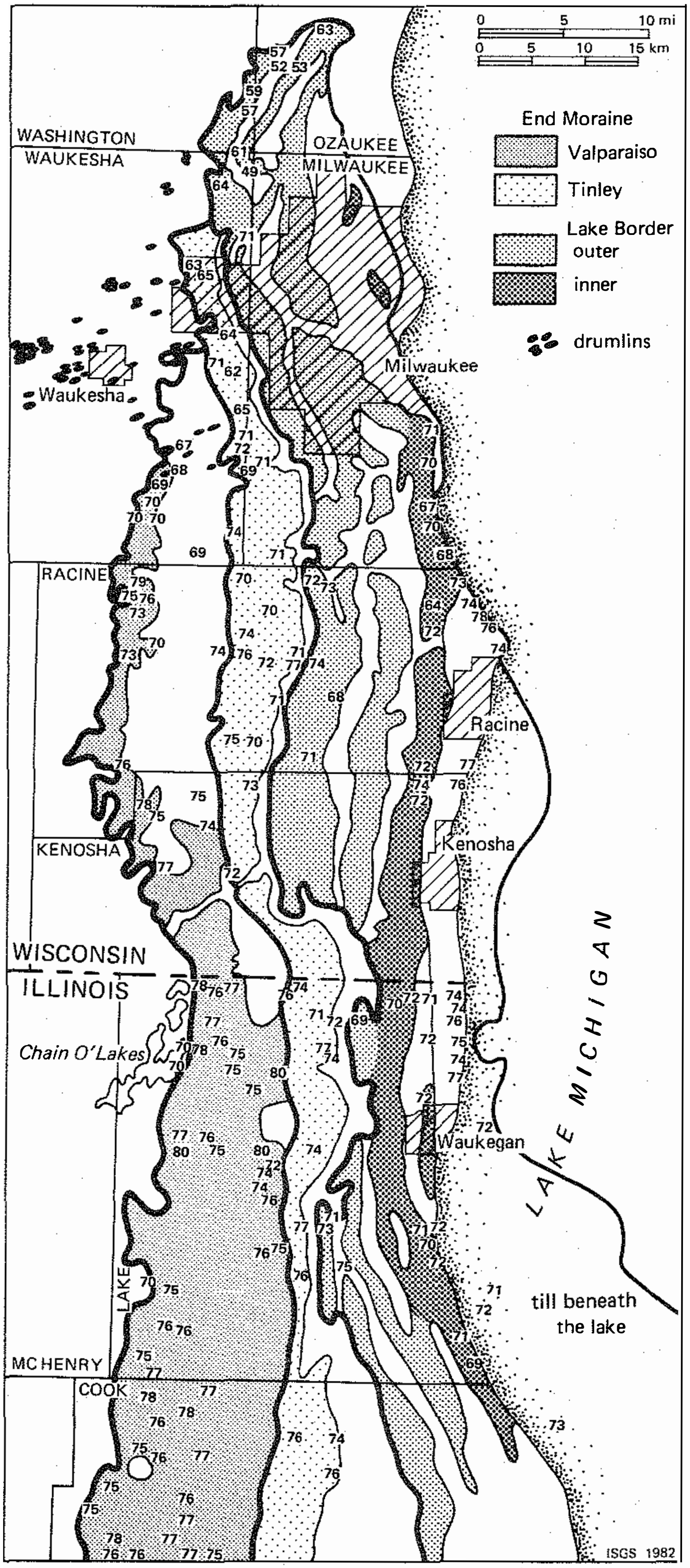


FIGURE 5.--Percentage of illite in the clay fraction of Wadsworth Till in the study area. Area of end moraine from Lineback (in press).

Lateral variation can also be noted in the texture of the Wadsworth till over the study area. Table 2 summarizes textural analyses of the till in the Valparaiso, Tinley, and Lake Border Moraines. The mean texture of the Wadsworth till in the Valparaiso Morainic System is sandier and less clayey than that of the Wadsworth till of the Tinley and Lake Border Moraines. The Tinley and outermost Lake Border Moraines are higher in clay content than the innermost Lake Border Moraines.

Variation in pebble lithologies has also been noted between the moraines composed of the Wadsworth Till Member (Willman and Frye, 1970). Black shale pebbles are more predominant in the till of the Tinley and Lake Border Moraines than in that of the Valparaiso.

VERTICAL VARIATION

Figure 4 illustrates typical stratigraphic variation in illite content within the Wadsworth till across the northern part of Illinois. In the Lake Border Moraines the less illitic (71 percent) Wadsworth till overlies the more illitic (76 percent) Wadsworth till, which is present at the surface in the Valparaiso Morainic System and beneath lacustrine sediment of the Lake Chicago plain. This relationship (a less illitic Wadsworth till over a more illitic Wadsworth till), commonly occurring with an intervening lacustrine or outwash sequence, is found in water-well and test-boring samples in Lake and Cook Counties of Illinois and can also be seen in the Illinois bluff exposures. Although some surface samples from the Tinley Moraine have less illite than do those at the surface in the Valparaiso, subsurface data indicate most of the moraine consists of till with more illite, similar to that of the Valparaiso Morainic System.

In the hummocky terrain of the Valparaiso Morainic System of Lake County another type of vertical variation occurs. Analyses of samples from water wells and test borings in this area show illite compositions of 75 to 76 percent interbedded with illite compositions of 70 to 71 percent. Some profiles have these randomly mixed compositions to depths of 35 m; most of the mixed profiles appear to contain nonhomogeneous till interstratified with lacustrine deposits. The two compositions are similar to those of the lower part of the Wadsworth till (76 percent illite) and the reddish-gray, silty till (70 percent illite) underlying the Wadsworth.

Till samples collected along the bluffs south of Milwaukee show vertical variation in illite composition with depth within continuous till units that are homogeneous in texture. For example, a unit may range progressively from 70 percent illite at the top to 65 percent illite at the base. In some exposures in Illinois and Wisconsin, Wadsworth till units of the same composition are separated by lacustrine and outwash deposits.

DISCUSSION

The Wadsworth till is the youngest till in Illinois and Indiana. Its distribution in the moraines immediately bordering the lake indicates that it was deposited by the last pulse of ice to reach the southern part of the Lake Michigan basin.

The distinctive characteristics (color, clay-mineral composition, amount and lithology of pebbles, matrix texture) of the Wadsworth till reflect its Lake Michigan source. The Paleozoic limestone, dolomite, and gray shale units of the basin are highly illitic and Wisconsinan tills derived from the Lake Michigan basin are typically gray and illitic (Willman and Frye, 1970). Ordovician, Silurian, and Devonian strata that border Lake Michigan are predominantly dolomite and shale, and these are by far the most common pebble lithologies found in the Wadsworth till. The clayey texture and scarcity of pebbles in the Wadsworth till are attributed to glacial reworking of Paleozoic clay and shale from the Lake Michigan basin and incorporation of proglacial lacustrine clay derived from disaggregated Paleozoic rocks of the basin. Dreimanis (1961) found that the tills of the Lake Erie basin derived principally from shale are coarser textured (less clayey) than those that also contain incorporated lacustrine clay and silt. The latter are similar in texture to the Wadsworth till.

One explanation for the variation in the clay-mineral composition within the Wadsworth till is that it is directly related to the relative amount of the glacial load entrained from the Lake Michigan basin. A decrease in illite from the time that the Wadsworth till was deposited at its outermost margin (Valparaiso Morainic System) to the time it was deposited on the lake floor may indicate a decreasing relative amount of entrainment of the highly illitic Lake Michigan basin material over time. This trend continued as the Woodfordian ice retreated northward and the Shorewood and Manitowoc tills were deposited. Changes in dominance of areas of erosion and entrainment have been explained by variation in the basal thermal conditions of the ice through time (Boulton, 1972b). Wickham and Johnson (1981) suggest that changes in the Lake Michigan portion of the Laurentide ice sheet occurred during Woodfordian time and can account for differences in the composition of some of the red and gray Woodfordian tills.

A second explanation for the changing composition and color of the clayey till that borders Lake Michigan is that the composition of glacial Lake Chicago sediment changed with time. Clayton (1983) suggests the possibility that influx of red sediment (less illitic) from the Lake Superior basin may have occurred between ice advances of latest Wisconsinan time although no connection between Lake Superior and glacial Lake Chicago has been confirmed. Change in the composition of glacial Lake Chicago sediment could also have resulted from a changing composition of the ice in the Lake Michigan basin (due either to change in the area of dominant entrainment or to change in the source rocks available for erosion). For this reason, the possibility of influx from Lake Superior is difficult to evaluate.

The fact that change in clay mineral composition is not entirely gradual, but instead is clearly associated with ice-margin positions (Valparaiso and Lake Border) suggests that in some cases fluctuation of the ice front accompanied change in source. This idea is supported by the fact that lacustrine and outwash sequences commonly occur stratigraphically between the less illitic "Lake Border" till and the more illitic "Valparaiso" till. The textural change between the till of the Valparaiso Moraines and the till of the Tinley and Lake Border fronts is consistent with a period of ice withdrawal and later readvance with incorporation of proglacial lake clay.

Change in illite with distance along north-south ice-margin positions may reflect differences in the length of flow path. The material deposited in the moraines at the southern margin of the lake might have been transported more than 100 km farther than the till in the same moraines west of Milwaukee. The smaller percentage of illite and the redder color of the till in the Tinley and Lake Border Moraines to the north indicate less incorporation of the gray Paleozoic sediment from the Lake Michigan basin than occurs in the till farther south. This is not surprising since flow paths of the ice which deposited the Wadsworth till west of Milwaukee would not have traversed the southern basin of Lake Michigan as would flow paths of the ice which deposited the Wadsworth till at the southern margin of the lake. Some differences in composition of the tills would be likely to occur, considering the differences in length of flow path in the Lake Michigan basin and the resultant differences in opportunity for incorporation of gray illitic Paleozoic sediment.

Progressive vertical variation in illite in homogeneous till as occurs in the lake bluffs south of Milwaukee may be due to a gradual change in dominance of entrainment areas or source rock eroded. This phenomenon is not uncommon in till units that occur between red (greater influence of Lake Superior basin source) and gray (dominance of Lake Michigan basin source) end members in the Wedron Formation of Illinois (Wickham and Johnson, 1981). Rock-stratigraphic classification of these intermediate units poses problems.

The mixed compositon of thick sequences in the Valparaiso Morainic System of Lake County, Illinois, is not well understood. The heterogeneity of the till and lacustrine deposits is consistent with a supraglacial origin (Boulton, 1972a). The interbedding of Wadsworth till compositions with the reddish-gray silty till compositions in vertical profiles can be explained by the advance and stacking of Valparaiso ice over older stagnant ice (or the shearing of older till into the Valparaiso ice). Ablation and resedimentation could have resulted in the interbedding of the two compositions and the heterogeneity of the sequences. The hummocky topography with numerous kettles and lakes is further evidence for supraglacial sedimentation due to regional stagnation of the ice which deposited the Valparaiso Moraines. The thinning and compositional changes in the Wadsworth till of the Valparaiso Morainic System in Waukesha County, Wisconsin, may be due to local incorporation of the sandy Haeger till of the Waukesha drumlin field.

SUMMARY

On the basis of this research, I propose the following sequence of events for the deposition of the Wadsworth till.

1. Late Woodfordian ice from the Lake Michigan basin advanced to the Valparaiso morainic front, overriding older Woodfordian till and abutting stagnant ice in the Chain O'Lakes lowland. This ice deposited the gray illitic Wadsworth till of the Valparaiso Morainic System.

2. The ice downwasted and the active ice margin retreated an unknown distance, possibly back into the present area of the lake. Proglacial drainage was blocked by the Valparaiso end moraines.

3. Ice advanced to the position of the Tinley Moraine. During the advance, the ice incorporated proglacial lake sediment and deposited Wadsworth till similar in composition but more clayey than that in the Valparaiso Morainic System.

4. As the ice margin retreated (at least back to the present area of the lake), Wadsworth till of the same composition as that in the Tinley Moraine was deposited. Proglacial drainage was blocked between the Tinley Moraine and the ice margin forming glacial Lake Chicago.

5. Ice advanced out of the lake basin, incorporating Lake Chicago sediment. Wadsworth till, similar in texture to that of the Tinley Moraine but with less illite, was deposited in the outer Lake Border Moraines over lacustrine sediment and more illitic Wadsworth till.

6. Wadsworth till was deposited behind several distinct ice-margin positions as the front fluctuated, generally retreating basinward. As the ice

front retreated northward in the Lake Michigan basin, Wadsworth till was deposited on the lake floor.

7. Change of dominance of areas of entrainment, source rocks eroded and/or influx of sediment from outside the Lake Michigan basin resulted in change in the composition and when the ice readvanced over the Wadsworth till to form an end moraine on the lake bottom, the redder, less illitic Shorewood till was deposited.

CONCLUSIONS

The gray, clayey Wadsworth till of Illinois and Wisconsin is a distinctive field unit that can usually be differentiated from other till units surficially and stratigraphically with the possible exception of the Yorkville till of Illinois. Although these two till units are very similar, the sandier Valparaiso Moraine forms a boundary between them where they are in contact at the surface. In the study area of Illinois the Wadsworth Till Member is a serviceable rock-stratigraphic unit suitable for formation rank and it is equivalent to what is being defined as the Oak Creek Formation in Wisconsin.

In Illinois a "Wadsworth Formation" can be subdivided, by means of analytical data, into two mappable rock-stratigraphic units: (1) a slightly sandy, relatively more illitic lower unit and (2) a clayey, relatively less illitic upper unit. The more illitic unit occurs in the Valparaiso and Tinley Moraines and beneath sediment of the Lake Chicago plain. The less illitic unit occurs in the Lake Border Moraines and beneath nontill sediment in southern Lake Michigan. These rock-stratigraphic units appear to lose their distinctive characteristics northward. The till in the northern part of the Tinley and Lake Border Moraines is considered to be a less illitic facies of the Wadsworth till.

If the Wadsworth till should be raised in rank from a member to a formation in the Illinois rock-stratigraphic hierarchy, the next logical step would be to reevaluate the rank and status of the younger two members of the Wedron Formation (the Shorewood Till Member and the Manitowoc Till Member).

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QUATERNARY STRATIGRAPHY OF SOUTHERN MILWAUKEE COUNTY, WISCONSIN
PRELIMINARY RESULTS

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INTRODUCTION

With the exception of Alden's studies of the Quaternary geology of southeastern Wisconsin (1906, 1918), no detailed investigation and interpretation of the glacial stratigraphy of southern Milwaukee County, Wisconsin, has been done. Previous stratigraphic studies in the Milwaukee and Menomonee River valleys, north of the area covered in this report, are limited to the engineering studies of Williams (1954) and Rose (1978) and the stratigraphic study by Need (this volume). Along the Lake Michigan shoreline the general stratigraphic relationships and engineering properties of the bluff materials are generally known from the work of Mickelson and others (1977) and Klauk (1978).

In order to obtain better information on the Quaternary deposits south of the Menomonee River valley and west of the Lake Michigan bluffs, a study of southern Milwaukee County has begun. The area under consideration is bounded on the north by Morgan Avenue, on the south by the Milwaukee-Racine County line, on the east by Lake Michigan, and on the west by the Milwaukee-Waukesha County line. To date, approximately 130 water-well records have been examined. As there is inconsistency among records, we plan to begin a drilling program this summer to obtain better records in areas where the subsurface geology is not well known. In addition, we plan to take geotechnical borings so that we may analyze sediment properties which in turn will assist us in stratigraphaic correlation.

GEOLOGICAL SETTING

The surficial deposits in Milwaukee County consist of till and outwash deposits interbedded with fine-grained, stratified lake sediment and have been reported by numerous workers beginning with Chamberlin in 1877. The deposits are Wisconsinan in age and were deposited during the Woodfordian and Greatlakean Substages (Frye and Willman, 1960; Evenson and others, 1976). During this time successive glacial advances and retreats coupled with the development of proglacial lakes left a series of unlithified deposits in southern Milwaukee County. The Wisconsinan glacier flowed from the north and northeast down the Lake Michigan basin into Illinois and simultaneously spread westward and southwestward out of the basin into Wisconsin. As a result, the Pleistocene materials in the county consist of till, outwash, and lacustrine sediment.

STRATIGRAPHY

The most detailed work on stratigraphy has been done along the Lake Michigan bluffs (fig. 1; Stop 5 of Mickelson and others, 1983). The materials found in the lake bluffs are primarily unnamed units of the Oak Creek Formation (Mickelson and others, in press) and consist primarily of till, outwash, and lacustrine sediment. Inland the unlithified deposits are predominantly composed of till and glaciofluvial sediment. In the northern part of the county lacustrine sediment is overlain by the lowest till unit (Till III, fig. 1) of the Ozaukee Mem-

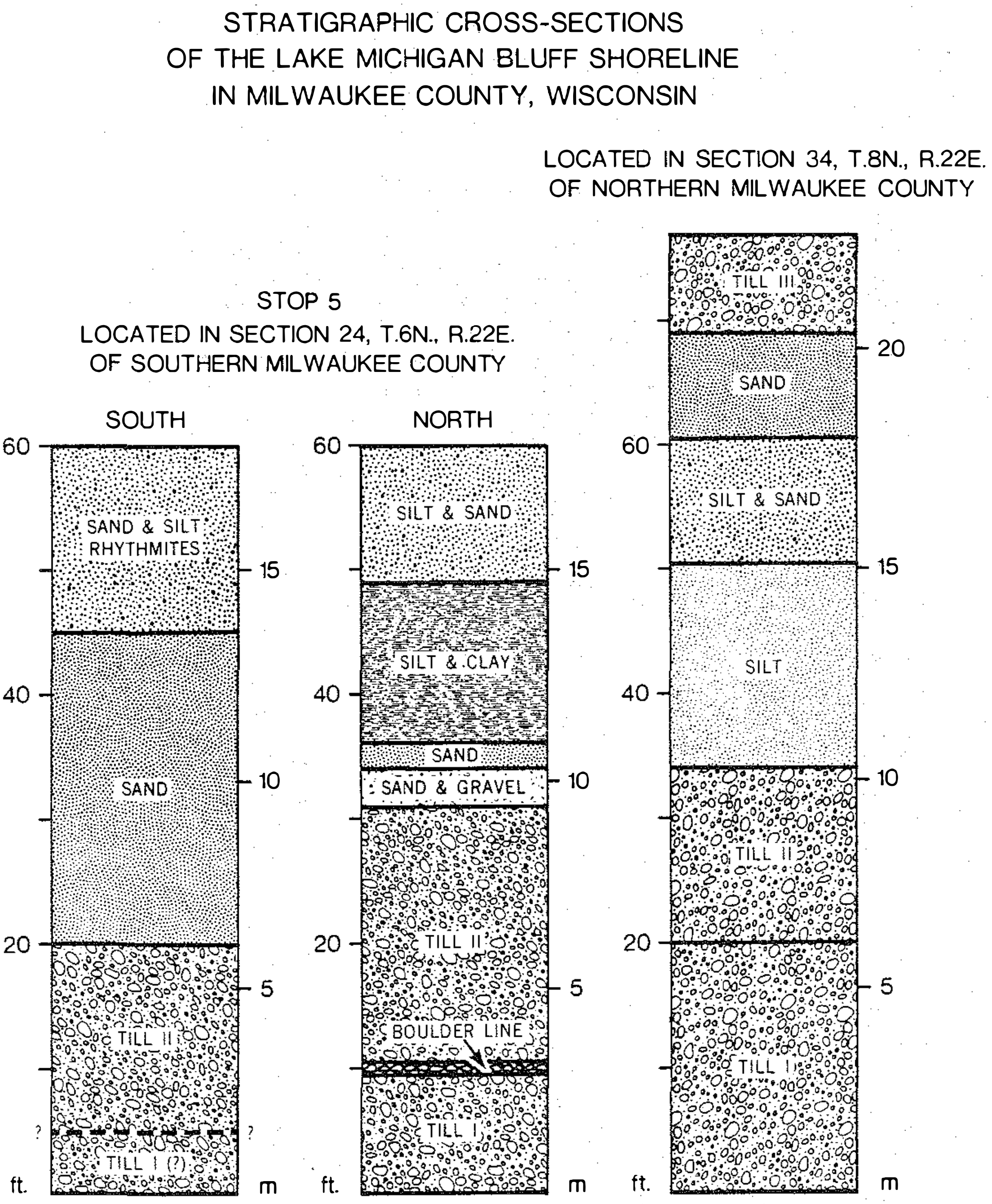

FIGURE 1.--Stratigraphic cross-sections of the Lake Michigan Bluff Shoreline in Milwaukee County, Wisconsin.

ber of the Kewaunee Formation (Mickelson and others, in press), and are also tentatively identified in the northwest quadrant of southern Milwaukee County.

The oldest till (Till I, fig. 1) exposed in the bluffs is the uppermost till member of the New Berlin Formation (Mickelson and others, in press). It is also tentatively identified as the lowest till unit in portions of southern Milwaukee County. The till was probably deposited during a glacial advance prior to 14,000 B.P. and probably correlates with the Haeger Till Member of the Wedron Formation of northeastern Illinois (Willman and Frye, 1970). Till I consists of material ranging in size from clay to boulders (2 m in diameter). The till at the bluffs and throughout the southern part of the county is primarily sandy silt with a large number of cobbles and boulders. Near the Lake Michigan shore the sand fraction ranges from 17 to 46 percent by weight, but as one moves west across the county there are areas where it is significantly sandier, containing up to approximately 70 percent sand by weight. The color of the till ranges from light brownish-gray (10YR 6/2) to light gray (10YR 6/1) to brown (7.5YR 5/4).

Till I is overlain by a boulder-lag deposit that separates it from Till II at the Lake Michigan bluffs. This separation is not detectable in water-well records in the County. The till, probably deposited at approximately 13 000 B.P., is much clayier, and is the lowest till unit of the Oak Creek Formation. The till is primarily clayey silt near the Lake Michigan shore, but varies inland from clayey silt to silty clay with the clay-silt fraction ranging from 65 to 98 percent by weight. Till II was probably deposited during several closely spaced fluctuations of the ice front based on the fact that it is interbedded with glaciofluvial sand and gravel at many localities and in

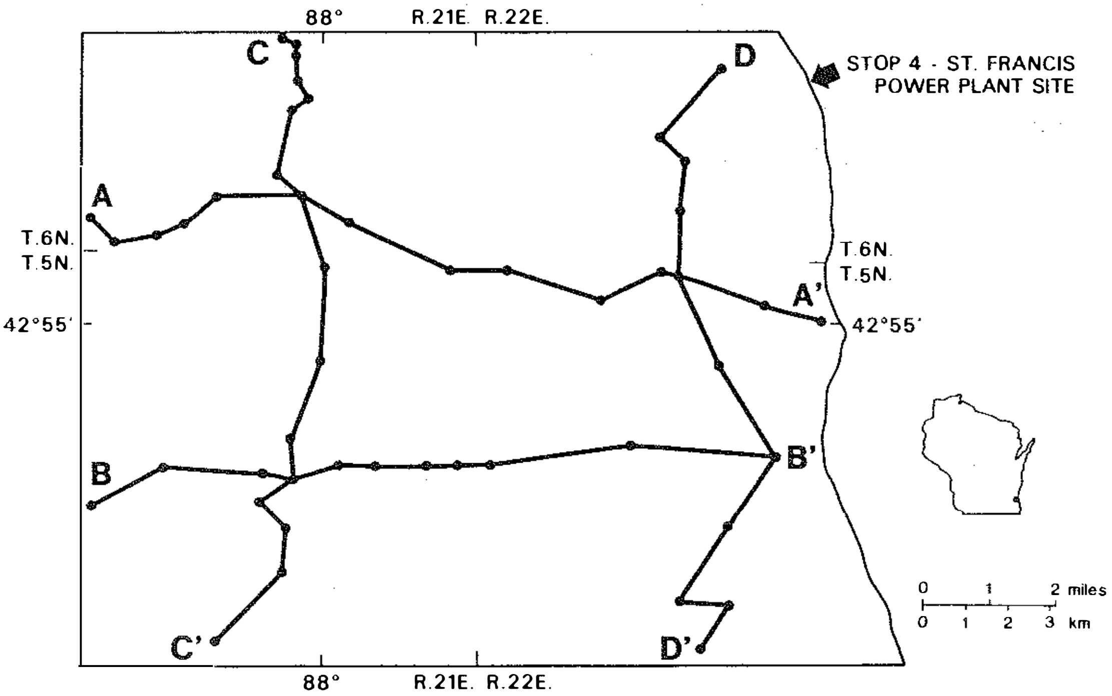

FIGURE 2.--Location map of cross-sections of the unconsolidated Pleistocene materials, southern Milwaukee County, Wisconsin.

some localities with lacustrine sediment. The till is correlatable with the Wadsworth Till Member of the Wedron Formation in Illinois (Willman and Frye, 1970). Schneider (in Mickelson and others, in press) believes that it is very probably "... equivalent in age to the upper parts of the Horicon Formation of the Green Bay Lobe." The color of Till II ranges from dark brown (7.5YR 4/2, 4/4) to gray (10YR 5/1) or light gray (10YR 7/1). The abundant clay in this till was probably caused by incorporation of ice-marginal lake sediments into the glacial debris as glaciers moved west southwestward out of the Lake Michigan Basin.

Along the Lake Michigan bluffs Till II is often interbedded with sand and gravel and the till may be divided into an upper and lower unit. From our preliminary work, most of the till in southern Milwaukee County appears to belong to this unit. On the cross sections (figs. 3 and 4), the interfingering relationships among the upper and lower unit of the till and the outwash and lacustrine sediment are readily identifiable. In general, the till is separated by lacustrine and occasional glaciofluvial sediment along the Lake Michigan bluffs, but further to the west till and glaciofluvial sediment dominates.

Finally, there is some evidence in the northwestern part of southern Milwaukee County of a younger till, Till III (fig. 1), the Ozaukee Member of the Kewaunee Formation (Mickelson and others, in press). The Ozaukee Member is found in northern Milwaukee County and appears to extend into the northern (especially northwestern) sections of southern Milwaukee County. It ranges from reddish-brown (5YR 5/3) to light reddish-brown (5YR 6/3).

SUMMARY

The stratigraphy in the Lake Michigan bluffs in southern Milwaukee County is well known and has been documented by Klauk (1978) and Mickelson and others (1977). Our preliminary attempts to extend that stratigraphy inland resulted in the construction of cross sections A-A', B-B', C-C', and D-D' (figs. 3 and 4). In those sections Till II appears to be the principal till unit in the southern part of the county as determined from water-well records, initial geotechnical boring data, and from surficial exposures. Tills I and III are of much lesser significance in the area. Till I, found in the lake bluffs, is the oldest till in the area and probably forms part of the lowest till unit found in portions of the cross sections. Till III is found only in portions of the northern part of the area.

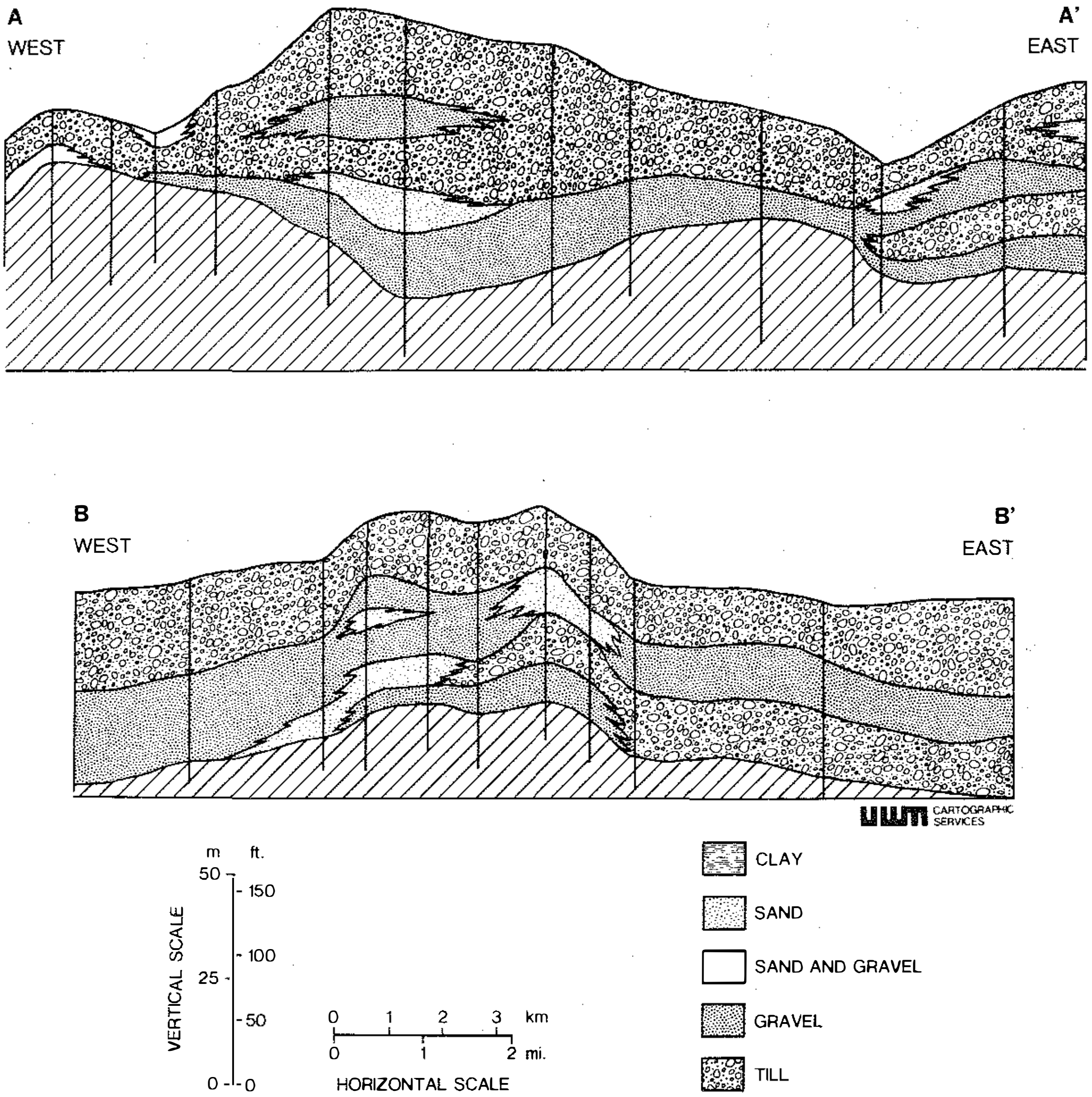

FIGURE 3.--East-west cross-sections A-A' and B-B' of the Pleistocene materials in southern Milwaukee County, Wiconsin. See figure 2 for section locations.

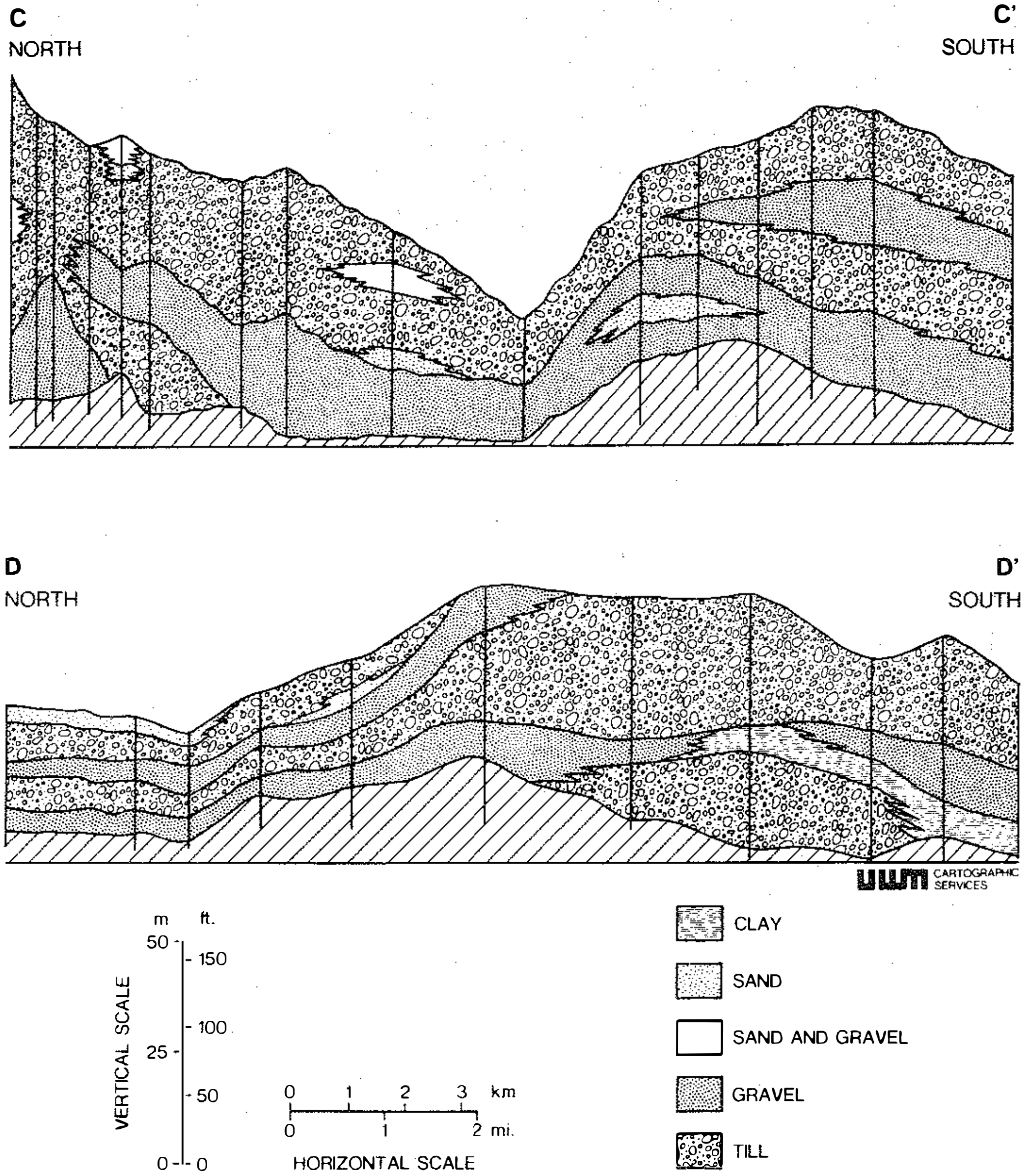

FIGURE 4.--North-south cross-sections C-C' and D-D' of the Pleistocene materials in southern Milwaukee County, Wisconsin. See figure 2 for section locations.

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QUATERNARY STRATIGRAPHY OF THE LOWER MILWAUKEE AND MENOMONEE RIVER VALLEYS, MILWAUKEE, WISCONSIN

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ABSTRACT

Numerous geotechnical borings have been drilled along the Milwaukee and Monomonee Rivers as part of the Milwaukee's Water Pollution Abatement Program, encountering as much as 60 m of Pleistocene and Holocene deposits. These deposits are differentiated into lithostratigraphic and lithogenetic units based on visual examination of split-spoon and Shelby-tube samples and a small amount of engineering test data.

The Pleistocene units consists of three distinct till units; fine-, medium- and coarse-grained, proglacial-lake sediment; and a complex and variable ice margin unit. The three till units correspond to till units 1, 2, and 3 described in bluff exposures along the Lake Michigan shoreline by Mickelson and others (1977) and to members of New Berlin, Oak Creek and Kewaunee Formations of Mickelson and others (1983). Two separate till sheets are present within the New Berlin Formation and three till sheets are present within the Oak Creek Formation. One till sheet from the Kewaunee Formation is present in the study area. This till sheet is the youngest till in the area and corresponds to the Ozaukee Member as defined by Mickelson and others (1983). Correlation of till sheets and lake sediment layers in the subsurface indicates the presence of a major meltwater outlet along the Menomonee River and a terminal ice-margin position for the youngest of the Oak Creek advances.

The Holocene units consist of fine-grained, organic-rich estuarine deposits and alluvial deposits that range in composition from silty sand to sand and gravel. This sediment occupies valleys that were eroded into the glacial deposits when the lake level was at the very low Chippewa stage. Valley filling occurred as the lake level rose to the Nipissing stage. Slight overconsolidation of some estuarine deposits and the interstratification of estuarine and alluvial deposits indicate that the lake level did not rise steadily at this time.

INTRODUCTION

More than 200 geotechnical borings were drilled along the Milwaukee and Menomonee River valleys as part of the Milwaukee Water Pollution Abatement Program (MWPAP). These borings , most of which were drilled during the last two to three years, provide an opportunity to study the subsurface stratigraphy of a large part of Milwaukee in detail. This paper is a progress report on efforts to analyze the large amount of high quality data collected from these borings. The findings are preliminary in nature and are concerned with the Pleistocene and Holocene deposits of the lower Milwaukee and Menomonee River valleys, deposits found to be as much as 60 m thick. The interpretations presented here are considered to be working hypotheses that will guide further studies.

My findings are based on visual examination of samples collected from the MWPAP geotechnical borings. The samples were taken with split-spoon and Shelby tube samplers in borings drilled using wash-rotary or hollow-stem auger techniques. Sampling intervals ranged from continuous to sampling on 5-ft centers. The samples, as well as boring logs and laboratory test data, became available to me through my work in the MWPAP. The visual examination was made to identify depositional environments so that subsurface conditions could be correlated between borings. Three lithostratigraphic units, the till units, and six lithogenetic units, the other sediment types, were identified through this process. These nine units are used to describe the general aspects of the Quaternary stratigraphy of the lower Milwaukee and Menomonee River valleys and serve as a starting point for further lithostratigraphic studies.

The Lower Milwaukee and Menomonee River valleys and the locations of borings drilled for the Milwaukee Water Pollution Abatement Program are shown in figure 1. The study area extends from Milwaukee Harbor west and north along the Milwaukee River to the North Avenue Dam, and west along the Menomonee River to the 27th Street Viaduct. Alden (1918) mapped the low-lying areas along the two rivers as terraces related to the Nipissing stage of Lake Michigan. In a compilation of old maps of Milwaukee, Rose (1978) indicates that these low areas were mostly wetlands with patches of drier ground. The upland area east and north of the Milwaukee River was mapped as red drift end moraine by Alden (1918), and the other upland areas were mapped as ground moraine of an earlier Lake Michigan Lobe advance with segments of discontinuous end moraines in several locations. The presettlement topography is shown in figure 2.

Previous stratigraphic studies of this area are limited to two engineering theses (Williams, 1954; Rose 1978) which were more concerned with foundation conditions and other engineering problems than Quaternary stratigraphy. Williams (1954) examined foundations conditions in the area roughly bounded by 12th Street, Juneau Avenue, Cass Street, and Menomonee River. Rose (1978) studied the engineering geology of an area roughly bounded by 12th Street, Wisconsin Avenue, Lake Michigan, and Greenfield Avenue. The work of Mickelson and others (1977) along the shoreline of Lake Michigan is relevant to the Pleistocene deposits in the area, but no comparable work on the Holocene deposits exists.

LITHOGENETIC UNITS

The Pleistocene and Holocene deposits found in the MWPAP borings are differentiated into three lithostratigraphic units, the till units, and six lithogenetic units, the other sediment types, the Pleistocene units include three distinct till units, fine-, medium-, and coarse-grained, proglacial lake sediment, and a complex and variable ice margin unit. A schematic diagram of the depositional environments that produced these deposits is shown in figure 3. The two Holocene units include fine-grained, organic-rich, estuarine and marshy backwater deposits, and coarse-grained point-bar and channel-lag, alluvial deposits. A schematic diagram of these depositional environments is shown in figure 4. The characteristics of the lithostratigraphic and lithogenetic units are presented below.

Pleistocene Units

The three distinct till units correspond to till units 1, 2, and 3 identified by Mickelson and others (1977) in their work on the bluff exposures along the Lake Michigan shoreline in Milwaukee County and adjacent areas. The till unit formerly called till 1 is now considered to be part of the New Berlin Formation, unit 2 is considered to be part of the Oak Creek Formation, and unit 3 is the Ozaukee Member of the Kewaunee Formation (Mickelson and others, 1983). These names will be used for the rest of this paper.

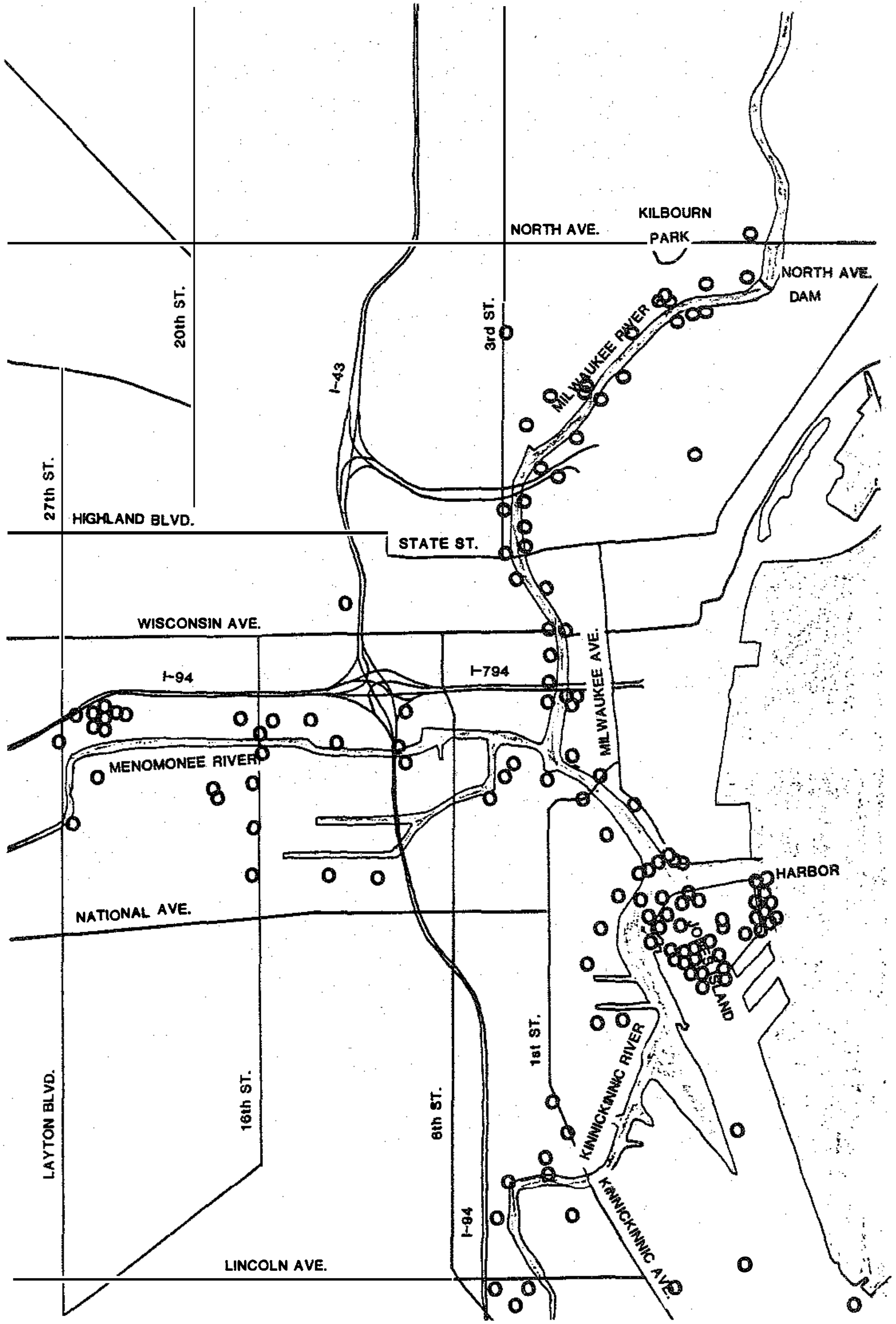

FIGURE 1.--Vicinity map of the lower Milwaukee and Menomonee River valleys. Dots show the locations of MWPAP geotechnical borings. Lines connecting selected borings are the sections shown in figures 8 and 9. Scale: 1 inch is approximately equal to 1 km (3225 ft).

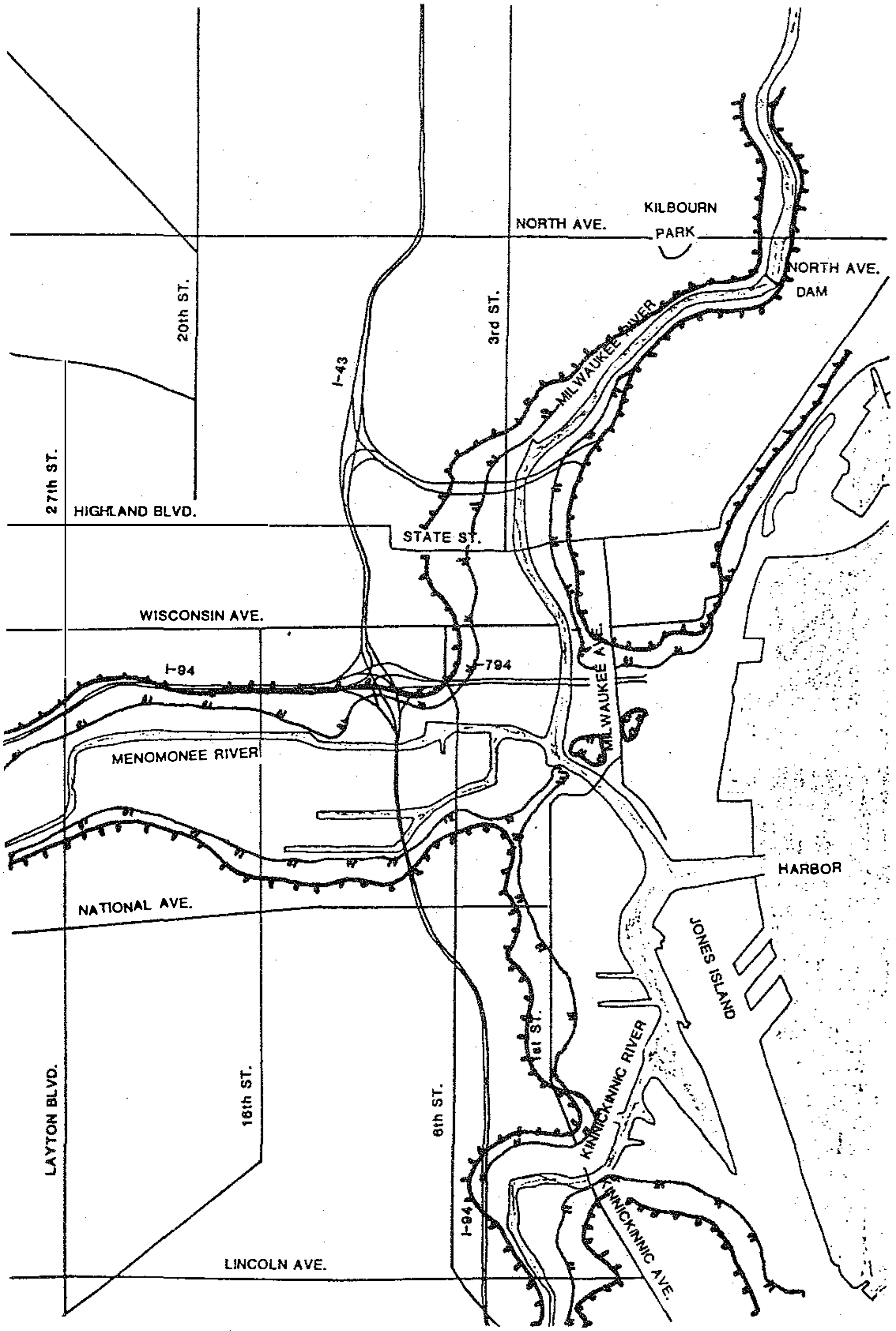

FIGURE 2.--Presettlement topography of the lower Milwaukee and Menomonee River valleys. Heavy lines are former bluffs with ticks on uplands. Light lines show extent of dry lowlands. Other lowlands were wetlands. Scale: 1 inch is approximately equal to 1 km (3225 ft). After Rose, 1978.

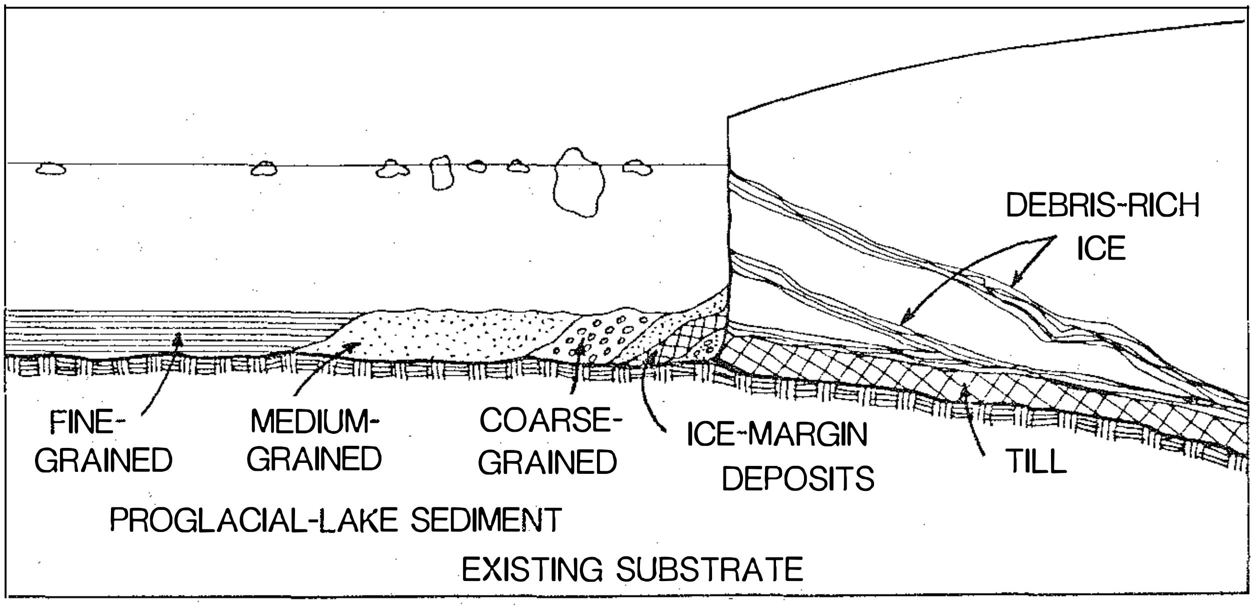

FIGURE 3.--Schematic diagram of glacial depositional environments for a calving ice margin.

The correlation of samples from the MWPAP borings to the units of Mickelson and others (1977) and Mickelson and others (1983) is based only on lithologic criteria distinguishable in visual examination. No sand:silt:clay or mineralogical data are yet available for samples recovered from the MWPAP borings. Thus, all of the grain-size descriptions presented below use engineering terminology with estimated textures shown in parentheses.

The New Berlin till, the oldest till found, is generally dense to very dense, light gray to brown, very poorly sorted, silty sand to silt that has a substantial amount of clay (loam to sandy loam) and commonly contains pebbles, cobbles, and boulders, Due to its gravelly character, borehole recovery of this till is usually poor and sample interpretation is sometimes difficult.

Holocene Units

The alluvial deposits originated in streams as channel and point-bar sediment. They are typically composed of loose to medium dense, sandy silt, and silty sand and gravel (silt loam to loamy sand). The estuarine deposits originated on marshy backwater areas and in shallow estuaries created as the lake level rose from the Chippewa stage to the Nipissing stage. The deposits are typically composed of organic-rich to peaty, silty clay and clayey silt, and they are generally soft to medium stiff and quite compressible.

GENERAL STRATIGRAPHY

The Quaternary stratigraphy of the lower Milwaukee and Menomonee River valleys is shown schematically in figure 5. The oldest Pleistocene deposits are part of the New Berlin Formation in which two till sheets are present. The next three till sheets belong to the Oak Creek Formation and may or may not be separated from each other or from the New Berlin Formation by lacustrine deposits. The till sheets of the Oak Creek Formation are overlain by till of the the Ozaukee Member in part of the study area. A major unconformity is present between the Pleistocene deposited and the overlying Holocene depos-

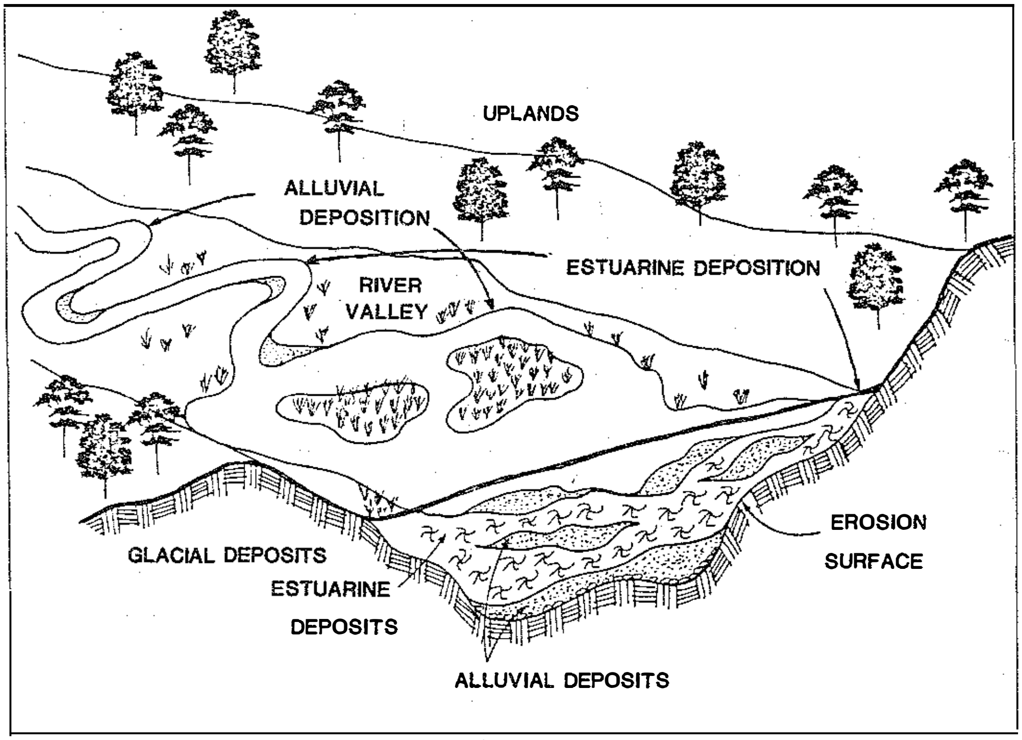

FIGURE 4.--Schematic diagram of postglacial depositional environments in the lower Milwaukee and Menomonee River valleys.

its. The oldest material overlying this unconformity is an alluvial deposit that commonly contains a large amount of gravel in the lower part of the deposit. The youngest sediment in the study area consists of estuarine deposits, which contain discontinuous lenses of alluvial deposits in places.

Samples recovered from the Oak Creek till typically stiff to hard (dense to very dense), gray to purplish or pinkish gray, silty clay to clayey silt, and clayey or silty sand (silty clay loam to silt loam to loam) in which the largest particles are usually fine pebbles. Cobbles and boulders are commonly encountered where this till directly overlies bedrock.

The Ozaukee till is typically stiff to hard, reddish brown, poorly sorted, silty clay to clayey silt (silty clay loam to silt loam) in which the largest particles are usually pebbles. This till corresponds to the red till mapped by Alden (1918) and was identified and characterized by Acomb and others (1982).

The three types of proglacial-lake sediment are distinguished primarily on grain-size distributions. The fine-grained sediment is typically composed of stiff to hard clay to clayey silt (clay to silty clay loam) that is commonly laminated and relatively well sorted. The medium-grained sediment is composed of medium dense to very dense, silty fine sand to silt (sandy loam to silt) with very little clay. The coarse-grained sediment is typically composed of dense to very dense, nonsilty sand and gravel (loamy sand to sand).

The ice-margin unit is interpreted to be present when closely spaced samples indicate interbedded lacustrine and till deposits. Individual beds

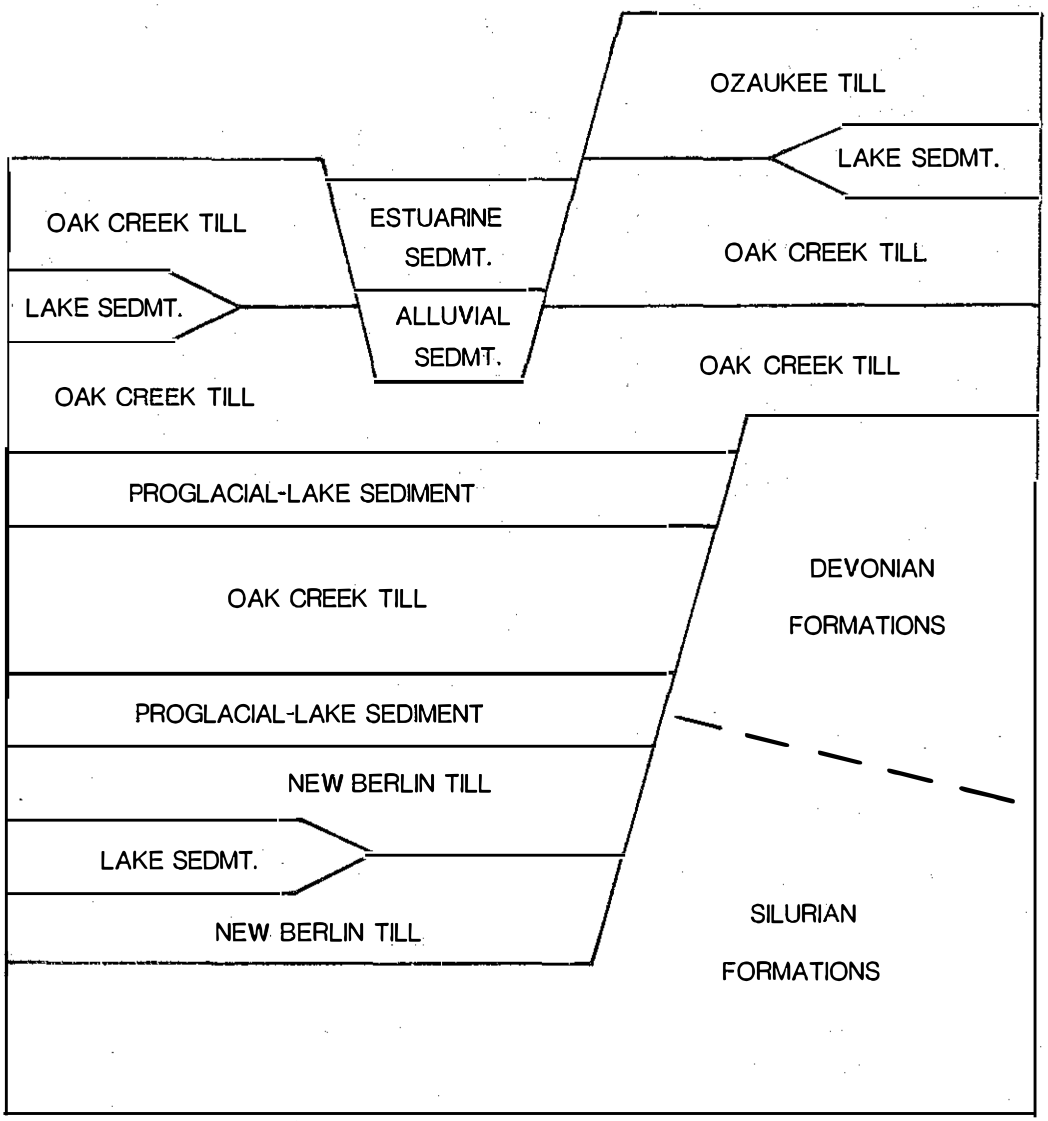

FIGURE 5.--Schematic diagram of stratigraphic relatioships among Quaternary deposits in the lower Milwaukee and Menomonee River valleys.

within the complex range from 0.2 to 2 m in thickness, but the amount of any given type of deposit and the sequence of their interbedding are quite variable. The rapid changes in depositional environment inferred from the interbedding of till and lacustrine deposits are indicative of a sedimentary complex that originated at the ice margin.

In general, the distribution of the till sheets is partly related to sub-Pleistocene topography and partly related to the extent of the glaciers that deposited them. The sub-Pleistocene topography is shown in figure 6. The main feature of this surface is the asymmetrical valley beneath the current Menomonee River valley with a steeply rising slope beneath the Milwaukee River valley. The distribution of the Holocene strata is related to the topography of the sub-Holocene unconformity, shown in figure 7, and the water level in the lake basin. The relationships are illustrated in figures 8 and 9, which are subsurface sections developed from selected borings along the Menomonee and Milwaukee Rivers.

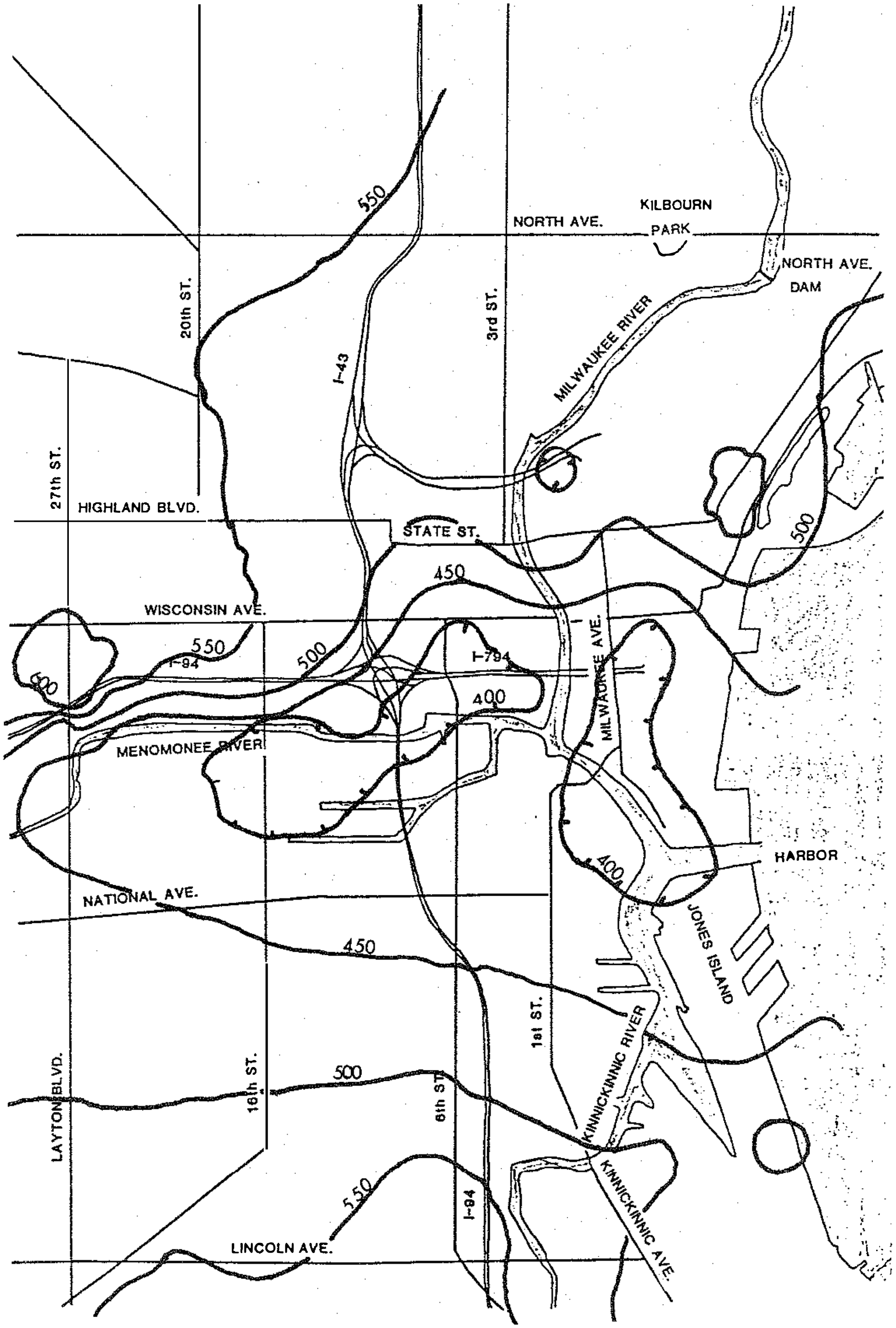

FIGURE 6.--Sub-Pleistocene topography of the lower Milwaukee and Menomonee River valleys. Scale: 1 inch is approximately equal to 1 km (3225 ft). Contour interval: 15 m (50 ft). Datum: Mean Sea Level--elevations shown are in feet.

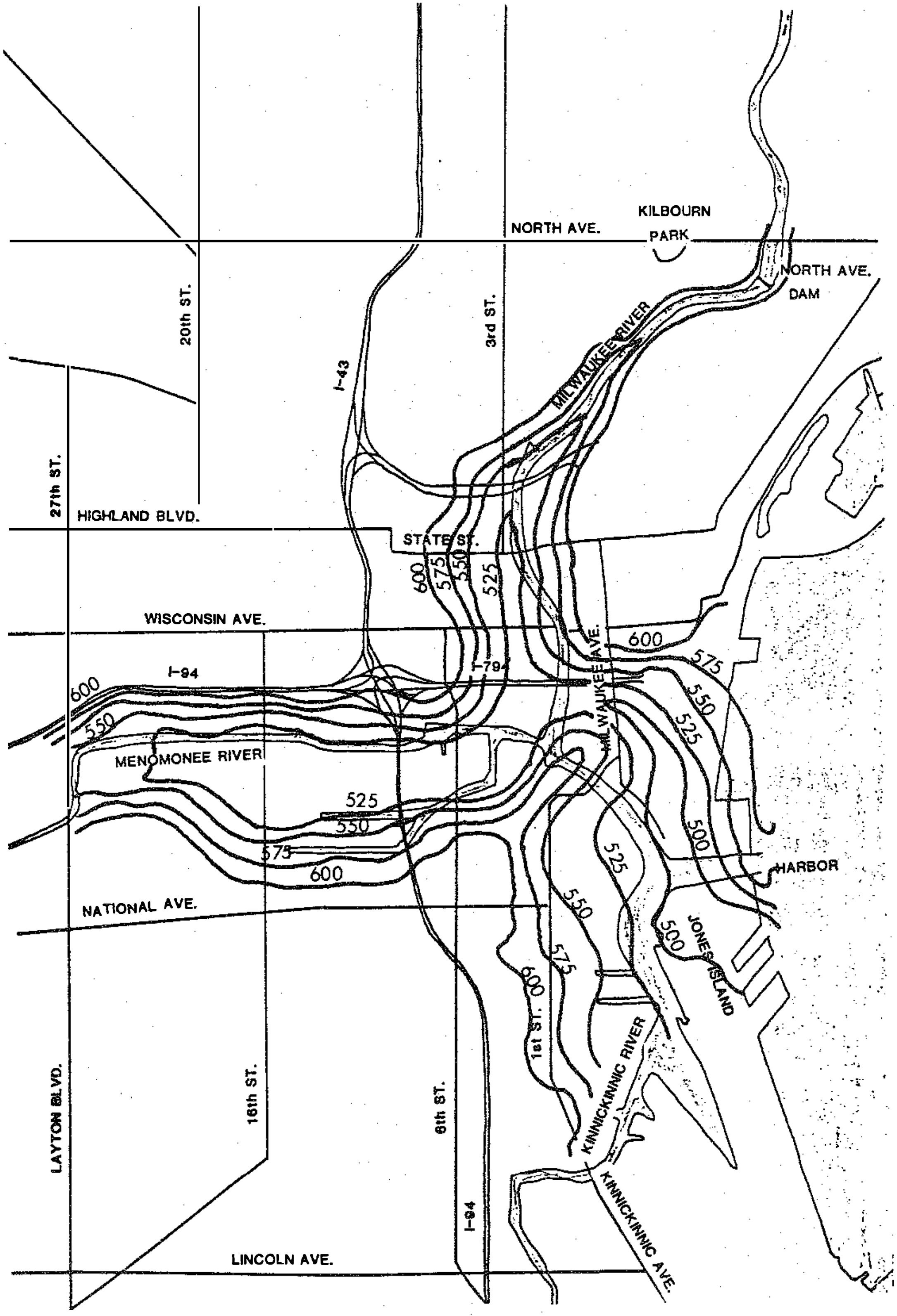

FIGURE 7.--Sub-Holocene topography of the lower Milwaukee and Menomonee River valleys. Scale: 1 inch is approximately equal to 1 km (3225 ft). Contour interval: 7.5 m (25 ft). Datum: Mean Sea Level--elevations shown are in feet.

New Berlin Formation

The New Berlin Formation seems to occur mainly within the deeper parts of the pre-Pleistocene valley along the Menomonee River and appears to he draped on the underlying topography. Presumably subsequent ice advances eroded these deposits from the higher parts of the sub-Pleistocene surface. Two layers of the sandy New Berlin till, separated by reddish-brown, fine-grained, proglacial-lake sediment, are present from the harbor area to the confluence of the rivers; but only a single till sheet appears to be present farther west. It has not been determined if the transition from more than one till sheet to a single till sheet is due to erosion of the intervening lacustrine deposit or if it marks the extent of the upper layer of New Berlin till.

Oak Creek Formation

The New Berlin Formation is generally separated from the Oak Creek Formation by proglacial-lake sediment. As shown in figures 8 and 9, the oldest till sheet in the Oak Creek Formation extends throughout the Menomonee River valley and almost extends to the pre-Pleistocene upland beneath the Milwaukee River. The bedrock high shown in the northern end of figure 9 is higher than much of the adjacent area. Thus, the oldest layer of Oak Creek till may extend, more or less continuously, across most of the area.

The middle layer of Oak Creek till is the oldest till sheet that is clearly not restricted in its areal extent by the sub-Pleistocene topography although its distribution still reflects the shape of the bedrock surface. A pinching out of this till sheet, shown in figure 8, is probably not indicative of a maximum ice-margin position. This interpretation is based on borings, located beyond the western end of the section, in which the middle layer of Oak Creek till is present. In the harbor area, the middle till sheet becomes a complex composed of till and lacustrine deposits. Beneath Jones Island, which has been extensively drilled, conditions in this stratigraphic interval change rapidly in short distances; in some borings, the middle layer of the Oak Creek till is completely absent. The reasons for the complexity are not clear. Along the Milwaukee River, the middle layer of Oak Creek till rises out of the pre-Pleistocene valley. The correlations shown in figure 9 are based on borings, located at the edge of the valley, that were not subject to as much postglacial erosion as those in the section.

The distribution of the youngest layer of Oak Creek till appears to be predominantly controlled by the extent of the glacier that deposited it. In the Menomonee River valley it occurs from the harbor area (not shown in the section) to the confluence of the rivers. At the confluence it has the form of an abrupt ridge, situated at right angles to the valley axis and extending up into the overlying Holocene deposits. Along the Milwaukee River, the youngest layer of Oak Creek till appears to occur only on the east side from the confluence of the rivers to North Avenue. At North Avenue, the till sheet is found on the west side, where a well defined segment of end moraine is present. The interpretation that the distribution of the youngest layer of Oak Creek till is controlled by the extent of the ice that deposited it is discussed below.

Ozaukee Member

The distribution of the Ozaukee till on the upland north and east of the Milwaukee River is presumed only on the basis of Alden's mapping because there are not yet sufficient borings to confirm or refute Alden's interpretation. Ozaukee till was encountered about 1.5 km north of the study area in a boring located at the top of the

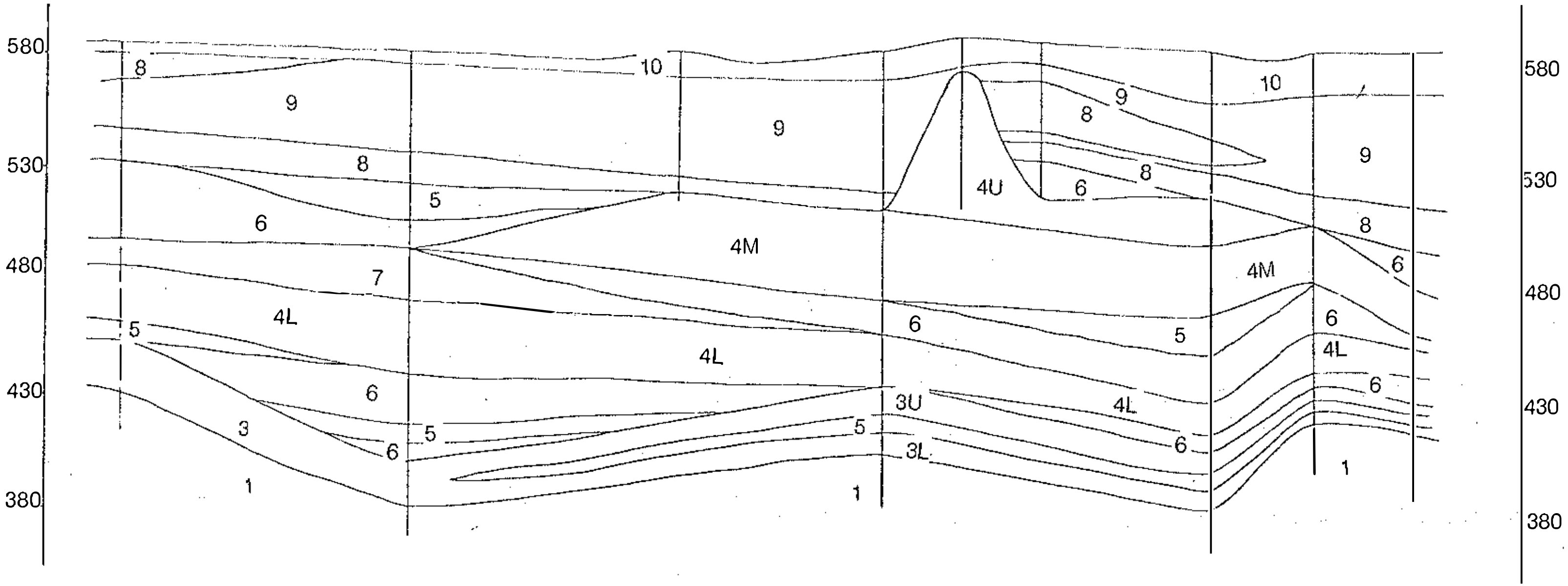

FIGURE 8.--Subsurface section of the Quaternary deposits along the lower Menomonee River valley. View is looking north. Deposits are identified by number below. The section shown crosses the section in figure 9 at the fifth boring from the right, and the dashed vertailc line indicates data projected from borings not in the section. Horizontal scale: 1 inch is approximately equal to 250 m (830 ft). Vertical scale: 1 inch is approximately equal to 25 m (83 ft). Datum: Mean Sea Level--elevations shown are in feet.

(1) Silurian formations. (2) Devonian formations. (3) New Berlin till. (4) Oak Creek till. (5) Fine-grained proglacial-lake sediment. (6) Medium-grained proglacial-lake sediment. (7) Coarse-grained proglacial-lake sediment. (8) Alluvial sediment. (9) Estuarine sediment. (10) Fill. U=upper till layer, M=middle till layer, L=lower till layer.

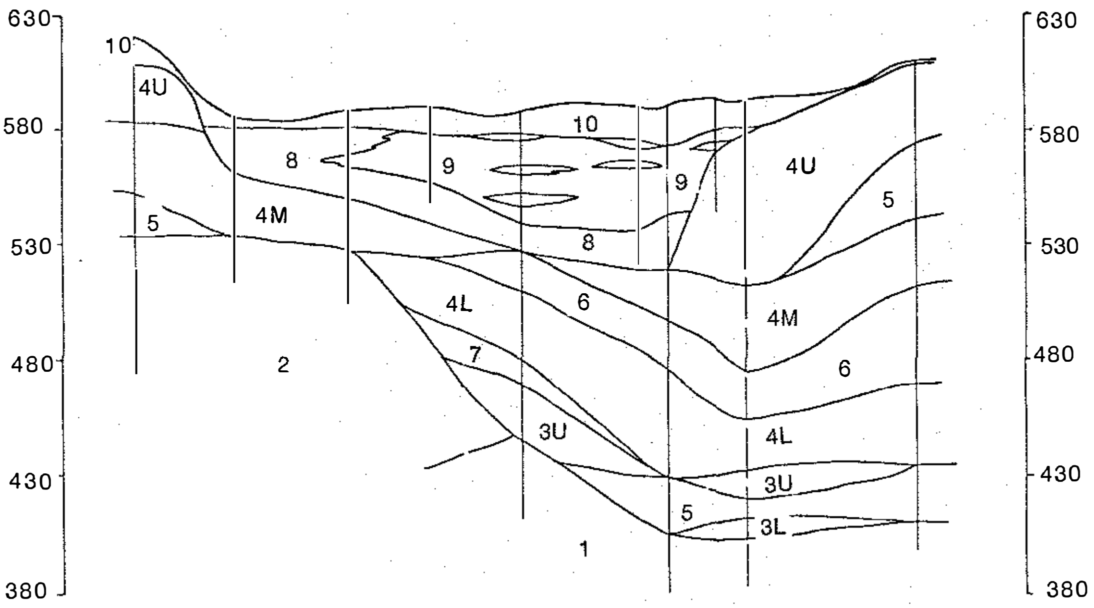

FIGURE 9.--Subsurface section of the Quaternary deposits along the lower Milwaukee River valley. View is looking east. Deposits are identified by number below. The section shown crosses the section in figure 8 at the second boring from the right, and the dashed vertical line indicates data projected from borings not in the section. Horizontal scale: 1 inch is approximately equal to 250 m (830 ft). Vertical scale: 1 inch is approximately equal to 25 m (83 ft). Datum: Mean Sea Level--elevations shown are in feet.
(1) Silurian formations. (2) Devonian formations. (3) New Berlin till. (4) Oak Creek till. (5) Fine-grained proglacial-lake sediment. (6) Medium-grained proglacial-lake sediment. (7) Coarse-grained proglacial-lake sediment. (8) Alluvial sediment. (9) Estuarine sediment. (10) Fill. U=upper till layer, M=middle till layer, L=lower till layer.

bluff overlooking the Milwaukee River. The distribution of this till sheet is such that it does not appear in either figures 8 or 9.

Alluvial Deposits

The distribution of the Holocene units is essentially coincident with the extent of the sub-Holocene valley, which probably formed by fluvial downcutting while the lake level was falling to and at the Chippewa stage. Most of the alluvial deposits occur in a continuous layer in the bottom of the sub-Holocene valley. The layer ranges up to 10 m in thickness. The alluvial deposits grade from sand and gravel at the erosion surface to silty sand at the upper contact with the estuarine deposits. The upper contact generally occurs at consistently higher elevations in the upstream direction. This relationship is somewhat distorted in figures 8 and 9 because the sections deviated from the valley axis. The basal alluvial layer is probably the result of fluvial aggradation caused by the lake level use from the Chippewa stage to the Nipissing stage.

Estuarine Deposits

The inability of the aggrading river to keep up with the rising water level eventually resulted in a transition to an estuarine environment in the sub-Holocene valley. This transition was probably time-transgressive. The estuarine deposits fill the rest of the buried valley, from the upper contact of the basal alluvial layer to a surface that coincides with the present lake level. Within the estuarine deposits are discontinuous lenses of alluvial deposits that may be the result of pauses in the rise of the lake level, or perhaps the temporary existence of local, low-order drainage systems on the valley sides. Toward the upstream ends of the buried sub-Holocene valleys, alluvial deposits seem to lap back over the top of the estuarine deposits. Because ancestral Lake Michigan rose to the Nipissing Stage, which is about 7.5 m higher than the present level, following the erosion event, it is possible that the Holocene deposits soils were once as much as 7.5 m thicker.

DISCUSSION

Basis of Correlations

The correlations presented in figures 8 and 9 are tentative because the laboratory analyses needed to establish a glacial stratigraphy in situations where several till sheets of similar lithology are present are not complete. Likewise there may be some errors in interpretation of poorly sampled sediment such as parts of the New Berlin Formation. The main guide for the correlations presented here was the till stratigraphy identified by Mickelson and others (1977) from their work along the bluffs of the Lake Michigan shoreline. The similarities of the till units in the two areas has already been mentioned; and, no evidence has been found that contradicts the shoreline stratigraphy. With that framework as a guide, correlations were made by working both from the bottom up and from the top down. These correlations were significantly influenced by the identification of what appears to be a terminal moraine for the youngest layer of Oak Creek till.

Terminal Moraine of the Youngest Oak Creek Advance

An end moraine, identified for the first time here, is interpreted to be the maximum ice-margin position of the advance during which the youngest layer of Oak Creek till was deposited. The evidence for a traceable end moraine includes the following:

(1) There is a buried, ridge-shaped body of till oriented perpendicular to the axis of the Menomonee River valley near the confluence of the Milwaukee and Menomonee Rivers. This ridge corresponds to a former point of dry lowland that extended into the wetlands in the valley bottom. This land, known as Walkers Point, is shown in figures 2, 7, 8, and 9.

(2) Two other areas of dry lowland, in line with Walkers Point, located northeast of the Milwaukee River.

(3) Alden (1918) mapped a sharp, well-defined ridge extending northwest from Kilbourn Park as end moraine.

(4) The higher parts of the upland north and east of the Milwaukee River trend northerly. This trend is difficult to completely explain as a result of events associated with the deposition of the Ozaukee till. The upland connects the fragment of end moraine identified by Alden with the Walkers Point end moraine remarkably well.

(5) A second buried ridge of till occurs across the Kinnickinnic River valley along Kinnickinnic Avenue.

(6) Subtle ridges and other high areas that cut across topographic trends of the uplands are present south of the Menomonee River and west of the Kinnickinnic River. These features can be used to connect the Walkers Point moraine to the ridge across the Kinnickinnic River valley.

The locations and spatial relationship of these features is shown in figure 10 which also shows the probable ice-margin position. The evidence that this end moraine marks the maximum extent of the ice that deposited the youngest layer of Oak Creek till consists of the following:

(1) Several borings on or east of this moraine have encountered three distinct layers of Oak Creek till, but no unequivocal occurrences of this kind have been found to the west.

(2) Pinkish gray colors in the uppermost Oak Creek till layer are restricted to the area east of the end moraine, although all of the uppermost Oak Creek till in this area is not pinkish gray.

(3) The moraine can be connected from the Kinnickinnic River to the St. Francis Power Plant site with a series of subtle ridge features. The St. Francis site is the most southern (and only clearly identified) occurrence of the youngest layer of Oak Creek till along the shoreline.

Meltwater Outlet Along Menomonee River Valley

There is generally not much surficial outwash mapped or encountered by MWPAP borings in the study area and adjacent to it. This is true even on areas east of the basin divide and above the elevation of the highest lake level that presumably had freely draining margins. This phenomenon was probably caused by the concentration of meltwater discharge at points along the margin that were abutted by proglacial lakes. The character of the proglacial-lake sediment in the Menomonee River valley. Specifically, the coarser-grained and medium-grained sediment are predominant relative to the fine-grained sediment. Furthermore, the coarse-and medium-grained sediment appears to occur in layers 9 to 15 m thick that are continuous for substantial distances in the western end of the valley. The relatively small amount of the coarse-grained sediment, as compared to the medium-grained sediment, may be due to source effects on the coarse fraction of the till is mostly pea gravel or slightly smaller so there was little coarse material available.

The deposition of material as the result of a meltwater concentration probably occurred during the time when the ice margin retreated from the vicinity of County Stadium to the vicinity of the present shoreline. Tracing a drainage path from the western end of the lower Menomonee River valley south of the main proglacial lake is not easy. If one can assume about 6 m of ground-surface lowering due to isostatic depression or a slightly higher local lake level, a poorly defined pathway can be traced from the vicinity of County Stadium south of the Kinnickinnic River basin, then southeast through Mitchell Field to the Oak Creek basin. This drainageway is shown in figure 11.

Character of Lake Level Rise to the Nipissing Stage

The nature and timing of the rise in lake level from the Chippewa stage to the Nipissing stage are not well documented. The deposits in the study area provide no data on when the rise began or on the rate of rise during much of the recovery, but they do provide information for approximately 30 m of the 105 m change. Radiocarbon dating of organic fibers in the estuarine deposits and pieces of wood recovered

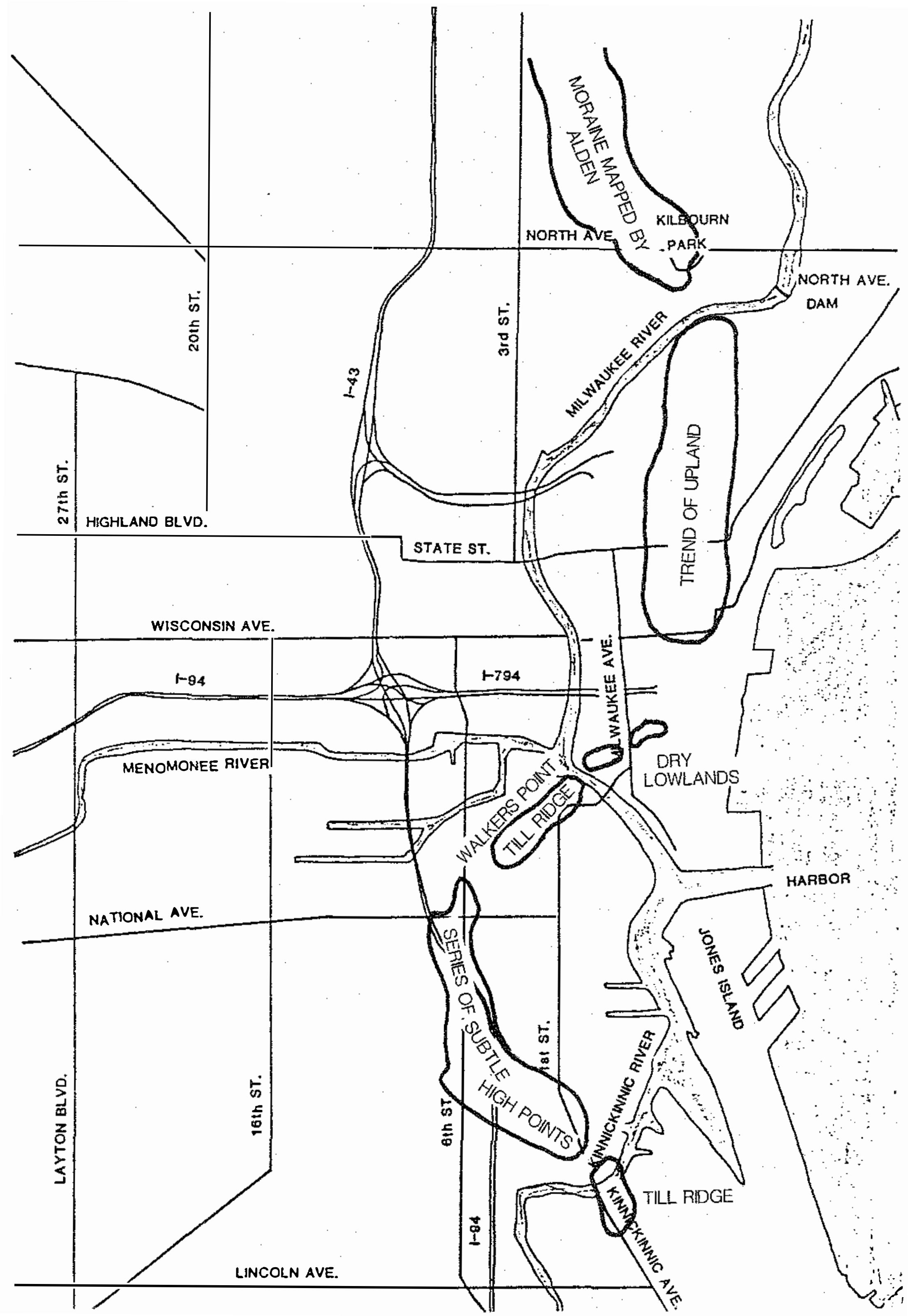

FIGURE 10.--Features used to identify and trace the Walkers Point end moraine. Scale: 1 inch is approximately equal to 1 km (3225 ft).

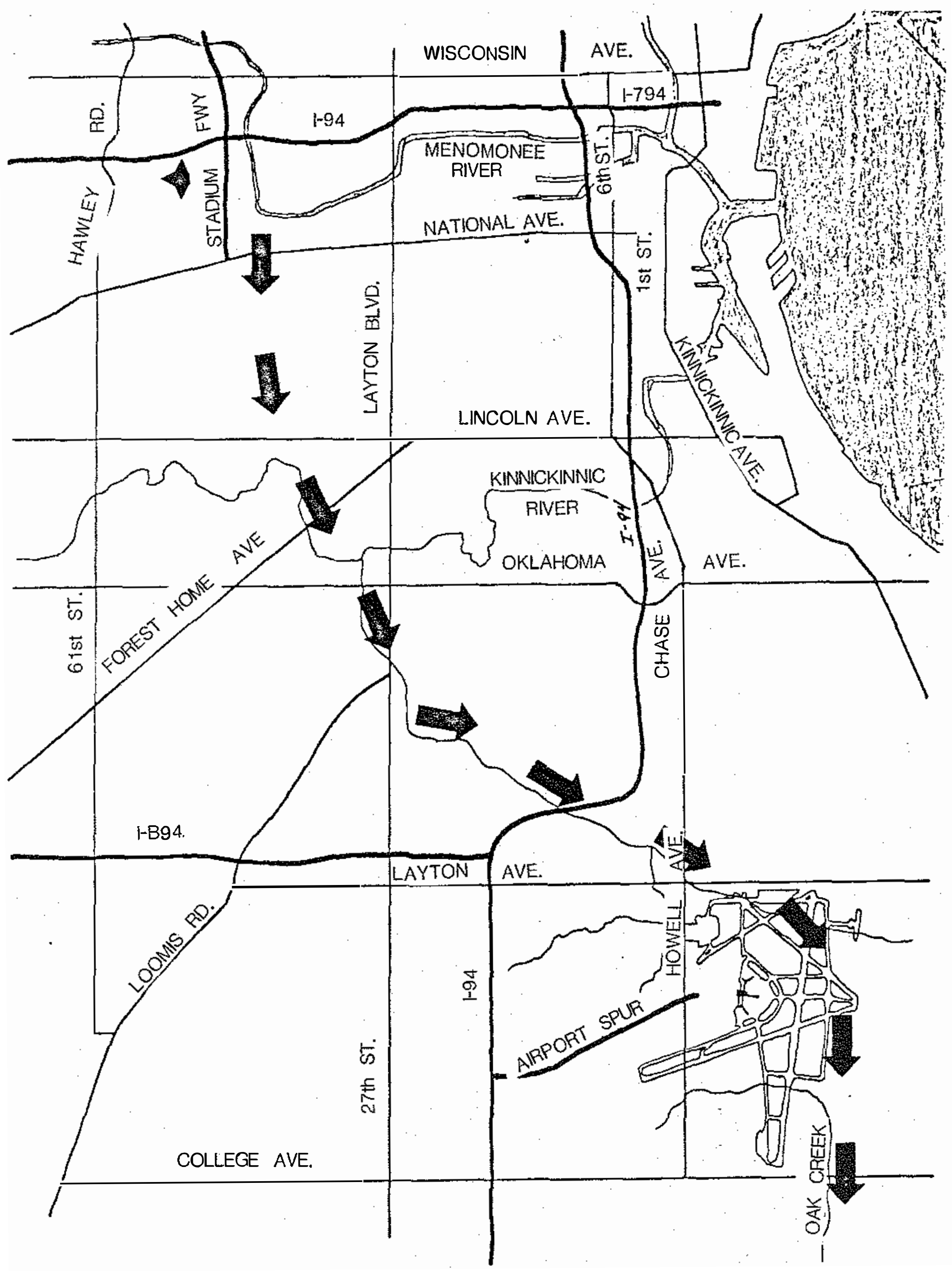

FIGURE 11.--Meltwater drainage path from the vicinity of County Stadium to the Oak Creek basin. The star is County Stadium. Scale: 1 inch is approximately equal to 1.9 km (6050 ft).

in samples of the basal alluvial deposit would provide data on (1) when the lake level had risen high enough to cause aggradation of the river, (2) when the first estuaries formed, and (3) the subsequent rate of lake level rise. The dates and rates would be minimum values because they actually apply to sedimentation events. Significant palynological data should also be obtainable from the estuarine deposits because they were deposited in an aggrading, quiet-water environment.

There is some indirect evidence regarding the character of the lake level rise already available. Several dozen consolidation tests were performed on samples of estuarine meterial. The results indicate that the esturaine deposits are slightly overconsolidated. Some of the overconsolidation could have been caused by sediment deposited while the lake occupied the Nipissing stage. Subsequent erosion of this hypothetical sediment would leave the underlying deposits overconsolidated. However, the observed overconsolidation cannot be fully explained as the result of overburden erosion. If the erosion of former overburden were the only cause of overconsolidation, the samples closest to the surface would be the most highly overconsolidated because the percentage in load reduction is greatest for such samples. The relationship between depth and overconsolidation does not have these characteristics; it is instead somewhat trendless.

A more likely cause for most of the overconsolidation and for the trendless relationship between overconsolidation and depth is dessication. This dessication could have occurred sporadically throughout deposition during pauses in lake level rise or slight lake level drops or both. Evidence for this idea is the occurrence of lenses of alluvial sediment within the thicker estuarine deposits. Although other explanations are possible, the alluvial lenses may reflect short periods of time during which the river prograded across existing estuarine deposits in response to a lower lake level.

Relationship to Earlier Studies

I have relied considerably on the till stratigraphy formulated by Mickelson and others (1977) from their work along the shoreline of Lake Michigan. This stratigraphy framework is consistent with the data from the MWPAP borings. Substantial agreement can also be seen among the data presented by Williams (1954) and Rose (1978) and this study although there are some differences in terminology and interpretation. Given the state of Quaternary geology when it was written, the study by William (1954) is remarkably perceptive in its geologic interpretations. Rose (1978) treated the geology of his study area more generally, and his criteria for distinguishing Pleistocene from Holocene deposits lead him to some erroneous conclusion. However, Rose did recognize the basic Holocene stratigraphy. There are two basic differences between the earlier studies and this study: (1) the interpretations in the earlier studies were made only from boring-log data whereas the interpretations presented here are based on boring logs and visual examinations of the actual samples, and (2) the interpretations presented here reflect the changes in both knowledge and methods that have occurred in Quaternary studies during the past 30 years.

SUMMARY

The Quaternary deposits of the lower Milwaukee and Menomonee River valleys are differentiated into three lithostratigraphic and six lithogenetic units on the basis of visual examinations of samples obtained from numerous geotechnical borings drilled for the Milwaukee Water Pollution Abatement Program. The Pleistocene units include three lithologically distinct till units, which correspond to till units 1, 2 and 3 of Mickelson and others (1977) and to members of the New Berlin, Oak Creek and Kewaunee Formations of Mickelson and others (1983), fine-, medium- and coarse-grained, proglacial-lake sediment, and a complex and variable ice-margin unit. The Holocene units include alluvial and estuarine deposits laid down as the lake level rose from the Chippewa stage to the Nipissing stage.

The stratigraphic framework of Mickelson and others (1977), which is consistent with the data from the MWPAP borings, was used to correlate between borings so the extent and distribution of the units could be evaluated and described. From correlations and other data at hand, an end moraine that may mark the maximum extent of the ice that deposited the youngest layer of Oak Creek till and a meltwater outlet along the Menomonee River valley are tentatively identified. Pauses in lake level rise or slight lake level drops are recorded in the stratigraphic record during the general lake level rise from the Chippewa stage to the Nipissing stage.

AUTHOR'S NOTE

The terminology used in this paper for the proglacial-lake sediment is different than that used in MWPAP GEOTECHNICAL REPORTS. Deposits referred to as fine-grained proglacial-lake sediment in this paper are called lacustrine silt and clay in the MWPAP reports, medium-grained sediment is called lacustrine sand and silt, and coarse-grained sediment is called (subaqueous) outwash. The terminology was changed for the purposes of this paper because one of the reviewers felt that most Midwestern Quaternary geologists would assume a glaciofluvial setting for the outwash rather than a glaciolacustrine one.

ACKNOWLEDGEMENTS

I would like to thank the Milwaukee Water Pollution Abatement Program and the Milwaukee Metropolitan Sewerage District for the opportunity to publish this paper. My thanks also go to David Mickelson, Lee Clayton, and Norm Lasca for their thorough reviews and helpful suggestions.

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THE EFFECT OF LAKE-LEVEL FLUCTUATIONS ON THE GEOMORPHIC EVOLUTION OF THE LAKE MICHIGAN BLUFFS IN WISCONSIN

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ABSTRACT

The purpose of this paper is to describe the effect of lake level fluctuations on the geomorphic evolution of coastal bluffs on the Lake Michigan shore in Wisconsin. Recent field stuies of morphologic features along approximately 100 km of bluff revealed six major kinds of bluffs. Twelve bluff profiles were measured two to three times per year in the field between 1974 and 1980, and additional bluff profiles were estimated at various times from 1937 to the present using air photographs.

The results from the short-term field measurements indicate that bluffs composed primarily of cohesionless sediment recede in parallel fashion. Bluff profile shape remains fairly constant as the rates of bluff toe and bluff edge erosion are nearly equal. The magnitude of failures on these bluffs is relatively small. On cohesive bluffs where adequate protection against severe toe erosion is present (wide beach, shallow nearshore water depths), parallel recession also occurs. In cases where cohesive bluffs are not well protected from intense toe erosion, the bluff toe and bluff edge erode at significantly different rates (non-parallel recession), and recession is caused by much larger failures. Lake level changes cannot be directly correlated with changes in bluff profile shape.

Evaluation of bluff change since 1937 indicates that the bluffs that show parallel recession over a short time period steepen and become more gentle in response to rising and falling lake levels. Also, bluff profile changes on these bluffs are relatively synchronous from profile to profile and failures tend to be small scale. Longer-term changes on those bluffs that show non-parallel recession over a short time period (cohesive bluffs, intense toe erosion), however, are not synchronous from profile to profile and cannot be correlated to lake level changes. Geomorphic change is caused by episodic large scale failures.

INTRODUCTION

As a coastal bluff erodes, its morphology also changes. The geomorphic changes taking place on a bluff are a result of a combination of passive and active factors in the environment. Passive factors are those inherent in the geologic medium; bluff stratigraphy, the engineering properties of bluff deposits, and bluff height. Active factors include things such as wave erosion, groundwater, wind erosion, and processes associated directly with precipitation (rainsplash, sheetwash). Temporal and spatial differences in these factors result in differences in failure mechanism, thus differences in bluff evolution.

Over the long term, wave action is the major factor causing changes in bluff form. Water level ultimately controls the intensity of wave erosion. The effect of water level and wave erosion on bluff morphology can be increased or decreased by various factors such as shoreline orientation, offshore bathymetry, and beach width. Thus, although water level along a particular coast is the same everywhere at one time, it can have different effects at different locations due to variability of the above factors.

The purpose of this study was to determine the effect of short and long-term lake-level changes on the geomorphic evolution of the coastal bluffs on the Lake Michigan shore in Wisconsin. Lake Michigan is an interesting area for study because lake levels are not controlled, lake levels have been measured since 1860, and have fluctuated almost 2 m during this time, and bluff stratigraphy and bluff height are quite variable along the shoreline.

METHODS OF ANALYSIS

Present-Day Bluff Morphology

Definition of the present-day bluff morphology provides a starting point from which recent geomorphic change can be evaluated. Morphological features of bluffs were examined along 100 km of bluff along Wisconsin's Lake Michigan shoreline (fig. 1). This investigation revealed the six major kinds of bluffs summarized in table 1. The aerial extent of these groups is shown in figure 1.

Recent Changes in Morphology

Once the variability in the present-day bluffs was established, it became possible to try to evaluate the effect of fluctuating lake levels on bluff evolution. Bluff changes have been documented over a 3- to 6-year period (considered short-term fluctuations) at four locations shown on figure 1. A total of 12 bluff profiles were measured 2 or 3 times a year at the four locations between 1974 and 1980.

Documenting changes in bluff morphology over a longer time is more difficult because no field measurements were possible. Selected profiles measured in the field were located on a series of air photographs dating back to 1937. The angle of the bluff could be estimated because bluff height was known and the horizontal distance from the bluff edge to the beach could be measured. By detecting changes in the tone of the photograph, it was also possible to determine the relative shape of the profile (that is, convex or concave, or combination). These photos were periodically viewed in stereo as a check for determining bluff shape. An average bluff top recession rate for a particular bluff reach was taken from Mickelson and others, 1977 and approximate bluff profile changes through time were then reconstructed. A more complete description of the method is provided by Peters (1982).

Lake-Level Fluctuations

Changes in bluff morphology have been evaluated with respect to historic water-level fluctuations in Lake Michigan (fig. 2). Note that the earliest air photographs available are from 1937, a time of relatively low water level. Since that time Lake Michigan has gone through two major high-water periods (the early 1950s and the 1970s and a major low-water interval in the late 1950s and early 1060s.

DOCUMENTED CHANGES IN BLUFF MORPHOLOGY

Evaluation of Profile Measurements

Bluff recession data for 9 out of the 12 profiles measured since 1974 are summarized in table 2. Three profiles at Notre Dame were not included because there was no change in morphology over the monitoring period. The Notre Dame site is within bluff group D, whose morphology is dominated by deep-seated rotational failures. Bluffs in this group are largely vegetated, suggesting that the slumps are very old. The geomorphic evolution of bluffs in group D will not be discussed further in this paper, because there appear to be no significant changes in these bluffs since 1937.

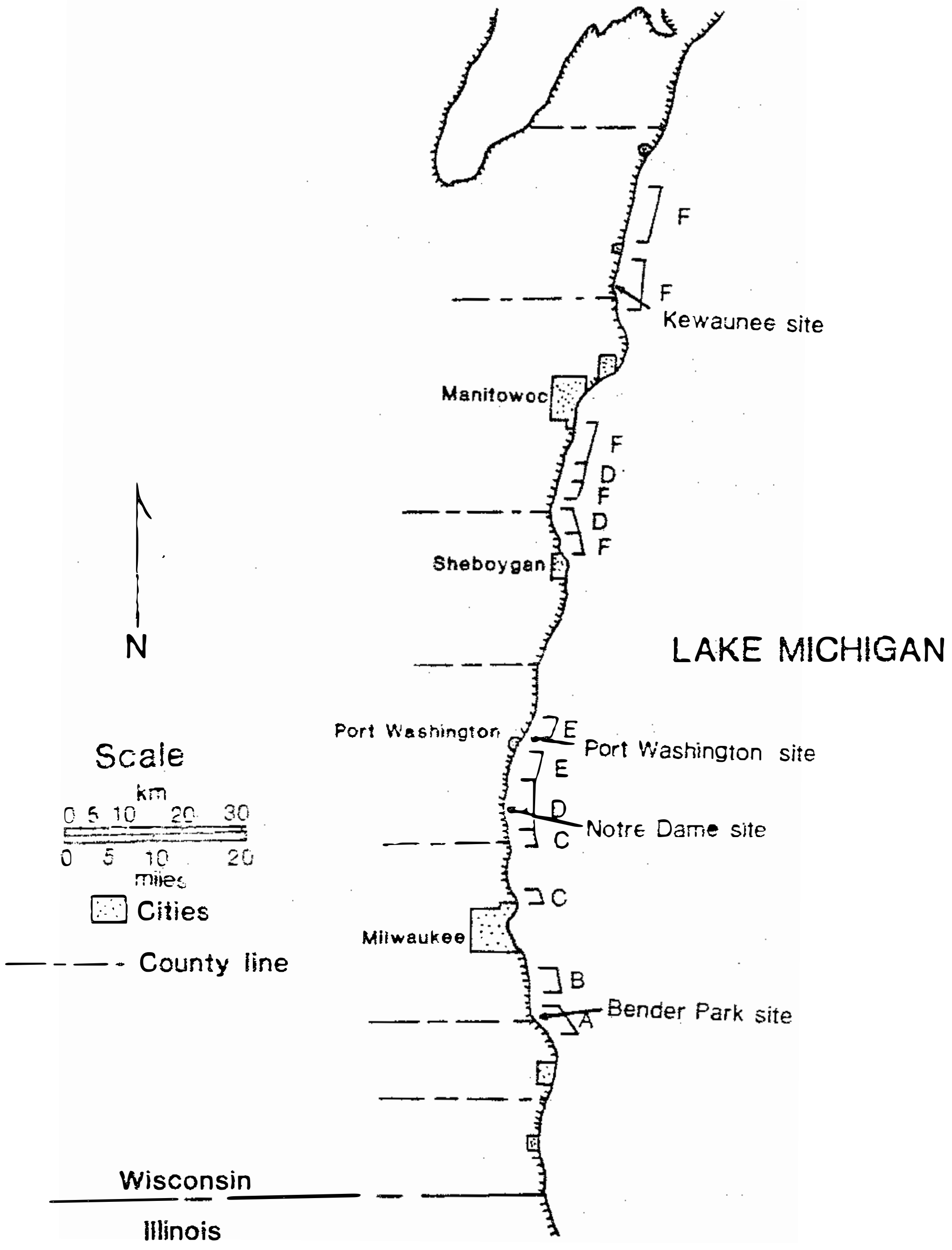

FIGURE 1.--Map of study area showing locations of bluff groups (A-F) and profile monitoring sites.

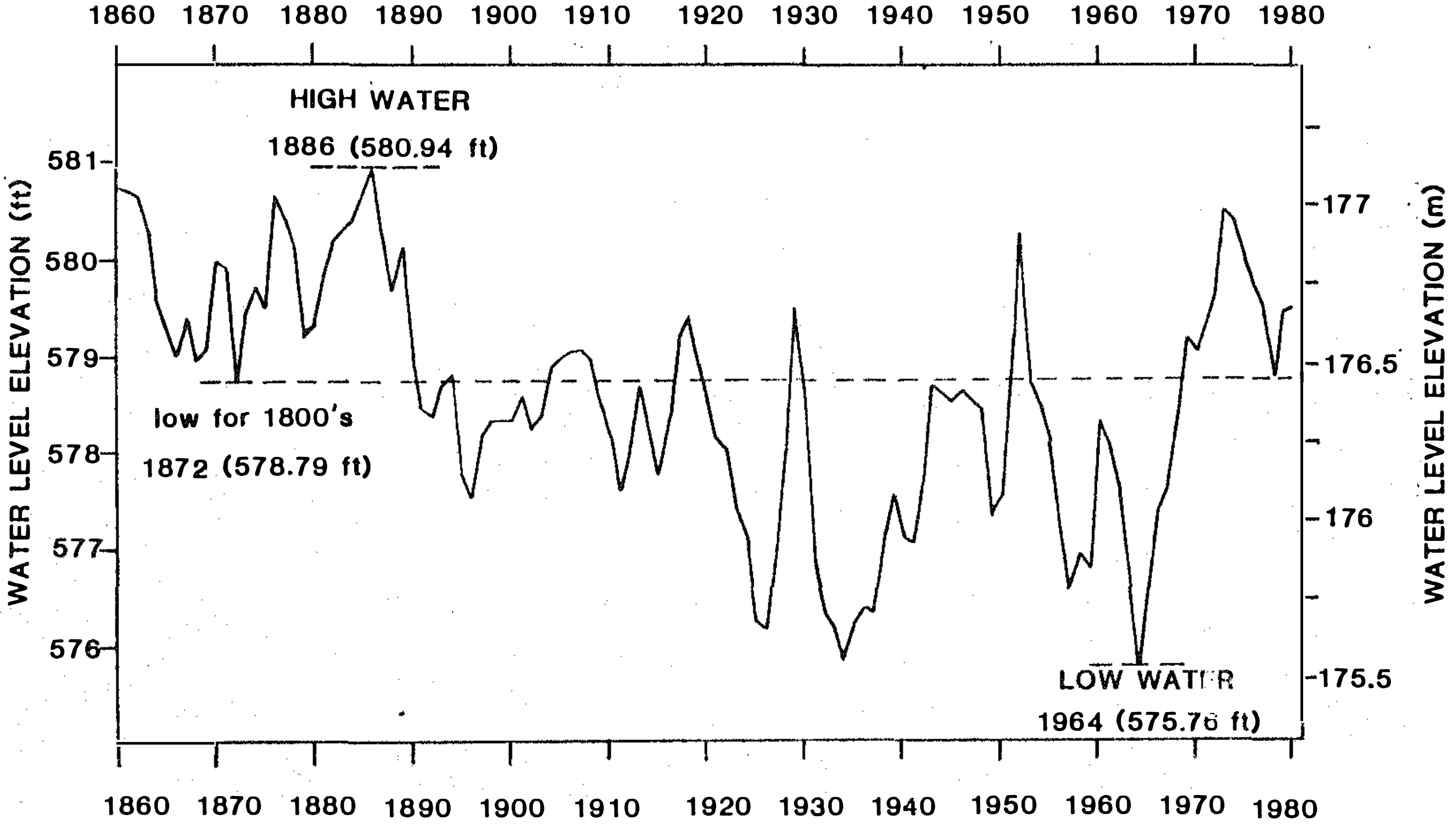

FIGURE 2.--Lake Michigan water levels, 1860-1980. (Source: U.S. Department of Commerce).

Group	Bluff Height	Bluff Angle	Nature of Bluff Face (plan view)	Bluff Profile Shape (x-section)	Other Comments
A	Medium to very high (14 to 37 m)	Generally steep (greater than 35°) except where protected	Variable; often highly scalloped top; sharp, well defined ridges.	Highly variable; ridges between gullies are commonly strongly convex with very steep lower bluff, but concave or straight bluff profiles common in gullies; compound (convex and concave) slopes where large slumps are present.	Till or glaciolacustrine units top and bottom with sand layer in middle; bluffs are subject to intense wave erosion and are unstable.
B	High (21 to 27 m)	Very steep (generally greater than 40°)	Mostly low relief, especially in upper bluff; some gullies in lower bluff.	Mostly straight or concave.	Cohesionless (sand and silt) material at top, cohesive (till or glaciolacustrine) sediment at bottom.
C	High to very high (24 to 37 m)	Moderate (30 to 35°)	Broad scallops, low relief.	Gently convex or straight.	Till or glaciolacustrine sediment throughout except for sand lens in middle; bluff not subject to intense wave erosion.
D	Very high in Ozaukee Co. (30 to 40 m), medium in Sheboygan Co. (12 to 18 m).	Low (about 25°)	Variable but generally low relief because slopes are mostly grassed or wooded due to old deep seated slumps now stabilized.	Compound, generally "stair-step" profile shapes	Till or glaciolacustrine sediment top and bottom with sand layer in middle; morphology dominated by deep seated slumps.
E	Medium to very high (18 to 37 m) lower to the north.	Moderate to steep (30 to 45°).	Broad scallops.	Generally straight or slightly convex.	Stratigraphy same as group D; toe erosion is intermediate between groups A and C.
F	Low to medium (6 to 20 m).	Very steep (greater than 40°).	Mostly low relief, but some scalloping in higher bluffs where cohesive sediment is present.	Mostly straight or concave, some convex where cohesive units are present.	Mostly cohesionless sediment to the south; more cohesive sediment to the north.

TABLE 1.--Summary of characteristics of bluff groups discussed in text.

TABLE 2.--Results of short-term bluff recession measurements.

Profile	Bluff Ht. m	Years Monitored	Recession (m)		Average Recession Rate (m/yr)	
			Top	Bottom	Top	Bottom
Bender Park 1	36	3.3	-1.8	-9.3	-0.6	-2.9
Bender Park 3	32	3.1 (toe) 3.5 (top)	-16.8	+1.5	-4.8	+0.5
Notre Dame 1	36	2.8	-3.0	-4.9	-1.1	-1.7
Port Wash. 1	27	5.7	-15.8	+2.8	-2.8	+0.5
Port Wash. 2	30	2.9	-3.3	-0.6	-1.2	-0.2
Port Wash. 3	31	2.7	0	-1.2	0	-0.5
Kewaunee 1	7	5.3	-2.6	-1.4	-0.5	-0.3
Kewaunee 2	14	5.8	-2.0	-2.4	-0.3	-0.4
Kewaunee 3	10	2.8	-0.5	-2.2	-0.2	-0.8

The results from the remainder of the profile measurements suggest two principal modes of bluff evolution. The first, which has been termed non-parallel recession (Vallejo, 1977), is defined as having bluff-edge and bluff-tow recession rates that are significantly different. This type of bluff recession occurs on bluffs composed primarily of cohesive sediment that undergo intense wave erosion. The best examples of this type of retreat are the Bender Park 3 and Port Washington 1 profiles. Bluff profile changes at Port Washington 1 are illustrated in figure 3. The bluff edge appears to be adjusting to bluff steepening that occurred prior to the first (1974) measurement (in 1974). Over the 6-year period the bluff toe actually shows a net accretion of material.

The second type of recession which has been called parallel recession (Vallejo, 1977), is defined as having bluff toe and bluff edge recession at about the same rate. This type of recession appears to be characteristic of bluffs composed primarily of cohesionless materials (sand or gravel). The Kewaunee bluffs, best illustrated by profile Kewaunee 2 (fig. 4) show parallel recession. In this case, bluff profile shape remains relatively constant and rapidly adjusts to wave erosion. Parallel recession is also suggested by the Port Washington 2 profile (fig. 5), although it is a cohesive bluff and is close to Port Washington 1. However, the intensity of wave erosion at the bluff toe of Port Washington 2 is much less than that of Port Washington 1 because a seawall adjacent to profile 1 has caused waves to refract directly toward the base of that profile.

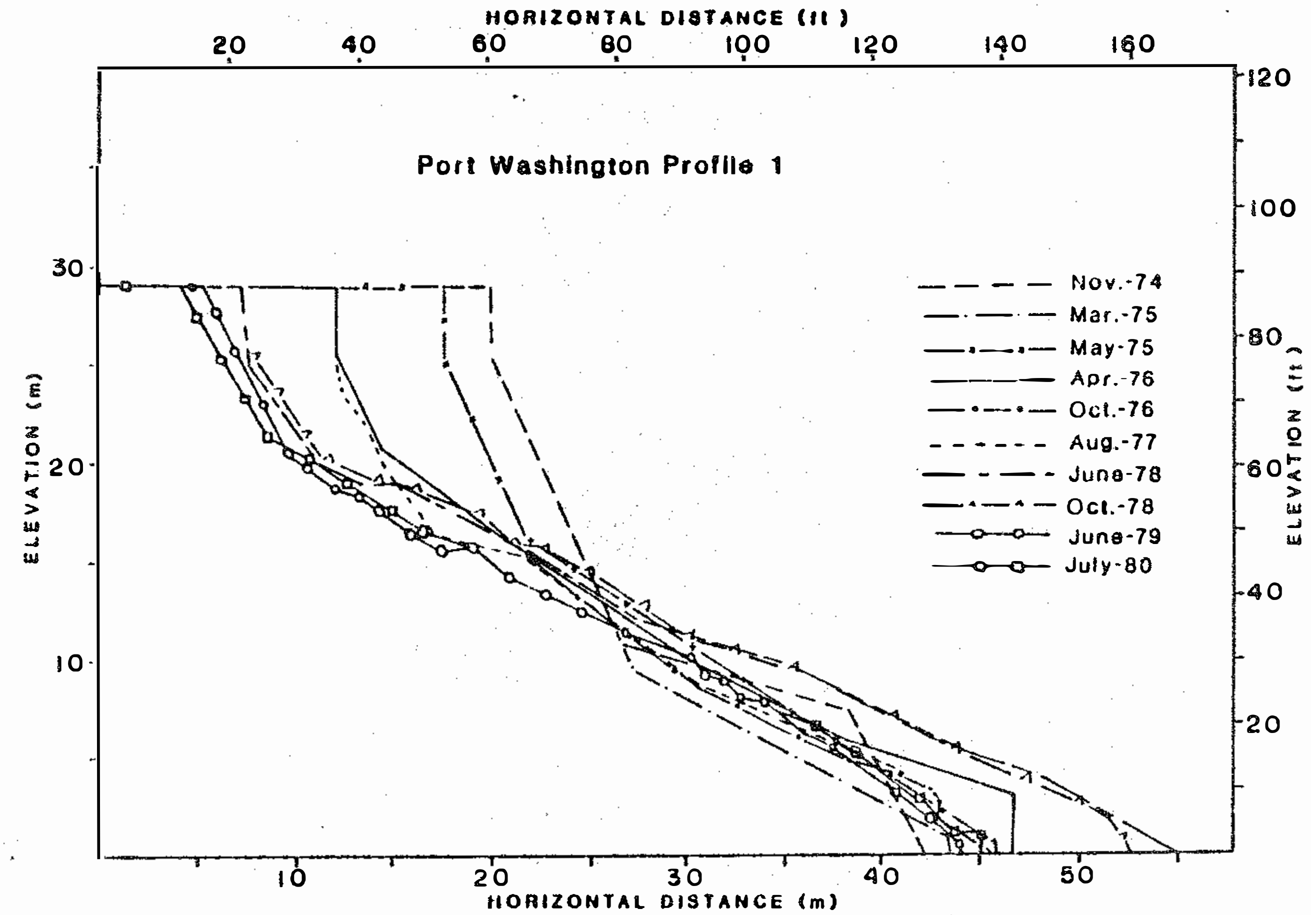

FIGURE 3.--Port Washington Profile 1, bluff profile changes, 1974 to 1980.

This difference in the behavior of nearby profiles is primarily the result of differences in beach width and offshore bathymetry, and therefore the amount of wave erosion taking place at the base of the bluff. Our measurements of bluffs between 1974 and 1980 show no direct correlation with lake-level changes. This lack of correlation is because a certain rise in water level has different effects in different places. At locations where the beach is narrow, a small rise in water level may lead to erosion of the bluff toe. The same increase in water level might have no effect at another place. Therefore, I will use the term "high effective lake level" to mean a lake level at which toe erosion is potentially taking place and "low effective lake level" to mean lake level low enough that the erosion is limited, even during storms.

Evaluation of Geomorphic Changes Since 1937

The results of the long-term analysis indicate that the geomorphic changes on the Lake Michigan bluffs depend on a combination of stratigraphy and effective lake level. Three combinations of these two factors are most common.

(1) Cohesionless sediment alternating, high and low effective lake level.

(2) Cohesive sediment alternating, high and low effective lake level.

(3) Cohesive sediment continually high, effective lake level.

The first of these is illustrated by most of bluff groups B and F (table 1). Changes in bluff angle on these

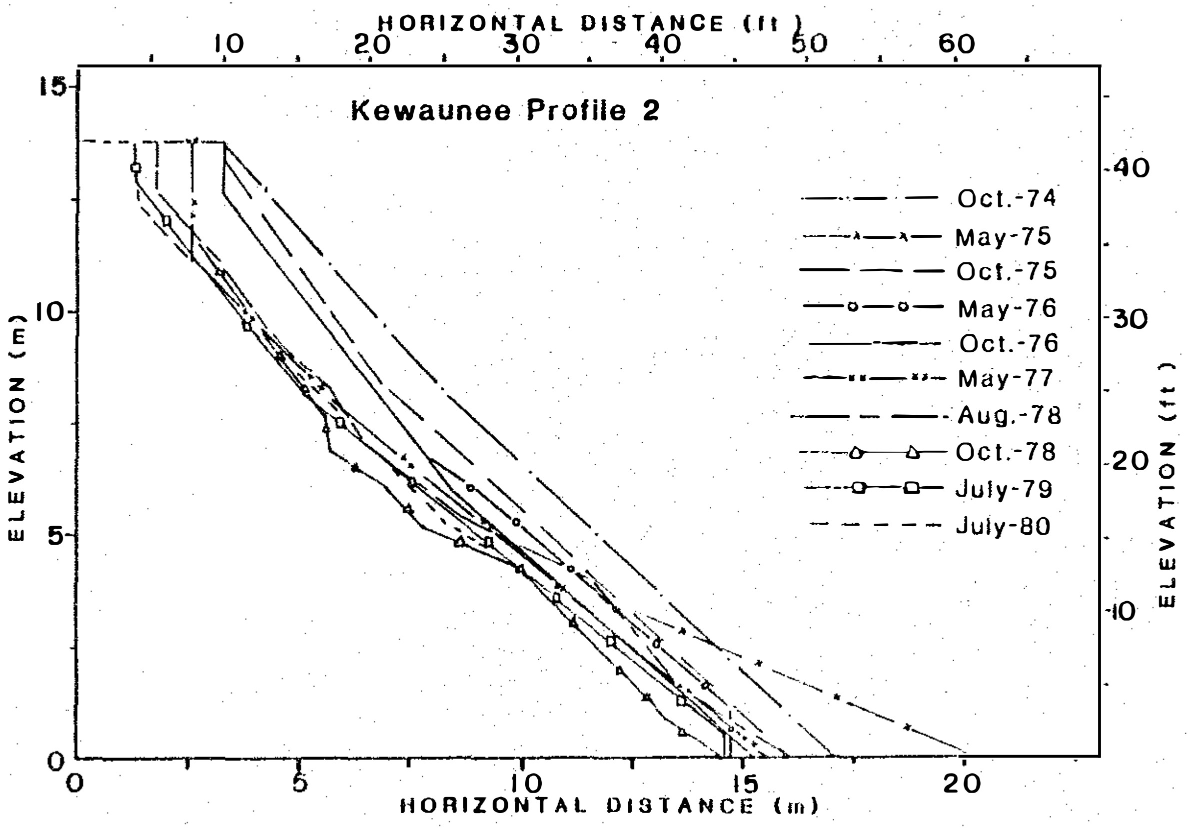

FIGURE 4.--Kewaunee Profile 2, bluff profile changes, 1974 to 1980.

bluffs can generally be correlated directly to changes in lake level. Figure 6 is a graph of bluff angle through time for group F, the symbols representing individual profiles within the group. A comparison of these changes to lake-level fluctuations over the same period (fig. 2) indicates that bluff angles were steepest during periods of high water and were lower during periods of low water. Unfortunately, no air photographs of these bluffs in the early 1950s were available. However, results from the late 1950s suggest a declining trend in bluff angle from the 1950s into the 1960s. It appears that regardless of the intensity of wave erosion at present or in the past, changes in bluff morphology are relatively synchronous from profile to profile. Differences in bluff angle between measuring points are not large, suggesting that small-scale failures (small slides and slumps, solifluction, sheetwash) are the principal means by which geomorphic change occurs. No large-scale mass movements are evident.

The second of these combinations of factors, cohesive sediment and alternating high and low effective lake levels, is illustrated by bluff group C and most of bluff group E. Bluff angle changes through time on bluff group C are shown in figure 7. Like the previous case, bluff angle changes are relatively synchronous from profile to profile, and bluff angle appears to have steepened and declined as lake level rose and fell.

The third case, that of high effective lake level and cohesive sediment, is represented by most of bluff group A, which includes the Bender Park bluffs, and the bluff at the Port Washington 1 profile, which is in group E. Bluff angle changes through time on some of the bluffs of group A are shown in figure 8. No clear correlation between lake level and bluff angle can be established here, in contrast to the previous two cases. In fact, some of the higher bluff angles occur during periods of low water, and vice versa.

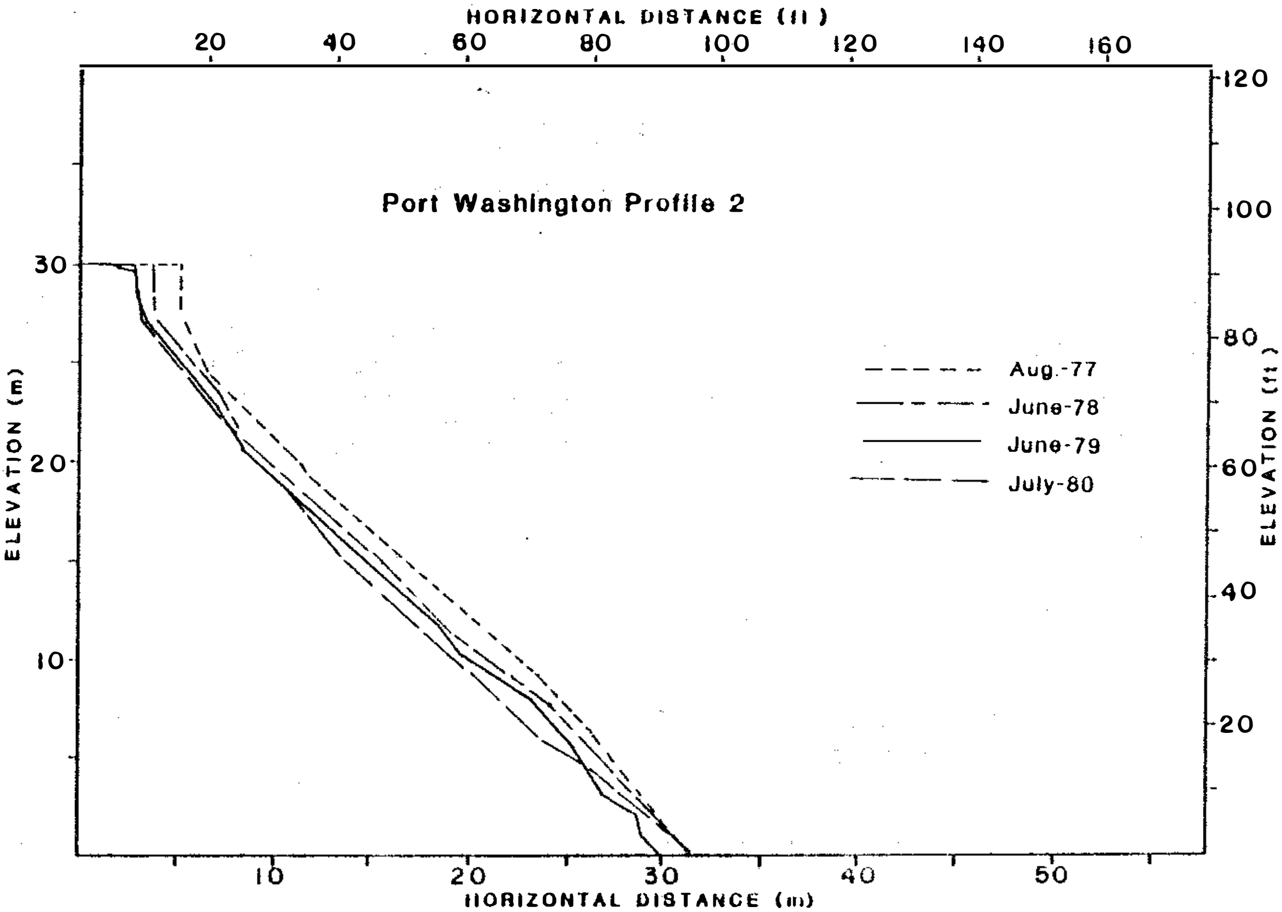

FIGURE 5.--Port Washington Profile 2, bluff profile changes, 1977 to 1980.

Significant changes in bluff angle between some of the measurements suggest that large scale failures have occurred. Figure 9 shows the approximate bluff profile changes through time for one of the profiles in fguure 8. It is evident that a large-scale slump occurred sometime in the mid-1960s.

DISCUSSION

Modes of Bluff Evolution

The results from the short-and long-term bluff monitoring suggest that there are two major modes of bluff evolution. The first is characterized by bluffs that respond directly to changes in lake level through time; that is, bluff angle steepens and declines in response to rising and falling lake level.

Bluffs that are composed largely of cohesionless material such as sand fall into this category. These include most of the bluff profiles in groups F and B. On truly cohesionless bluffs (where the effective cohesion intercept (c' = 0) scale failures cannot occur. The influence of the c' parameter on bluff geometry is discussed in detail in Edil and Haas (1980) and Edil and Vallejo (1980). Although the profiles in groups F and B mentioned above are not truly cohesionless, their geomorphic evolution is such that they can be treated as cohesionless.

Bluffs of group C and most of group E also appear to retreat in a nearly parallel fashion or respond to short-term changes in lake level. Despite the generally cohesive nature of the materials in these bluffs, no large

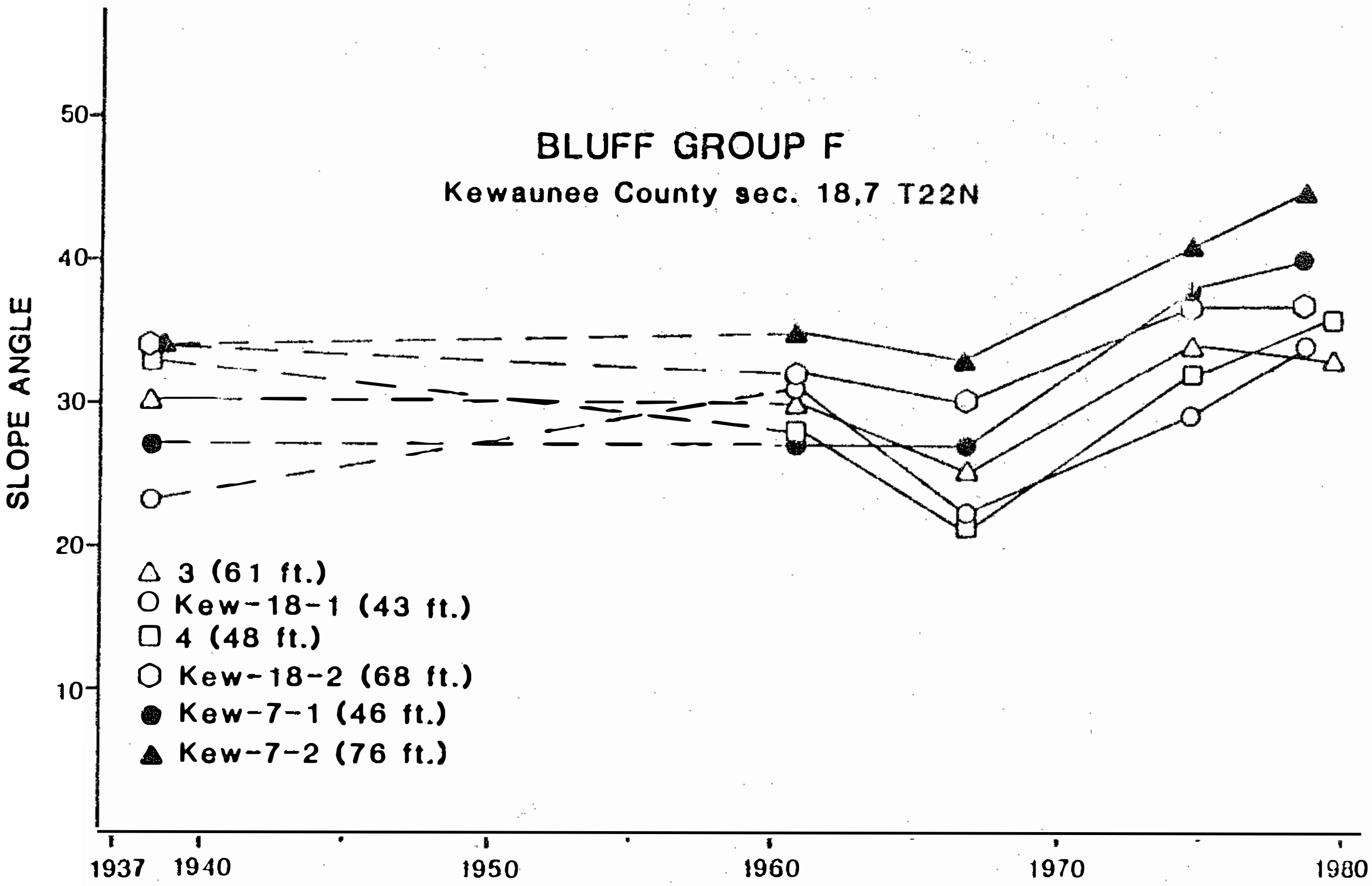

FIGURE 6.--Bluff group F, Kewaunee County, bluff angle changes through time. Bluff heights in parentheses.

scale failures have occurred throughout the monitoring period. Because effective lake level has generally remained low, it is likely that wave erosion has occurred at a sufficiently slow rate that weathering on the bluff slope could keep pace with it. Freeze-thaw and wetting and drying break up the cohesive sediment so that it can eventually be transported downslope by shallow slides and slope wash. In this manner bluff angle could vary without any large scale failures occurring. This mode of geomorphic evolution was described by Hutchinson (1973) for some of the bluffs composed of the London clay.

The second mode of bluff evolution is one marked by periods of gradual change in bluff morphology interrupted by episodes of large-scale mass movement. This occurs only on cohesive bluffs where effective lake level is continuously high. It appears that geomorphic change occurs in this manner regardless of lake level fluctuation as long as effective lake level remains high. Over the short term, these bluffs are characterized by nonparallel recession (see, for example, fig. 5).

Threshold Lake Levels

These results suggest that the geomorphic evolution of coastal bluffs is governed in part by the existence of threshold lake levels that, when exceeded, initiate some significant geomorphic change. This concept of a threshold is basically the same as that advanced by Schumm (1973) for defining landform evolution.

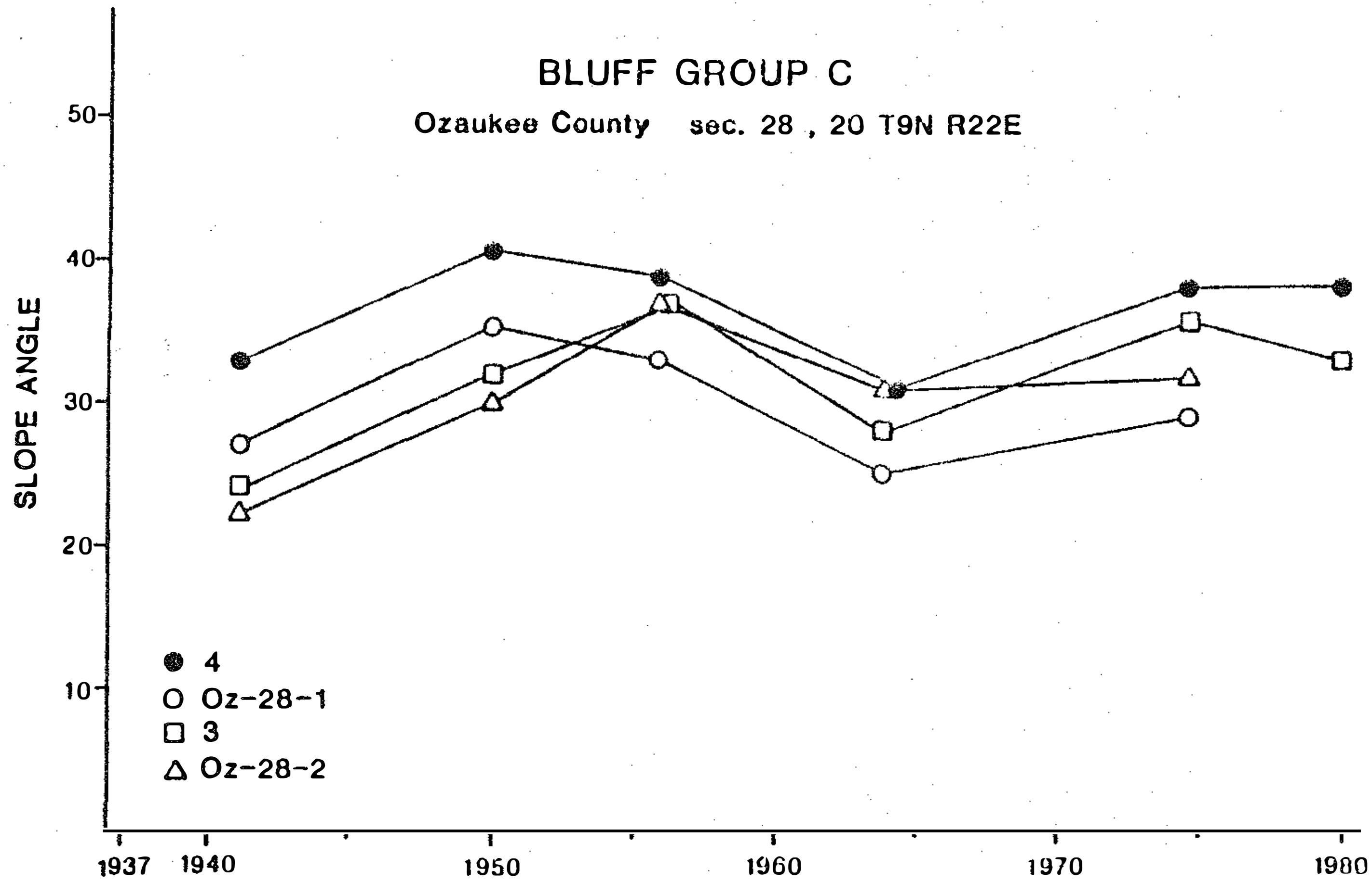

FIGURE 7.--Bluff group C, bluff angles through time.

There is some lake level below which bluff-toe erosion will not occur because waves do not strike the base of the bluff. In this case waves do not remove material from the base of the bluff and the bluff face behaves like any inland slope.

Evidently, for high bluffs composed of cohesive material, there is another, higher, threshold. On these bluffs, if water level rises sufficiently high, cutting at the base of the bluff causes oversteepening. This, in turn, leads to large-scale slumping followed by smaller-scale slumping that takes place high on the bluff. This progression of events takes place irrespective of water level change after the initial oversteeping has taken place.

The upper lake-level threshold is only relevant for cohesive bluffs, because bluffs composed primarily of cohesionless sediment are not susceptible to large scale bluff failures. Neither of these thresholds is a single lake level throughout the coastal zone in Wisconsin because of variations in beach width, offshore bathymetry, and shore orientation.

The results suggest that once the upper lake-level threshold is exceeded, the bluff angle steepens to an angle above which large scale mass movement is likely. For the high bluffs in Milwaukee and Ozaukee Counties, the bluff angle above which slumping occurs is about 45°. For the lower bluffs in Sheboygan County, the data are less abundant but it appears that 50° is a minimum value. If bluff angles on

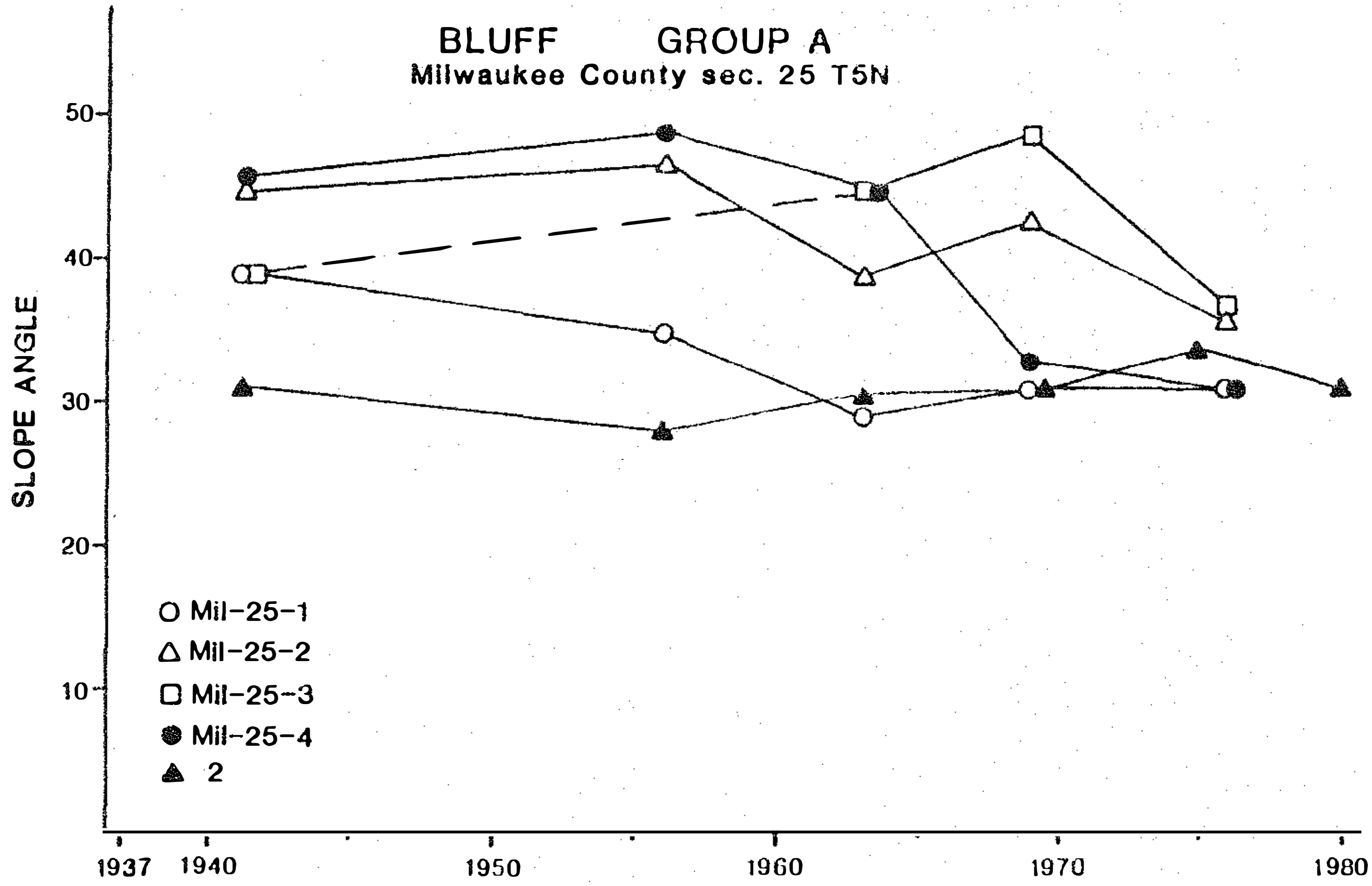

FIGURE 8.--Bluff group A, bluff angle changes through time.

these bluffs do not exceed these values, large scale mass movement will not occur. These observed angles agree fairly well with those predicted by slope stability charts developed by Vallejo and Edil (1979).

Lake Level and Bluff Response Models

My perception of the effect of lake-level fluctuations on bluff evolution is represented graphically in figures 10 and 11. In the case shown in figure 10, lake level is maintained between the two thresholds discussed above. In other words, lake level fluctuates but never drops below the level where some erosion of the bluff toe takes place and is never above the level at which major steepening of the bluff takes place. Bluff angle varies directly with lake level, with a short time lag between peak lake level and peak bluff angle. Short term fluctuations in bluff angle, such as those shown by the short term monitoring, are superimposed on the longer term fluctuations. Time periods between peak bluff angles correspond to periods between peak water levels. During the 1900's these intervals have varied from approximately 10 to 25 years. This type of geomorphic evolution takes place on non-cohesive bluffs and some cohesive bluffs where oversteepening due to wave erosion does not occur.

Geomorphic evolution on cohesive bluffs is represented in figure 11. When lake level is between the two thresholds geomorphic change is the same as that shown in Figure 10. When the upper lake level threshold is continuously exceeded, however, the bluff will steepen and eventually fail as a

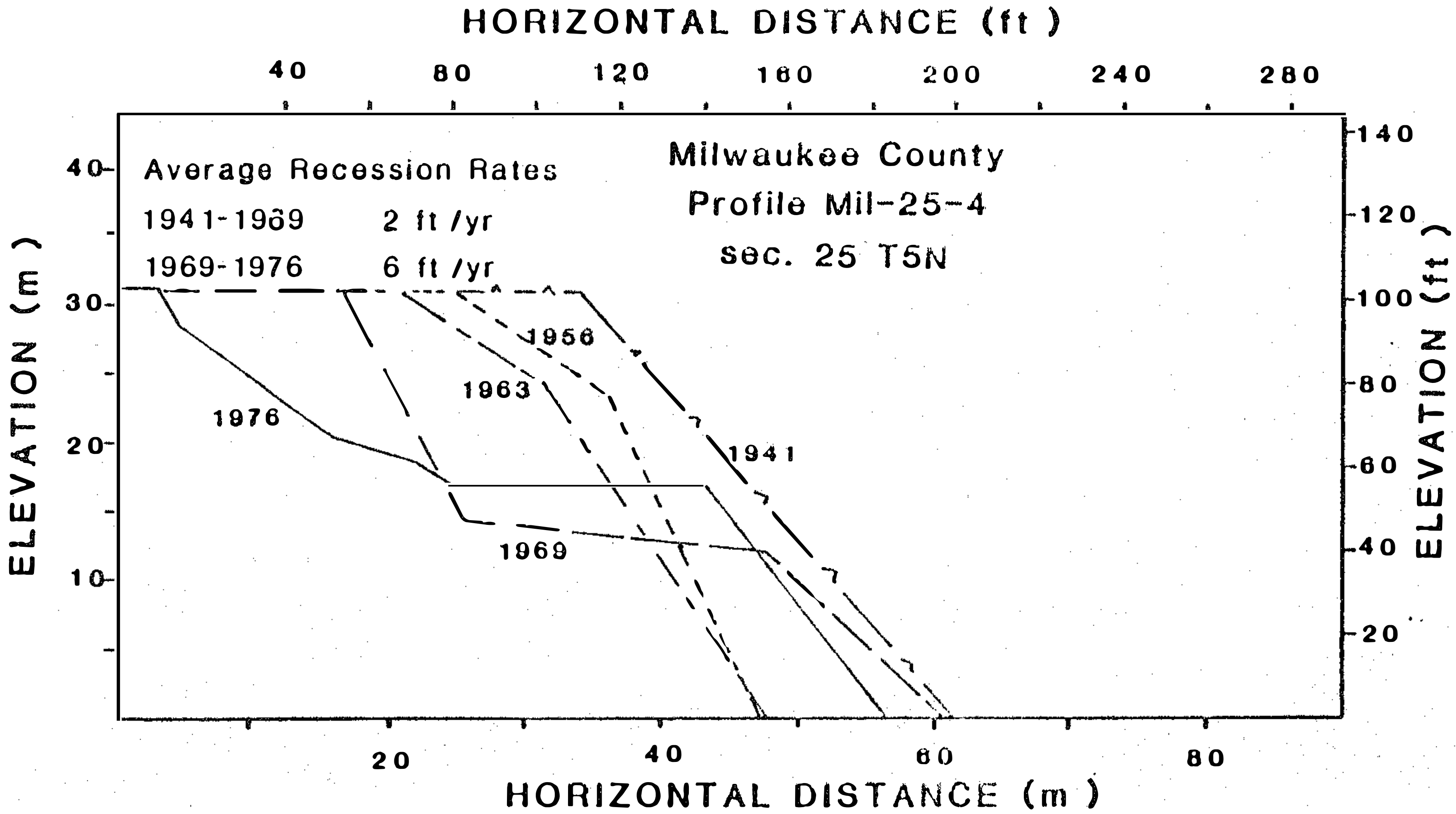

FIGURE 9.--Profile Mil-25-4, approximate bluff profile changes through time. This is an example of a group A bluff.

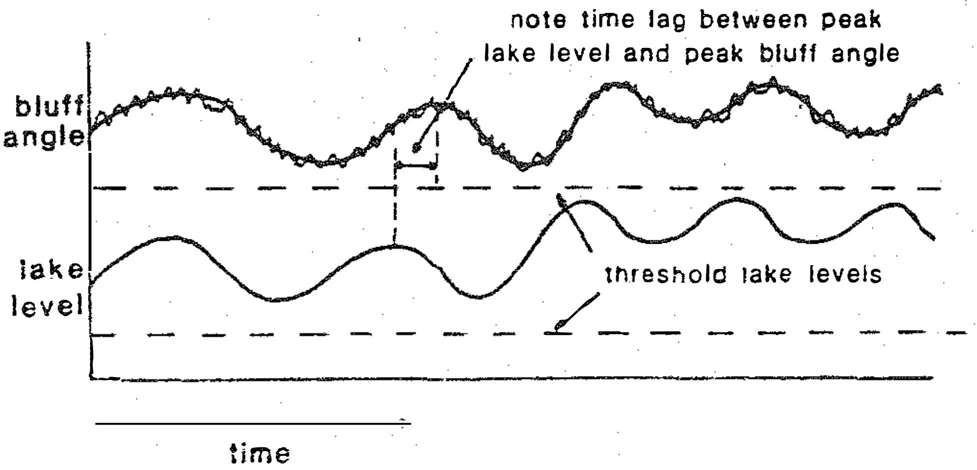

FIGURE 10.--Sketch showing the proposed relationship between water level and bluff angle when water level is high enough to cause erosion at the base of the bluff but low enough so that oversteepening does not occur.

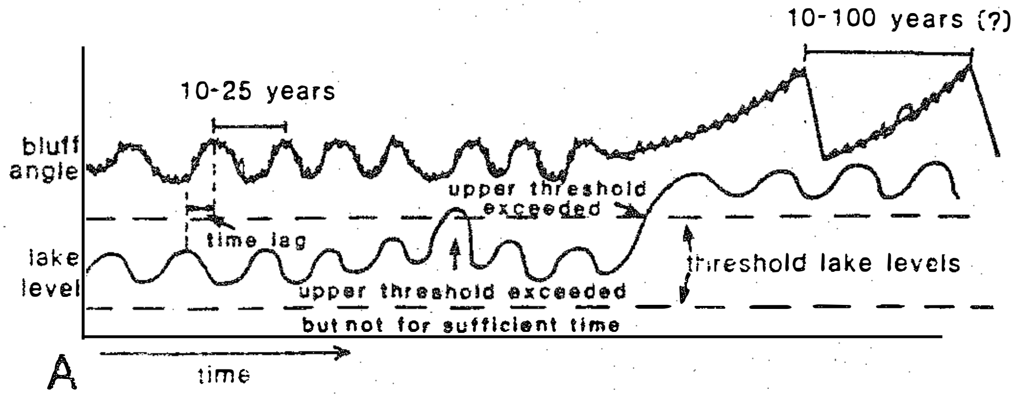

FIGURE 11.--Sketch showing the proposed relationship between lake level and bluff angle on cohesive bluffs that experience a sustained water level high enough to cause oversteepening.

large slump. This sequence of periodic mass movement probably continues as long as the upper threshold continues to be exceeded. One complete cycle of this sequence has not been documented for the Lake Michigan bluffs. However, based on known recession rates of bluffs undergoing this type of geomorphic change, the time between major failures varies from about 10 to 100 years, depending on the bluff height and the recession rate of the toe.

SUMMARY

Geomorphic evolution of the Lake Michigan coastal bluffs in Wisconsin can be described by relatively simple models relating the degree of wave erosion through time with bluff stratigraphy. On bluffs composed of cohesionless sediment, bluff angle steepens and declines in response to rising and falling lake levels. Geomorphic change will be caused only by shallow slides, flow and slopewash. On bluffs composed primarily of cohesive sediment, bluff angle varies as described above only if the lake remains at a level where the amount of material being removed by waves at the toe of the slope is roughly equal to the amount coming down the slope. In environments where the lake is higher, the rate of bluff toe erosion will begin to exceed the rate of erosion on the bluff, resulting in over steepening and eventual large scale mass movement. This sequence probably repeats itself if the lake remains sufficiently high. This high lake-level threshold is not a single lake level everywhere along the shoreline, but varies depending on factors such as shore orientation, offshore bathymetry, and beach width.

ACKNOWLEDGEMENTS

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WISCONSINAN STRATIGRAPHY AND GLACIAL SEQUENCE IN SOUTHEASTERN WISCONSIN

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ABSTRACT

The Wisconsinan Stage is represented in southeastern Wisconsin by eleven formally named and defined rock-stratigraphic units of formation or member rank. These units are distinguished from one another by their stratigraphic position and lithologic characteristics, which are summarized in this paper. Particular emphasis is placed on the lithostratigraphy of late Wisconsinan units associated with the activity of the Lake Michigan Lobe during the Woodfordian Subage. Several unnamed, undifferentiated, and informal units of glacial, glaciofluvial, lacustrine, and eolian origin are also known to be present.

The Altonian Substage (Early Wisconsinan) is represented by the Walworth Formation, which consists of the Foxhollow Member, the Allens Grove Member, and the Clinton Member (in ascending order), and by the Capron Member of the Zenda Formation. These units are present in Rock and Walworth Counties, where they all occur in an area bounded by the Rock River on the west and by late Wisconsinan moraines on the north and east. Relatively little is known about the details of the ice advances responsible for the deposition of these units, however, partly because of their limited distribution and surface expression

The Woodfordian Substage (Late Wisconsinan) is represented by the Tiskilwa Member of the Zenda Formation, the Horicon Formation, the New Berlin Formation, the Oak Creek Formation, and the Ozaukee Member of the Kewaunee Formation. Except for the Tiskilwa Member, which occurs mainly in the shallow subsurface, all these units cover large areas of southeastern Wisconsin. All but the Horicon Formation were deposited by the Lake Michigan Lobe or its sublobes and by their associated meltwater streams. Till of the Horicon Formation was laid down by the Green Bay Lobe, which buried much of southeastern Wisconsin, formed the classical drumlin field of that area, and terminated at the Johnstown Moraine on the west and south and at the Kettle Interlobate Moraine on the east.

Both the New Berlin and Oak Creek Formations appear to represent several ice advances. The farthest advance to result in the deposition of sandy New Berlin till was that of the Delavan Sublobe, which shaped the Waukesha drumlin field and continued southwestward to its terminal Darien Moraine. The northwest side of the lobe terminated at the Kettle Moraine; thus, the Horicon and New Berlin Formations are considered to be age equivalents in southeastern Wisconsin.

A large proglacial lake, here called glacial Lake Milwaukee, is postulated for the Lake Michigan basin during stagnation and retreat of the Delavan Sublobe. When the Lake Michigan Lobe subsequently readvanced out of the basin, it incorporated large amounts of lacustrine silt and clay into the Oak Creek Formation. As the lobe pushed westward, it overran stagnant ice from the Delavan Sublobe and terminated along the Valparaiso Moraine. Later readvances reached the Tinley and Lake Border Moraines, and these were followed by still another advance that left red clay-rich till of the Ozaukee Member in a belt adjacent to the lake north of Milwaukee.

INTRODUCTION

This paper summarizes the lithostratigraphic record and the sequence of glacial events during the Wisconsinan Age in southeastern Wisconsin. In accord with the general theme of the field trip for which this is written, emphasis is placed on Late Wisconsinan (Woodfordian) stratigraphy and events. Emphasis is also placed on the activity of the Lake Michigan Lobe.

For nearly half a century following the publication of Alden's second U.S. Geological Survey professional paper on the Quaternary geology of southeastern Wisconsin in 1918, the glacial deposits of this area received virtually no attention until the studies of Ned Bleuer and Norman Lasca were initiated in the mid-1960s. The results of these investigations were incorporated in the guidebook prepared for the 1970 Annual Meeting of The Geological Society of America in Milwaukee (Black and others, 1970). Since that meeting, our knowledge of Wisconsinan stratigraphy and the glacial sequence of this area has been substantially supplemented, and thus it seems appropriate to review the subject for this 1983 meeting of the North-Central Section of the Society.

Five areas of activity have contributed to the acquisition of new knowledge during the past 13 years. They are as follows:

(1) Completion of graduate dissertations by Lawrence Acomb, Carl Fricke, Thomas Johnson, and G. Richard Whittecar under the direction of Professor David Mickelson at the University of Wisconsin-Madison.

(2) Surficial mapping by personnel of the Wisconsin Geological and Natural History Survey, mainly by David Hadley in Walworth County.

(3) Shore erosion and bluff stability studies along the Lake Michigan shoreline. The principal effort was a comprehensive project conducted during the summer of 1976 that was supported by a major grant to the State from the federal Office of Coastal Zone Management, National Oceanic and Atmospheric Administration, under the provisions of the Coastal Zone Management Act of 1972. Financial assistance was also provided by the Wisconsin Geological and Natural History Survey. Dave Hadley was Principal Investigator, Dave Mickelson and I were Co-Investigators, but many persons contributed to the success of the project (Mickelson and others, 1977).

(4) Continuing regional studies by myself of the glacial stratigraphy and landforms of southeastern Wisconsin. Commencing in 1971, these studies were supported initially by a research grant from the Wisconsin Alumni Research Foundation and subsequently by field expenses from the Wisconsin Geological and Natural History Survey and by research grants from the Committee on Research and Creative Activity of the University of Wisconsin--Parkside.

(5) Cooperative studies during the past two years with personnel of the Illinois State Geological Survey, including Ardith Hansel, Leon Follmer, Herbert Glass, and John Kempton.

A significant result of the increased attention to Quaternary studies in southeastern Wisconsin and throughout the State during the past decade has been the establishment of a formal, though as yet incomplete, rock-stratigraphic classification for deposits of the Quaternary Period (Mickelson and others, 1983). That classification is used in this paper.

ALTONIAN SUBSTAGE

Four early Wisconsinan (Altonian) till units are apparently present in southeastern Wisconsin (fig. 1). Working in the area south and west of the prominent Woodfordian moraines and east of the Driftless Area, Bleuer (1970) mapped three Altonian till units. The oldest of these he informally named the "Janesville till," which--with its associated ice-contact stratified drift called the "Janesville gravel"--Bleuer thought was probably deposited during Early Altonian time and correlated with one of the units in the lower part of the Winnebago Formation of Illinois. The two younger units were mapped by Bleuer as the Argyle and Capron tills, which he believed correlated directly with the Argyle Till Member and the Capron Till Member, respectively, of the Winnebago Formation of Illinois (Frye and others, 1969; Willman and Frye, 1970).

Fricke (Fricke and Johnson, in press), on the other hand, recognized four Altonian tills: in ascending stratigraphic order, the Foxhollow till, the Allens Grove till, the Clinton till, and the Capron till. From lithologic and drill-hole data, he concluded that the Allens Grove till is equivalent to the Argyle Till Member of Illinois and that the overlying Clinton till, previously correlated and mapped by Bleuer as the Argyle, is a separate and distinct unit between the Allens Grove (Argyle) till and the Capron till, both in Wisconsin and in northern Illinois (fig. 1). The Clinton has not been formally named in Illinois, however. Fricke's Foxhollow till, which in Wisconsin is known only from drill holes, appears to be present in exposures near Rockford, but like the Clinton it has not yet been accorded formal recognition by the Illinois State Geological Survey. The status of Bleuer's Janesville till is uncertain; Fricke (Fricke and Johnson, in press) inferred that it is equivalent to his Allens Grove till, but it might equate with the Foxhollow.

Because the lithologic characteristics of the Altonian tills differ from one another, it is assumed that each was deposited by a separate advance of the ice, probably all from the Lake Michigan basin. Very little is known, however, about the details of these advances, and most of the tills have little or no surface expression. Only a very sketchy interpretation of glacial history is possible, therefore.

Walworth Formation

Three mid-Altonian units constitute the Walworth Formation (Mickelson and others, 1983). In ascending order, they are the Foxhollow Member, the Allens Grove Member, and the Clinton Member (fig. 1). All three of these units are best known from southeastern Rock County and adjacent southwestern Walworth County in an area that is bounded on the west by the Rock River, on the north by the Johnstown Moraine, and on the east by the Darien Moraine and the Capron Ridge (fig. 2). Only the Clinton Member, however, is presently known to occur at the surface. All three units were likely deposited prior to 40 000 B.P. by glacier ice from the Lake Michigan basin.

Foxhollow Member

The Foxhollow Member (Mickelson and others, 1983) includes gray loam till that is present in the subsurface of southeastern Rock County, southwestern Walworth County, and part of northern Illinois. It occurs mainly as a fill in preglacial or early Pleistocene bedrock valleys, notably the Troy Valley (Alden, 1904, 1918; Green, 1968), which trends southwestward across southern Walworth County.

Foxhollow till is distinguished from the other two members of the Formation by having less sand (44 percent) and by a lower ratio (less than 0.8:1) of light to dark dolomite grains in the coarse-sand fraction. The Foxhollow is

TIME-STRATIGRAPHIC UNITS			ROCK-STRATIGRAPHIC UNITS		
Holocene Stage			Definite lacustrine sediments		
Wisconsinan Stage	Greatlakean Substage		Possible lacustrine sediments		Peoria loess
	Twocreekan Substage		Forest bed and moss mat		
	Woodfordian Substage	Port Huron	Glacial Lake Chicago sediments		
			Ozaukee Member of the Kewaunee Formation		
		Cary	Oak Creek Formation		
			New Berlin Formation (Lake Michigan Lobe)	Horicon Formation (Green Bay Lobe)	
		Tazewell	Tiskilwa Member of the Zenda Formation		
	Farmdalian Substage		Paleosols formed on Clinton Member (?)		
	Altonian Substage		Capron Member of the Zenda Formation		
			Walworth Formation	Clinton Member	
				Allens Grove Member (= Janesville till?)	
				Foxhollow Member	

FIGURE 1.--Stratigraphic units of the Wisconsinan Stage in southestern Wisconsin.

also considered to have the lowest average illite content (53 percent) of all the tills in southeastern Wisconsin (Fricke and Johnson, in press; Mickelson and others, 1983), but in my opinion the X-ray diffraction data are not sufficiently different to distinguish the unit from other tills in the area (table 1).

Allens Grove Member

The middle unit of the Walworth Formation is the Allens Grove Member. It includes pink sandy till that lies beneath the Clinton Member in southeastern Rock County.

Allens Grove till has about 53 percent sand and thus is texturally intermediate between the less sandy Foxhollow till and the sandier Clinton till (table 1). It is also intermediate between the other two members of the Walworth Formation in the ratio of light-to-dark dolomite in the coarse-sand fraction. Two groups of samples from Allens Grove till have significantly different clay-mineral compositions (table 1), according to Fricke and Johnson (in press). Perhaps the most diagnostic characteristic of Allens Grove till is its pinkish-tan or salmon color.

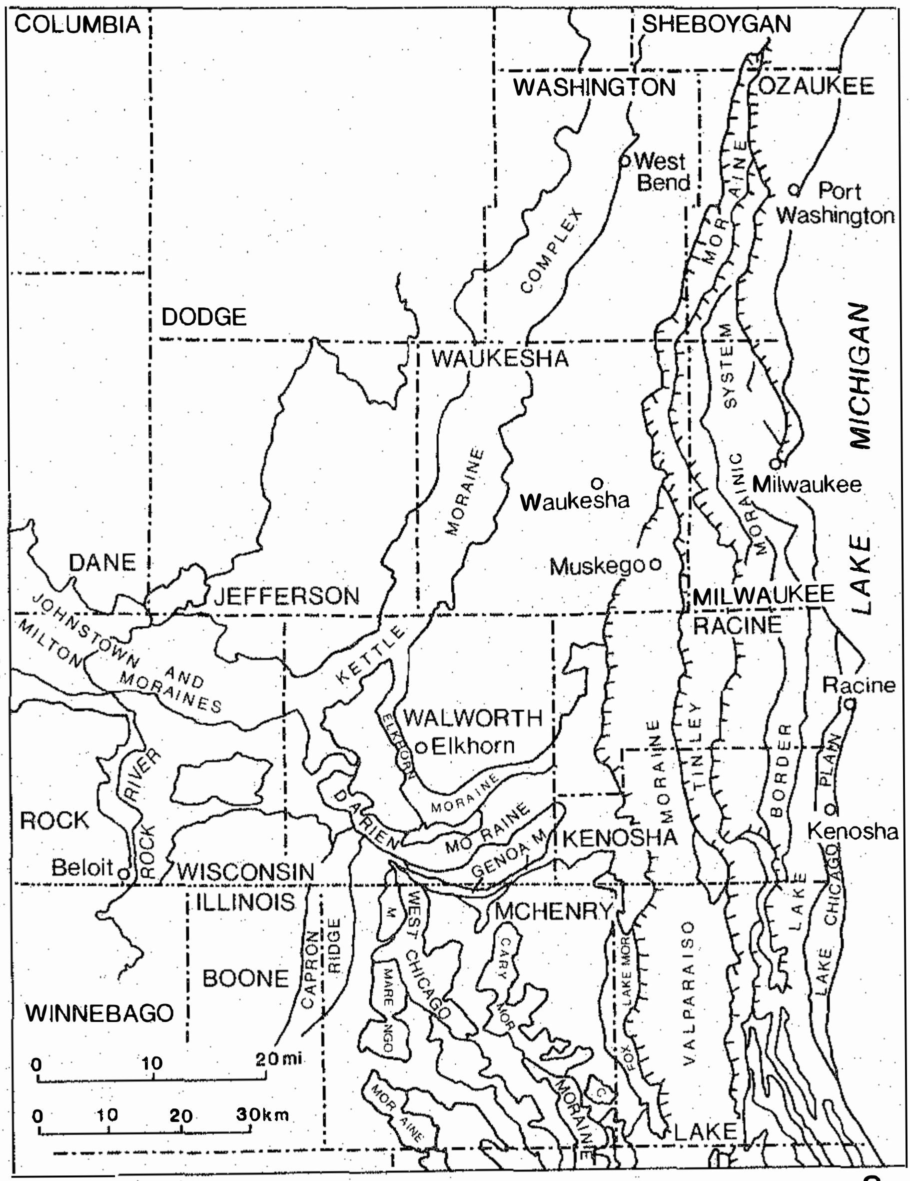
The Allens Grove till extends southward into northern Illinois, where it is called the Argyle Till Member of the Winnebago Formation (Frye and others, 1969; Willman and Frye, 1970). At some places in Illinois, the Argyle till is overlain by the Plano Silt Member of the Winnebago Formation (Kempton and Hackett, 1968), which consists of silt, organic silt, and peat. Finite radiocarbon dates on wood and other organic material range from 32 600 to 41 000 B.P. Other dates are greater than 40 000 B.P. (Willman and Frye, 1970, table 1).

Clinton Member

The youngest unit of the Walworth Formation is the Clinton Member (Fricke and Johnson, in press; Mickelson and others, 1983), which includes sandy loam till and associated sand and gravel that occurs at the surface in southern Rock and southwestern Walworth Counties. As already stated, the unit was mapped by Bleuer (1970) as the Argyle till on the assumption that it was equivalent to the Argyle till of Illinois. Its eastern surficial extent is the north-south-trending Capron Ridge, but Fricke and Johnson (in press) have confirmed that Clinton till is definitely present beneath the younger Capron till in the ridge. It is also present west of the Rock River; its distribution in this area is patchy, but it appears to extend westward in tributary valleys to the Sugar River, nearly 12.9 km west of the Rock-Green county line (Bleuer, 1970, p. J-18).

Clinton till has the most sand (61 percent) of the three members of the Walworth Formation (table 1). It also has the highest ratio of light-to-dark dolomite in the coarse-sand fraction (greater than 1.3 to 1), according to Fricke and Johnson (in press). Like the underlying Allens Grove Member, two groups of samples of Clinton till have significantly different percentages of clay minerals (table 1). Although the till is most commonly light yellowish brown (10YR 6/4) or light brown (7.5YR 6/4), a pink color (7.5YR 7/4 or 7.5YR 8/4) is also somewhat characteristic, particularly when the till is dry (Bleuer, 1970, p. J-14). Fricke and Johnson (in press) suggested that this may be due to the local incorporation of material from the underlying Allens Grove Member.

Bleuer was obviously puzzled by a less sandy till that he found beneath his Argyle (now Clinton) till at depths of 2 to 6 m below the upland


COLUMBIA
SHEBOYGAN
WASHINGTON
OZAUKEE
West Bend
Port Washington
COMPLEX
MORAINE
MORAINIC SYSTEM
DODGE
WAUKESHA
MICHIGAN
MORAINE
Waukesha
Milwaukee
LAKE
DANE
Muskego
JEFFERSON
MILWAUKEE
RACINE
JOHNSTOWN AND MILTON MORAINES
KETTLE
Racine
WALWORTH
Elkhorn
ELKHORN
MORAINE
RIVER
ROCK
MORAINE
TINLEY
BORDER
PLAIN
MORAINE
DARIEN
MORAINE
GENOA M
Kenosha
KENOSHA
Beloit
ROCK
WISCONSIN
ILLINOIS
MCHENRY
CAPRON RIDGE
M
WEST CHICAGO
CARY
MOR
LAKE MOR
LAKE
CHICAGO
BOONE
MARENGO
VALPARAISO
LAKE
WINNEBAGO
FOX
MORAINE
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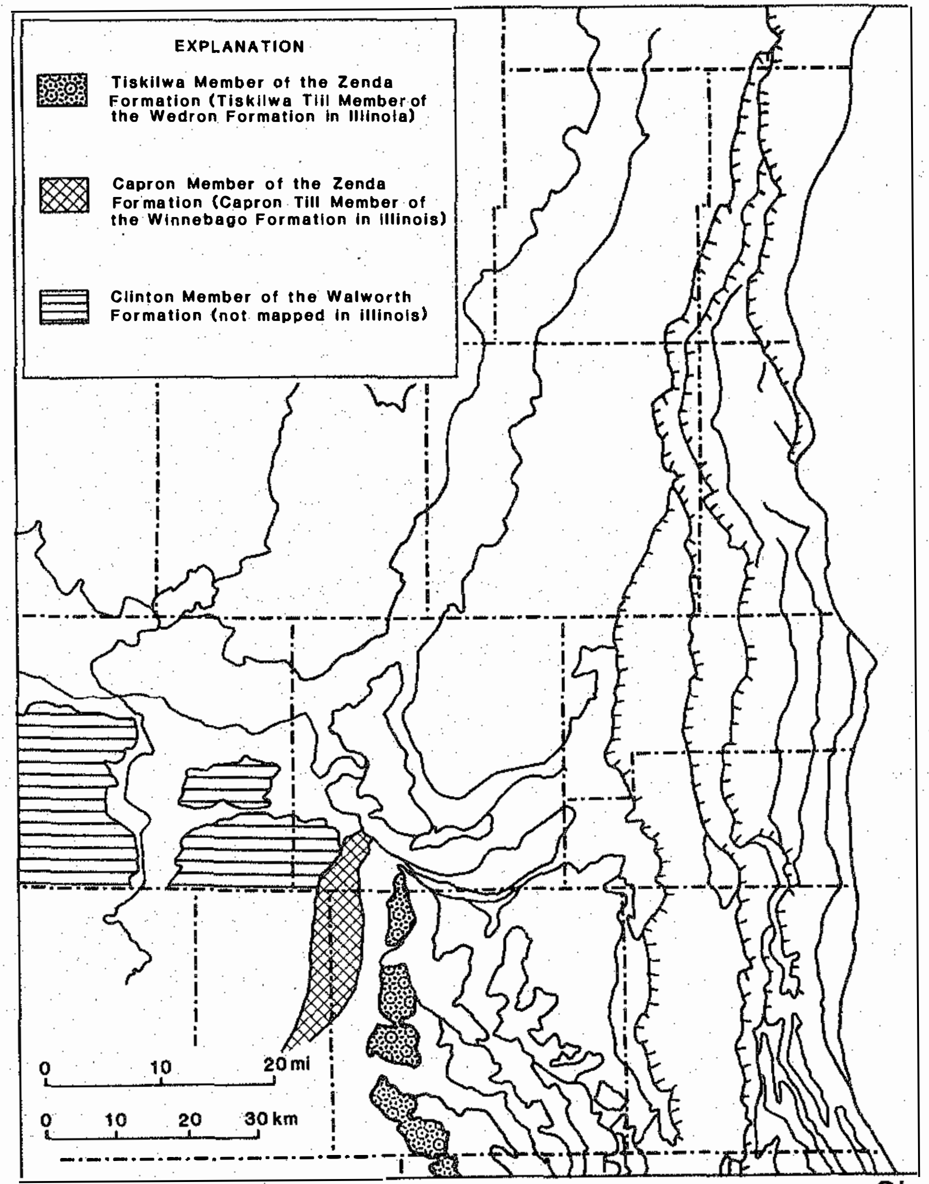
LAKE
0 10 20 mi
0 10 20 30 km

2a


EXPLANATION
Tiskilwa Member of the Zenda Formation (Tiskilwa Till Member of the Wedron Formation in Illinois)
Capron Member of the Zenda Formation (Capron Till Member of the Winnebago Formation in Illinois)
Clinton Member of the Walworth Formation (not mapped in Illinois)
0 10 20 mi
0 10 20 30 km

2b

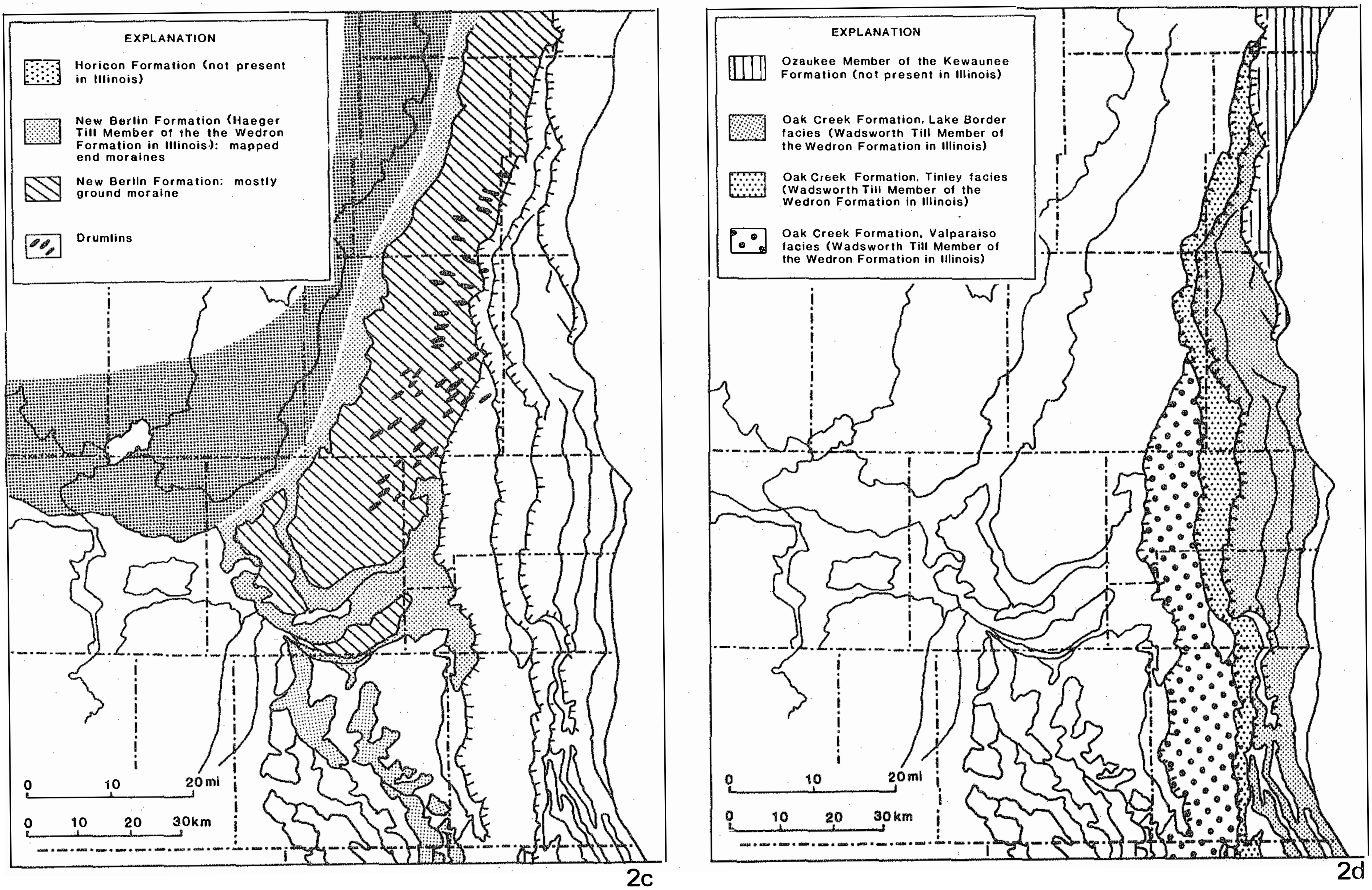


FIGURE 2.--Glacial geology of part of southeastern Wisconsin showing moraines and counties (2a) and distribution of Wisconsinan rock-stratigraphic units (2b, 2c, 2d). Moraines as shown do not necessarily represent the interpretations of the author; rather, an attempt is made to show relationships mapped by several workers. Hachured lines represent distal edges of younger rock-stratigraphic units. Wisconsin part compiled from Alden (1904, 1918), Thwaites (1956), Hadley and Pelham (1976), and the author's field maps; Illinois part compiled from Leighton and Willman (1953) and Willman and Frye (1970).

Stratigraphic Unit	Grain Size of Matrix (< 2 mm)				Clay-mineral Composition (< .002 mm)				Source of Data
	Sand (%)	Silt (%)	Clay (%)	N	Expandable Clay Mins (%)	Illite (%)	Kaolinite + Chlorite (%)	N	
Ozaukee till	13	47	40	(19)[a]	20	60	20	(20)	Acomb and others, 1982
Oak Creek till	12	44	44	(68)[b]	15	72	13	(55)	ISGS, H.D. Glass
Horicon till	72	17	11	(24)[c]					Allan, 1967
New Berlin till	58	29	13	(15)[b]	17	66	17	(26)	ISGS, H.D. Glass
Tiskilwa till	42 39	35 39	23 22	(8)[b] (?)[d]	18	67	15	(24)	ISGS. H.D. Glass Fricke & Johnson, in press
Capron till									
Upper phase	41 40	35 42	24 18	(3)[b] (5)[d]	28	61	11	(3)	Fricke & Johnson, in press Bleuer, 1970
Lower phase	27 24	38 45	35 31	(2)[b] (3)[d]	28	61	11	(2)	Fricke & Johnson, in press Bleuer, 1970
Clinton till	61	27	12	(85)[b]	26 45	60 45	14 10	(85)	Fricke & Johnson, in press
Argyle till	62	28	10	(app 30)[d]					Bleuer, 1970
Allens Grove till	53	35	12	(40)[b]	26 39	61 47	13 14	(40)	Fricke & Johnson, in press
Janesville till	47	40	13	(app 40)[d]					Bleuer, 1970
Foxhollow till	44	37	19	(22)[b]	28	53	19	(22)	Fricke & Johnson, in press

N (00) = number of samples. Grain-size boundaries: [a] Boundaries are 2 mm, 0.062 mm, and 0.002 mm.

[b] Boundaries are 2 mm, 0.062 mm, and 0.004 mm. [c] Boundaries are 2 mm, 0.05 mm, and 0.002 mm.

[d] Precise boundaries not stated.

Table 1. Average grain-size distribution and clay-mineral composition of tills in southeastern Wisconsin.

surface. Ten samples of this lower till averaged 47 percent sand, 38 percent silt, and 15 percent clay. Whereas the surficial till is rich in Niagaran dolomite, the lower till is rich in local dolomite (Bleuer, 1970, p. J-16). A till with lithologic characteristics similar to this lower till was also found stratigraphically below the Argyle (Clinton) north of Turtle Creek. Bleuer tentatively correlated both this unit and the lower till south of Turtle Creek with his Janesville till. It seems reasonable to conclude that Bleuer's sub-Argyle (sub-Clinton) till units equate with Fricke's Allens Grove or Foxhollow tills.

Fricke (Fricke and Johnson, in press) reported the presence of a fossil B horizon formed on the Clinton till beneath flatter upland surfaces. At the type section of the Clinton Member in southeastern Rock County, the paleosol has a reddish-brown B2t horizon and a brown beta horizon formed in the upper 1.7 m of the Clinton till. At the type section of the Allens Grove Member, where it is overlain by about 8.2 m of Clinton till, a paleosol also occurs at the top of the Clinton Member. At both localities the section is capped by 1 to 2 m of loess, which is assumed to be Peoria loess. Although the paleosol has been stripped from steeper slopes by erosion, Fricke suggested that it may be present along the footslopes beneath a loess and colluvial cover.

Bleuer (1970, p. J-16) reported the discovery by Robert Engel of the Soil Conservation Service of an organic-rich, sandy A1 horizon overlying gleyed, leached sandy loam till. The soil is buried by 1.5 m of Peoria loess.

The Robein Silt, on which the Farmdalian Substage of Illinois is based, is not known to be present in southeastern Wisconsin. However, the paleosols described by both Fricke and Bleuer may well represent Farmdalian time in southeast Wisconsin.

The Clinton Member appears to be the oldest stratigraphic unit in southeastern Wisconsin about which ice-flow direction can be inferred from geomorphic evidence. Between the Capron Ridge and the Rock River outwash terrace, the upland is characterized by a distinctly drumlinoid topography. First recognized by Buell (1895) before the turn of the century, the landscape was nicely described by Bleuer (1970, p. J-15) in the following manner:

> "Drainage is deranged and youthful, and, except for those areas adjacent to Turtle Creek or the Rock River valley, the drainage is almost wholly controlled by the subdued constructional topography. Much of the area is a series of broad, imperfectly drained to poorly drained lineated lowlands between low, gently sloping lineated hills. Local relief is less than 60 feet within the area.
>
> "The lineations are not parallel everywhere east of the Rock River, contrary to Alden (1918, Pl. III) and Leighton and Brophy (1966, Fig. 2, p. 484). The topography south of Turtle Creek has a general west-southwest lineation, but individual ridges are oriented between this trend and east-west. Orientations of upland crests north of Turtle Creek are west-northwest and suggest a locally divergent flow. This diversity of orientation may be in part due to the effect of bedrock topography upon glacial deposition."

Bleuer correctly points out that the topography west of the Rock River valley is grossly different from that east of the river and that the surface morphology is bedrock controlled. Ice flow west of the Rock River was from the east-southeast, according to Bleuer

(1970, p. J-14), rather than from the east-northeast as in the area between the Rock River and the Capron Ridge. He recognizes the possibility, however, that the lineated landscape of this latter area may not be directly related to the surface till, but instead to an older till (Bleuer, 1970, p. J-16). This possibility seems to be unlikely.

Zenda Formation
Capron Member

The youngest Altonian unit known to be present in southeastern Wisconsin is named the Capron Member of the Zenda Formation (Mickelson and others, 1983). The Capron Member occurs at the surface only in a small area of southwestern Walworth County, where it is found in the north-south-trending Capron Ridge (fig. 2). The Capron Ridge enters Walworth County from Boone and McHenry Counties, Illinois, where the unit was named the Capron Till Member of the Winnebago Formation (Frye and others, 1969; Willman and Frye, 1970) for the village of Capron located on the ridge 10 km south of the Wisconsin-Illinois boundary.

The Capron till is generally a medium-grained till, although two distinct compositional phases have been recognized, both in Illinois (Frye and others, 1969; Willman and Frye, 1970) and in Wisconsin (Bleuer, 1970, p. J-11; Fricke and Johnson, in press)--a lower siltier phase and an upper sandier phase (table 1). In Illinois the more sandy unit has more expandable clay minerals and less illite, but in Wisconsin the clay-mineral composition of the two phases appears to be similar, as well as resembling the clay-mineral content of one group of samples from both the Allens Grove and Clinton tills (table 1). The till is moderately compact and calcareous, as in Illinois, and is light brown (7.5YR 6/4) to brown (7.5YR 4/4) in color. Capron till can be distinguished from till of the older Walworth Formation and the younger Horicon Formation by its distinctly finer grain size and its slightly darker or pinker color.

Like older Altonian till in southeastern Wisconsin, the Capron till was deposited by the Lake Michigan Lobe (Frye and others, 1969, p. 6; Bleuer, 1970, p. J-12). Nearly 80 percent of the pebbles are dolomite, and about half of the stones identified by Bleuer (1970, p. J-11) were Niagaran dolomite pebbles. Frye and others (1969, p. 6) concluded that the intermediate composition of the Capron till, in terms of both its illite and Devonian black shale content, indicates primary glacier scour along the western side of the Lake Michigan basin.

The Capron Member was apparently deposited between 30 000 and 35 000 years ago. Its age is established by stratigraphic relations in Illinois, where the unit overlies the Plano Silt Member of the Winnebago Formation and underlies the Robein Silt. The Plano Silt is at least 35 000 radiocarbon years old, and the Robein Silt has radiocarbon dates between 21 000 and 28 000 B.P. (Willman and Frye, 1970). Thus the Capron Member is Late Altonian.

About 7 km of the Capron Ridge occurs in Wisconsin. Near the state line the ridge has a maximum relief of about 27 m. It descends slightly from south to north and is apparently overlapped and truncated on the north by outwash deposits and by the northwest-southeast-trending Darien Moraine. The eastern toe of the ridge is buried by proglacial sand associated with the Darien-Marengo-West Chicago morainic belt. Along the western edge of the ridge, Capron till blankets the Clinton Member of the Walworth Formation (Fricke and Johnson, in press).

Although it is commonly thought to be an end moraine, very little is actually known about the origin of the Capron Ridge. According to Bleuer (1970,

p. J-12), drift thicknesses of more than 10.5 m were penetrated by power auger at several sites along the crest of the ridge. Near the north end of the ridge crest, however, bedrock was encountered at depths of only 0.6 to 1.8 m, and borings in the eastern part of the ridge indicate the presence of an older till at depths ranging from 1.5 to 6.1 m. He concluded, therefore, that some of the relief of the Capron Moraine is due to a core of older till or high bedrock.

WOODFORDIAN SUBSTAGE

Five Late Wisconsinan (Woodfordian) stratigraphic units are formally recognized in southeastern Wisconsin. These units range in age from about 18 000 or 20 000 years to 12 500 or 13 000 years. In ascending stratigraphic order, they are the Tiskilwa Member of the Zenda Formation, the New Berlin and Horicon Formations (age equivalents), the Oak Creek Formation, and the Ozaukee Member of the Kewaunee Formation (fig. 1 and Mickelson and others, 1983). Peoria loess and unnamed lacustrine deposits are also present.

Almost certainly, further field and laboratory investigations will result in the subdivision of some of these units and thus lead to refinements of our current rock-stratigraphic framework for this area. The New Berlin Formation, for example, is known to consist of two principal members, a lower sand and gravel unit and an upper till unit, but neither is formally defined at this time. The Oak Creek Formation very likely represents two, three, or possibly even four advances of the Lake Michigan Lobe that left deposits that may eventually be distinguished from each other lithologically and correlated with specific morainic ridges. For a more detailed treatment than presented in this paper of the Oak Creek Formation and its correlative unit in northeastern Illinois, the Wadsworth Till Member of the Wedron Formation, the reader is referred to accompanying papers in the guidebook by Hansel (1983) and Need (1983).

Zenda Formation
Tiskilwa Member

The earliest incursion of ice into southeastern Wisconsin during the Woodfordian Subage occurred about 18 000-20 000 B.P. It is represented by till of the Tiskilwa Member of the Zenda Formation (Mickelson and others, 1983). This unit was named the Tiskilwa Till Member of the Wedron Formation (Willman and Frye, 1970) from a road cut in Bureau County, Illinois, 8 km northwest of Tiskilwa in the Bloomington Moraine (Frye and Willman, 1965, p. 95).

Tiskilwa till in Illinois is "sandy, pink-tan to reddish tan-brown, and generally is described as pink till" (Willman and Frye, 1970, p. 68). Tiskilwa till in Wisconsin is similar. Typically it has a 5YR hue, but ranges in color from reddish brown (5YR 4/3, 5YR 4/4, or 5YR 5/4) or yellowish red (5YR 4/6) to brown (7.5YR 5/4) where it is oxidized. Where unoxidized, it is commonly dark reddish gray (5YR 4/2) or weak red (2.5YR 4/2).

Till of the Tiskilwa Member is slightly to moderately stony. Grain-size analyses indicate that the matrix of the till contains an average of about 42 percent sand, 35 percent silt, and 23 percent clay (table 1). In some places a more sandy phase of the till is present. A single sample from one of the formally designated Wisconsin reference sections for the Tiskilwa Member contains 65 percent sand, 24 percent silt, and 11 percent clay; in contrast, three samples of the more typical till from the same exposure average 42 percent sand, 36 percent silt, and 22 percent clay. To date it has not been possible to determine the distribution of the more sandy facies, partly because of the similarity in both color and texture between the sandier Tiskilwa till and till of the younger New Berlin Formation that has been contaminated with Tiskilwa till as a result of erosion and assimilation. In fact, the two are virtually indistinguishable, even in relatively deep, fresh cuts.

The more typical Tiskilwa till is lithologically similar to till of the older Capron Member of the Zenda Formation. Both are pink, medium-textured tills with approximately the same grain-size distributions (table 1). Capron till is less red, however, according to Bleuer (1970, p. J-11 to J-13) and normally has a 7.5YR hue rather than the 5YR hue that is typical of Tiskilwa till. Tiskilwa till is readily distinguished from both the older Clinton till and the younger (uncontaminated) New Berlin till by its pinkish color and distinctly finer grain size. New Berlin till also has more pebbles than the Tiskilwa till.

In McHenry County, Illinois, just south of the Wisconsin state line, Tiskilwa till composes the Marengo Moraine, a prominent north-south-trending end moraine. According to Willman and Frye (1970, p. 108), the Marengo Moraine represents the outermost moraine of the Harvard Sublobe of the Lake Michigan Lobe. It is one of the higher and more prominent end moraines in Illinois, being about 65 km long and 5 km wide; it generally rises 45 to 60 m above the outwash plain in front (to the west) of the moraine. Although it has been correlated in the past with the Bloomington Moraine, the exact relationship between the moraines now appears to be somewhat uncertain (Willman and Frye, 1970, p. 108).

Less than a kilometer north of the Wisconsin-Illinois boundary the Marengo Moraine is overlapped from the east by the northwest-southeast-trending Darien Moraine, the terminal moraine of the Delavan Sublobe of the Lake Michigan Lobe (Alden, 1904, 1918; Schneider, 1982), and its proglacial outwash deposits. It can be traced northward, however, chiefly by mapping the distribution of pink Tiskilwa till, which is exposed at or near the surface in a belt roughly 10 to 18 km wide that extends from the state line northward through Walworth County to the Kettle Moraine. The high topography north and south of Lake Geneva is certainly part of the Marengo Moraine, irregularly blanketed with a thin veneer of younger drift. Very probably, Tiskilwa till forms the core of much of the Elkhorn Moraine, which Alden (1904, 1918)) considered to be a recessional moraine of the Delavan Sublobe but which we now believe is largely the northward continuation of the Marengo Ridge, partially buried beneath a thin cover of New Berlin till. It is in this latter area that Tiskilwa till and contaminated New Berlin till are difficult or impossible to distinguish in many exposures. Yet in many others sharp contacts of apparently pure tills establish the relative age of the two units.

The Tiskilwa Member is also known to be present at many localities farther east, where it is normally buried beneath thick drift of the New Berlin and Oak Creek Formations. It has not been observed, however, in bluff exposures along the Lake Michigan shoreline.

In summary, pink Tiskilwa till was deposited by the Harvard Sublobe from the Lake Michigan basin sometime between 18 000 and 20 000 B.P. The Harvard Sublobe advanced westward to the location of the Marengo Moraine--a prominent landscape feature in northern Illinois that may be traced northward as a buried topographic high beneath deposits of a later advance.

New Berlin Formation

The New Berlin Formation was named by Schneider (Mickelson and others, 1983) for coarse-grained drift of the Delavan Sublobe of the Lake Michigan Lobe (Alden, 1904, 1918; Schneider, 1982). As previously stated, the formation consists of two principal members, a lower sand and gravel unit and an upper unit that is mostly till. Neither unit has been formally defined.

Both members of the New Berlin Formation are commonly present where the formation is at or near the surface in southeastern Wisconsin. This area includes much of Waukesha and Walworth Counties and smaller parts of Kenosha, Racine, Milwaukee, Washington, and Ozaukee Counties. Geomorphologically, the formation covers the area in and behind (northeast of) the Darien Moraine, between the Kettle Interlobate Moraine on the west and either the Valparaiso or Tinley Moraine on the east (fig. 2). It extends eastward in the subsurface to Lake Michigan, at least in some places, because it is exposed near the base of the bluff as far south as Sheridan Park in southern Milwaukee County. Whether the New Berlin Formation is present beneath thick deposits of the Oak Creek Formation in eastern Racine and eastern Kenosha Counties is not known, but it seems probable that it was at least deposited in that area.

The New Berlin Formation takes its name from the city of New Berlin in eastern Waukesha County, where the formation is well exposed in numerous gravel pits in the Waukesha drumlin field (fig. 2). Its type section, in fact, is a compound gravel pit in the heart of the drumlin field. The formation is also well exposed in road cuts and in gravel pits farther to the southwest in southern Waukesha, northwestern Racine, and Walworth Counties.

The lower (sand and gravel) unit is commonly the thicker of the two members; it ranges in thickness from 0 to about 12 m. The upper member of the formation is generally thinner, ranging up to about 10 m in thickness; in some places, however, it is only a meter or two thick. The full thickness of the formation is exposed in several gravel pits in Waukesha and Walworth Counties, where the sharp contact between the top of the Tiskilwa Member of the Zenda Formation and the base of the New Berlin Formation defines the floors of the pits.

The lower member of the New Berlin Formation is interpreted as outwash sediment deposited in front of and around the margins of the advancing Delavan Sublobe. The upper member is interpreted as basal till. Whittecar and Mickelson (1979) have postulated that both an "advance" till and a "retreat" till are present in the Waukesha drumlin field, based upon a study of internal structures in the drumlins. The formation also includes thick, coarse ice-contact stratified deposits, which reach their greatest extent adjacent to the Fox River in western Kenosha, western Racine, and eastern Walworth Counties.

The upper member of the New Berlin Formation is typically gravelly sandy loam till, averaging about 58 percent sand, 29 percent silt, and 13 percent clay in the matrix (table 1). The grain size is variable, however, and in some places the till is considerably more sandy, containing as much as 70 or 72 percent sand. In other places it is less sandy and is gravelly loam.

Oxidized till is yellowish brown (10YR 5/4 to 7.5YR 5/4 or 7.5YR 4/4) or, less commonly, brown (10 YR 5/3); unoxidized till is grayish brown (10 YR 5/2 or 2.5Y 5/2). The till everywhere, except of course where leached, is strongly calcareous and has a pH of about 8. The characteristics of New Berlin till are due to the presence of very high amounts of crushed dolomite in all size fractions. Dolomite also dominates the stone assemblage, which includes a wide variety of igneous and metamorphic rock types.

Illite is the most abundant clay mineral of New Berlin till, constituting about 66 percent of the clay-mineral complex; expandable clays and kaolinite plus chlorite are nearly equal in abundance, each accounting for 17 percent of the total, as determined by H. D. Glass of the Illinois State Geological Survey (table 1).

Till of the New Berlin Formation is readily identified, therefore, by its high and diversified pebble content, sandy texture, brown to yellowish-brown color, and high carbonate content. Where New Berlin till is thin and contains assimilated till from the underlying Tiskilwa Member of the Zenda Formation, as in and near the area of Alden's (1918) Elkhorn Moraine in Walworth County, it has a distinct pinkish cast, contains less sand, more clay and is difficult to distinguish from the Tiskilwa.

Moraine Relations

The New Berlin Formation is correlated with the Horicon Formation of the Green Bay Lobe and is also considered to equate with the Haeger Till Member of the Wedron Formation of Illinois (Willman and Frye, 1970). The Haeger till and associated sand and gravel deposits cover many square kilometers in northeastern Illinois, particularly in McHenry County, where they constitute the West Chicago Moraine. In northwestern McHenry County, 16 km south o the Wisconsin state line, the northwest-southeast-trending West Chicago Moraine climbs onto the proximal (east) side of the north-south-trending Marengo Moraine (fig. 2). The morphological relationship is clear, especially when it is tied to the lithostratigraphic evidence. The overlap of the West Chicago Moraine across the Marengo Moraine is completed a kilometer or so north of the state line, but neither the morphologic nor the stratigraphic evidence is so clear as farther south.

The terminus of the Delavan Sublobe was clearly the Darien Moraine, which trends northwest-southeast across Walworth County and which is generally conceded to be equivalent to the West Chicago (Fricke and Johnson, in press). The possibility is raised here that the two moraines may not be so related. This possibility is suggested by a reentrant along the moraine front and by a slightly different trend on opposite sides of the reentrant. This possibility is further suggested by the presence of aligned depressions southeast of Walworth, which continue the trend of the front of the Darien Moraine northwest of Walworth and which are clearly transverse to the orientation of the West Chicago Moraine immediately to the south. The low area conceivably represents an ice-marginal trough at the snout of the Delavan Sublobe.

The exact morphologic relationship of the Darien to the West Chicago Moraine is obscure because the two moraines meet in the same area as the transgression of the West Chicago Moraine across the Marengo Moraine is completed (fig. 2). Despite the fact that the West Chicago Moraine overlaps the Marengo Moraine, its north end descends into the bedrock valley of Lake Geneva (Green, 1968, p. C137). Thus, the West Chicago Moraine could, in turn, be overlapped by the Darien. If this is indeed the case, the age difference does not appear to be substantial, however.

Waukesha Drumlin Field

The Delavan Sublobe (called the Delavan lobe by Alden) probably entered southeastern Wisconsin from the Lake Michigan basin sometime between 16 000 and 14 000 years ago. The central part of the ice mass crossed the area headed about S. 45 to 50° W., as indicated by striae (Chamberlin, 1877, p. 204) and by the orientation of drumlin axes in the Waukesha drumlin field, the lobe terminated on the southwest in the northwest-southeast oriented Darien Moraine, as postulated by Alden (1904, 1918).

More than 600 drumlins and associated elongate ridges are present in the Waukesha drumlin field, which was first described and mapped by Alden (1918, p. 30; pl. 1) and which was more recently described and figured by Whittecar and Mickelson (1979). In the main part of the drumlin field in eastern and south-central Waukesha County, the features are typically 0.8 to 1.3 km long and 15 to 30 m high. Nearly all of the drumlins appear to be cored with gravel of the lower member of the New Berlin Formation.

Like those of the Green Bay Lobe and other drumlin fields, the drumlins of the Waukesha area show a radiating or fan-shaped pattern (fig. 2). Most of the features in the main part of the field are oriented between S. 40° W. and S. 60° W. North of the latitude of Waukesha, however, the trend becomes more westerly, so that in north-central Waukesha County many of the drumlins are oriented east-west. Still farther north, as in southeastern Washington County, the features assume a northwest-southeast orientation (fig. 2). It seems abundantly clear from the morphologic evidence that the Delavan Sublobe radiated to the west and northwest as it approached its terminal position along the Kettle Interlobate Moraine. Much mor field work is needed in this area and farther north, however, in order to determine and confirm the stratigraphic and areal relations of the several lithologic units known to be present between the Kettle Moraine and the western limit of red till assigned to the Ozaukee Member of the Kewaunee Formation.

To the southwest along the main flow direction, the strong linear pattern grades into weakly fluted topography, which in turn gradually deteriorates in the down-ice direction as the terminal position of the lobe is approached. Whittecar and Mickelson (1979, p. 360) have stated that the density of drumlins decreases from about six drumlins per km^2 nearly 50 km from the terminal moraine to almost no drumlins about 10 km from the moraine; they observed that it is nearly the same decrease as in the drumlin field of the adjacent Green Bay Lobe. The southwesterly flow of the Delavan Sublobe may well have been impeded by the north-south-trending Marengo Moraine, which was overridden and blanketed with grayish brown till but which contributed its pink Tiskilwa till to the basal load of the Delavan glacier.

Southern and Eastern Extent of the Delavan Sublobe

The southern and eastern limits of the Delavan Sublobe are unknown. Alden (1904, 1918) considered the southern limit of the ice to be the Genoa Moraine (fig. 2), a general east-west-trending moraine but with distinct convexity to the south, which he mapped adjacent to the state line between the junction of the Marengo and Darien Moraines on the west and the Valparaiso Moraine on the east. The Darien Moraine was continued eastward by Alden (fig. 2) from the junction as a recessional moraine a few kilometers behind the Genoa Moraine. The recessional Elkhorn Moraine was likewise continued eastward, north of the recessional Darien position. All three of these Delavan Sublobe moraines merge on the east with the Valparaiso Morainic System, according to Alden's interpretation.

Although I concur with Alden that the areas in southeastern Walworth and western Kenosha Counties mapped by him as the Genoa and Darien Moraines were covered by the Delavan Sublobe, I have been unable to identify and trace his end moraines. This entire area, including southwestern Racine County as well, is underlain almost exclusively by stratified drift and is characterized by a complex of kettle lakes, small kames, pitted outwash, ice-contact slopes, remnants of unpitted outwash surfaces, eskers, and other stagnant-ice features. In a few places the crests of northeast-southwest-oriented hills composed of New Berlin till and similar linear hills apparently made entirely of gravel rise some 5 to 15 m above their surroundings. The origin of this interesting area is not wholly clear, but it is currently interpreted as stagnation moraine. The linear features composed of till are believed to be drumlins formed by the Delavan Sublobe flowing to the southwest, but they were subsequently buried beneath supraglacial debris let down during a period of massive stagnation. This topography likely extended some unknown distance to the east and was subsequently overrun by later advances of the Lake Michigan Lobe, so that it is now largely concealed beneath fine-grained till belonging to the Oak Creek Formation.

Horicon Formation

The Horicon Formation (Mickelson and others, 1983) consists of till and associated sediment of the Green Bay Lobe, which covered much of eastern Wisconsin in late Woodfordian time. North of Lake Winnebago the formation is buried beneath red till of the Kewaunee Formation, but to the west and south of the red-till area the Horicon Formation is at the surface throughout a multi-county area that covers much of the southeastern part of the state, including the Wisconsin drumlin field. The deposits of the formation are bounded on the west and south by the Johnstown Moraine and on the east by the Kettle Interlobate Moraine (fig. 2).

Till of the Horicon Formation in southeastern Wisconsin is very similar to that of the New Berlin Formation, from which it is areally separated by deposits of the Kettle Moraine. Typically it is calcareous, yellowish-brown stony sandy loam. The matrix of the till from twenty-four drumlins in Jefferson County in the south-central part of the Green Bay Lobe average 72 percent sand, 17 percent silt, and 11 percent clay (table 1; Allan, 1967). The average gravel content of the same twenty-four samples was 27 percent. Calcium-carbonate equivalent ranged from less than 25 percent to more than 45 percent, averaging 34 percent (Allan, 1967). Till of the Green Bay Lobe (Horicon Formation) can be distinguished from till of the Lake Michigan Lobe (New Berlin Formation) presumably by its fewer Niagaran dolomite pebbles and its proportionally more abundant Ordovician dolomite clasts.

Although subunits of the Horicon Formation are formally recognized on the west side of the Green Bay Lobe in Langlade and Marathon Counties (Mapleview Member) and on the east side of the Green Bay Lobe in Door and Kewaunee Counties (Liberty Grove Member), the formation is undifferentiated in southeastern Wisconsin.

The Horicon Formation is correlated with the New Berlin Formation of the Delavan Sublobe and with the Haeger Till Member of the Wedron Formation in Illinois (Willman and Frye, 1970). Maher (1981) recently presented evidence from Devils Lake to show that retreat of the Green Bay Lobe from the Johnstown Moraine began about 12 500 years B.P. Two wood dates of 12 800 ± 220 B.P. (WIS-48; Black and Rubin, 1968, p. 104, 111) and 13 120 ± 130 B.P. (WIS-431; Black, 1976, p. 97) attest to the growth of a spruce forest in the deglaciated area of the Green Bay Lobe somewhat earlier, however.

Thus, the Horicon Formation appears to be at least 13 500 years old; it was probably deposited in southeastern Wisconsin about 14 000-15 000 years ago.

Oak Creek Formation

The coarse-grained New Berlin Formation is overlain by a much finer textured unit named by Schneider (Mickelson and others, 1983) the Oak Creek Formation. The unit takes its name from the City of Oak Creek south of Milwaukee; the type section is a Lake Michigan bluff exposure just north of the Oak Creek Power Plant in the southeastern corner of Milwaukee County.

The Oak Creek Formation includes fine-grained till, lacustrine clay, silt, and sand; and some glaciofluvial sand and gravel. The lacustrine and glaciofluvial sediments seem to be more characteristic of the formation near Lake Michigan than farther west, where the unit is predominantly till. Although its maximum thickness is unknown, bluff exposures alsong the Lake Michigan shoreline in southern Milwaukee County show that the Oak Creek Formation reaches a thickness of at least 35 m in some places.

The Oak Creek Formation occurs as the surface drift in a north-south belt that extends from the Illinois state line northward through Kenosha, Racine, Milwaukee, and eastern Waukesha Counties into Ozaukee and Washington Counties (fig. 2). The eastern boundary of the formation from the state line northward to Racine is the lacustrine plain of glacial Lake Chicago. Between Racine and Milwaukee the formation extends to Lake Michigan, and from Milwaukee northward it is overlapped by the Ozaukee Member of the Kewaunee Formation, which borders the lake in this area and farther north. The western limit of the Oak Creek Formation, at least through Kenosha, Racine, and southeastern Waukesha Counties, is the Valparaiso Moraine, whose distal margin is followed, in general, by the southward-flowing Fox River (fig. 2). North of here, in the Muskego area, the Valparaiso Moraine becomes subdued and is apparently overridden by the Tinley Moraine, which carries the Oak Creek Formation northward for another 50 km or so.

In addition to being the surface drift in the Valparaiso Moraine, the Oak Creek Formation is the principal component of the Tinley Moraine and the several ridges of the Lake Border Morainic System. It also, of course, underlies the ground moraine areas between the end moraines. East of the front of the Tinley Moraine, which Alden (1918) considered to be the outermost member of the Lake Border system, Oak Creek till is generally much thicker than farther west.

Oak Creek till everywhere is strongly calcareous and fine grained, normally containing between 80 and 95 percent silt and clay in the matrix. The texture of the till ranges from silty clay through clay loam and silty clay loam to silt loam. Most commonly, however, the deposit is either a silty clay or silty clay loam till. The average composition is about 12 percent sand, 44 percent silt, and 44 percent clay (table 1). Stones are small and not terribly abundant. Dolomite dominates the pebble assemblage, but the till contains a considerable variety of igneous and metamorphic rock types from the Canadian Shield; basalt is particularly common. The igneous and metamorphic rock assemblage is neither so rich nor so varied as in the New Berlin Formation, however. Perhaps the most diagnostic item is the presence of dark gray shale chips, which presumably were derived from the Lake Michigan basin.

Illite is the dominant clay mineral in the less-than-2-μm fraction of the till; it averages 72 percent of the clay-mineral composition. Expandable clay minerals and kaolinite plus chlorite are about equal--15 and 13 percent, respectively, according to analyses made by H. D. Glass of the Illinois State Geological Survey.

Oak Creek till normally has a 10YR hue. The color of the oxidized till nearly everywhere is brown (10YR 4/3 to 10YR 5/3), yellowish brown (10YR 5/4 to 10YR 5/6), or dark yellowish brown (10YR 4/4). In a few places it has a 7.5YR hue (7.5YR 4/4, brown). Where the till is unoxidized, it is gray (10YR 5/1).

During the several advances of the Lake Michigan Lobe that were responsible for the Oak Creek till, the ice moved out of the Lake Michigan basin with a more westerly heading than marked the advance of the Delavan Sublobe. Whereas ice of the Delavan Sublobe flowed S. 45° W. across southeastern and south-central Waukesha County, northwestern Racine County, and eastern Walworth County, later movements appear to have been almost due west. This is suggested in Kenosha and Racine Counties by the general north-south orientation of all end moraines that are made of Oak Creek till. Farther north, in Milwaukee, northeastern Waukesha, southeastern Washington, and southern Ozaukee Counties, most of these ridges show a distinctly westward bulge, but the nature of their convexity still suggests ice flow from east to west.

East-west flow of the Lake Michigan Lobe is supported by the orientation of glacial striae. At the Vulcan Materials Company new quarry on the north side of Racine, for example, striations strike about S. 80° W. At the old Horlick quarry on the Root River in Racine, now known as Quarry Lake Park, Alden (1918, p. 203) observed striae trending S. 83 to 93° W. At the old Moody quarry on the north slope of the Menomonee Valley in mid-Milwaukee, striations oriented S. 86° W. were reported by Chamberlin (1877, p. 201).

Valparaiso Moraine

Many of the concepts presented in this paper differ significantly from those presented elsewhere. Some of these differences arise from correlation and nomenclature problems; others are the obvious result of differences in interpretation from other workers and from state to state. Among these differences are the temporal and spatial relations of the Valparaiso Moraine, and it seems desirable to discuss these relations briefly at this point.

In northern Illinois as many as nine named moraines are recognized within the Valparaiso Morainic System (Willman and Frye, 1970, p. 111-113; pl. 1; Willman, 1971, p. 47, 54-55; fig. 16), although some of the moraines that may be contemporaneous are given different names in different areas (Willman, 1971, p. 47). Three of these named moraines are mapped by the Illinois State Geological Survey to the Wisconsin state line (Willman and Frye, 1970, pl. 1; Willman, 1971, fig. 16); the outermost of these is the West Chicago Moraine, and east of the West Chicago are the Cary and Fox Lake Moraines (fig. 2). Behind (east of) the Fox Lake Moraine, the Valparaiso is undifferentiated.

The relationship of the West Chicago Moraine to the Darien Moraine has already been discussed. The continuation of both the Cary and Fox Lake Moraines in Wisconsin is obscure or unrecognizable. Thus only the undifferentiated Valparaiso can be carried northward into Wisconsin with certainty. For this reason and also because the distal edge of the undifferentiated Valparaiso closely coincides with the western limit of the Oak Creek Formation, I recognize _only_ this moraine as the Valparaiso. Such recognition is in virtual accord with the nomenclature used by Alden (1904; 1918, p. 231; pl. 4). Thus, the distal edge of the Valparaiso in Wisconsin is offset from the distal edge of the Valparaiso system in Illinois by about 32 km at the state line.

My interpretation of the age relationship of the Valparaiso Moraine to the Darien Moraine is not in agreement with Alden's interpretation, however. According to Alden (1918, p. 231), the moraines of the Delavan Sublobe are ". . . the correlatives and direct continuations of the Valparaiso morainic system of southern Kenosha County"--a relationship that Alden reiterated in many statements. "It appears that the main front of the glacier continued at the broad morainal belt bordering the Fox River in Kenosha County and for some distance to the southward during the whole time of the Delavan lobe and of its melting back to eastern Waukesha County" (Alden, 1918, p. 231).

My own investigations indicate that southeastern Wisconsin was covered by the Delavan Sublobe prior to the advance of the Lake Michigan Lobe to the position of the Valparaiso Moraine and that the Valparaiso Moraine is younger than the Darien, rather than correlative with it (Schneider, 1982). These conclusions are based upon (1) the lithologic difference between the till units of the New Berlin and Oak Creek Formations, (2) stratigraphic superposition of the Oak Creek Formation above the New Berlin Formation, and (3) topographic unconformity between the northeast-southwest-oriented landforms formed by the Delavan Sublobe and the north-south orientation of the Valparaiso and younger end moraines, which truncate the obliquely trending features.

Glacial Lake Milwaukee

Wastage of the Delavan Sublobe prior to the deposition of the Oak Creek Formation was apparently accompanied by general withdrawal of the ice from eastern Wisconsin into the Lake Michigan basin. Although there is strong evidence to indicate that the duration of this withdrawal was fairly short, the distance of the withdrawal must have been substantial. The ice front probably receded to a position relatively far north in the Lake Michigan basin--at least sufficiently far to allow the formation of a sizable proglacial lake in the southern part of the basin. The existence of such a lake, here called glacial Lake Milwaukee, is inferred from the fact that when the Lake Michigan Lobe readvanced into southeastern Wisconsin and northeastern Illinois, it laid down a much finer grained deposit (Oak Creek till in Wisconsin, Wadsworth till in Illinois) than that of the underlying New Berlin Formation. Oak Creek till is not only much less stony than New Berlin till, but the matrix contains nearly 50 percent less sand and therefore a total of 50 percent more silt and clay than New Berlin till (table 1). This drastic difference in grain size can best be explained by the erosion and incorporation of fine-grained lake sediment. Scouring of the bedrock floor of the lake and assimilation of shale does not appear to be a wholly adequate explanation, though this certainly must also have occurred, as indicated by the abundance of shale chips in the till. If a proglacial lake was in fact present in the southern part of the Lake Michigan basin between the Valparaiso and Tinley advances, as postulated initially by Bretz (1951, p. 404-406; 1955, p. 107) and subsequently accepted by Hough (1958, p. 164-165; 1963, p. 90), surely a much larger lake existed immediately prior to the advance of the Lake Michigan Lobe to its Valparaiso position.

The extent and level of glacial Lake Milwaukee are unknown. No significant sequence of fine-grained lacustrine sediments between the New Berlin and Oak Creek Formations has yet been discovered to verify the existence of the lake. Nearly all of the area between the Fox River and the Lake Michigan shoreline is underlain by thick post-New Berlin till, particularly east of the distal margin of the Tinley Moraine. Thus, the stratigraphic record of Lake Milwaukee would only be seen in the subsurface, if indeed the level of the lake was sufficiently high to permit transgression very far inland beyond the modern shoreline. This possibility seems very unlikely, inasmuch as the highest known subsequent stages in the southern part of the lake basin (Glenwood I and Glenwood II) attained levels only 18 m higher than the present lake. The stratigraphic record of Lake Milwaukee, therefore, may be present only in the lake basin proper, and most of that record could well have been removed by the deep scouring of the basin that is attested by the abundance of shale in the Oak Creek till. Thus, it is unlikely that the extent of glacial Lake Milwaukee can be accurately determined. It does seem probable, however, that all or much of the southern Lake Michigan basin was occupied by the lake, in order to account for the high percentage of fine-grained materials in the tills that comprise much of the Valparaiso, Tinley, and Lake Border Moraines, which enclose the south end of the lake basin in southeastern Wisconsin, northeastern Illinois, and northwestern Indiana.

Valparaiso and Tinley Advances

Despite its apparent size, Lake Milwaukee appears to have had a relatively short life, because stagnant masses of the Delavan Sublobe had not completely melted before being overrun during the earliest advance of the Lake Michigan Lobe to deposit fine-grained till of the Oak Creek Formation. The ice pushed westward to the longitude of the Fox River, where it terminated at the Valparaiso Moraine on the east side of the Fox River valley in Kenosha, Racine, and southeastern Waukesha Counties (fig. 2). Except for part of southern Kenosha County, however, Oak Creek till in and behind the Valparaiso Moraine is relatively thin. Much of the relief within the moraine reflects an older stagnation topography, presumably related to the Delavan Sublobe, that is veneered with a thin, irregular blanket of Oak Creek till. Kames and similar topographic elements composed of ice-contact stratified drift are responsible for much of the relief of the moraine.

From its Valparaiso terminus the ice either backwasted to the Tinley Moraine or retreated some unknown distance and then readvanced to the Tinley position (fig. 2). Morphologic evidence and limited data on grain-size distribution strongly suggest that retreat and readvance is the more likely possibility. The greater thickness of Oak Creek till east of the Tinley margin has already been mentioned. Palimpsest landforms such as those in the Valparaiso belt are absent east of the Tinley front, and windows of pre-Oak Creek drift are unknown.

The most visible expression of the differential thickness of the Oak Creek Formation east and west of the Tinley front can be seen in the ditribution of ice-block depressions. From the Tinley Moraine eastward to the Lake Michigan shoreline, in a belt 19 to 25 km wide through eastern Kenosha, eastern Racine, and Milwaukee Counties, not a single natural lake marks the landscape. West of the Tinley front, by contrast, the topography is characterized by numerous kettle lakes. About 30 named lakes of moderate to large size occur in a belt that extends from the Illinois state line northward through western Kenosha and western Racine Counties into southeastern Waukesha County; there the lakes terminate in the Muskego area, where the Valparaiso Moraine is subdued and overlapped by the Tinley front. Even a casual examination of a state highway map reveals the approximate boundary between the lake belt to the west and the lake-deficient zone on the east. U.S. Highway 45 roughly parallels the distal edge of the Tinley Moraine; in some places the road and the morainic front are nearly coincident, in other places the highway is about 3 km east of the front. Only a single lake is present east of the highway, and this occurs between the moraine and the highway, where the latter is west of the distal margin.

While it is true that many of these lakes are in the Valparaiso Moraine, many ocur west of the moraine in association with pitted outwash and stagnant-ice features. Thus it appears that their occurrence within the Valparaiso Moraine is related to the kames and other stagnation features that predate the deposition of Oak Creek till. I conclude, therefore, that although the eastern edge of the lake belt is clearly limited by the distribution of thick Oak Creek till in the Tinley Moraine, the western extent is totally unrelated to the western edge of the Oak Creek till sheet.

In summary, then, a large area of stagnant ice of the Delavan Sublobe was overrun from the east by the Lake Michigan Lobe, which was carrying a rich subglacial (and englacial?) load of fine-grained lacustrine sediment derived from glacial Lake Milwaukee. The ice pushed westward to the Valparaiso Moraine, but in doing so it left only a thin blanket of basal Oak Creek till--perhaps because the ice was thin or perhaps because the time of deposition was short, as suggested by Willman (1971, p. 55). In any event, the thickness of the deposit was insufficient in most places to alter significantly the general character of the landscape. The ice front then withdrew an unknown distance to the east, perhaps into the lake basin, and then readvanced to its Tinley Moraine position. During this readvance, however, a much thicker layer of basal Oak Creek till was laid down, sufficiently thick to bury and obscure the stagnant-ice topography beneath. Only that part of the older terrain west of the Tinley front was thus preserved for the geomorphic record.

Retreat and readvance of the Lake Michigan Lobe to the Tinley Moraine--rather than simple recession of the ice front to that position--is supported by preliminary grain-size studies, which indicate that till of the Tinley advance is finer grained than that of the Valparaiso. Samples of Oak Creek till from the Tinley Moraine contain, on the average, about 8 percent less sand and 14 percent more clay than Valparaiso samples. The lower clay content of the Valparaiso facies is partially compensated by a higher silt content, however, so that total silt and clay in the Tinley samples averages only 8 percent greater than in the Valparaiso. Nevertheless, the ratio of silt and clay to sand in till of the Tinley Moraine (12 to 1) is more than twice that in the till of the Valparaiso advance (5.5 to 1). Only three of the 21 samples of presumed Tinley till that were analyzed contained less than 90 percent total silt and clay; two of these samples were collected at the edge of the Tinley Moraine, and the value for the third sample was 89 percent. Only two of 25 samples of Valparaiso till analyzed contained more than 90 percent silt and clay, although many values were in the mid to high 80s.

Although it has been stated (Hough, 1963, p. 90) that Tinley till contains a higher percentage of silt and clay than the Valparaiso due to the incorporation of lake deposits from Early Lake Chicago, an actual difference in grain-size distribution has never been demonstrated. Deposits in the two moraines have been considered to be indistinguishable, both in northeastern Illinois (Bretz, 1955, p. 81) and northwestern Indiana (Schneider, 1968, p. 275), as well as in Wisconsin. "To the eye and hand, the Valparaiso till is indistinguishable from the Tinley," Bretz stated, but added "it is possible that mechanical analyses may someday show differences between the two . . ."

Whether the finer texture of the Tinley facies described above can be attributed to the assimilation of additional fine-grained lacustrine sediments from the Lake Michigan basin (Early Lake Chicago?) is unknown. The Valparaiso facies may simply be more sandy due to the incorporation of sand from the underlying New Berlin Formation. In either case or in both, however, the difference in grain size argues for a distinct retreat of the ice following its Valparaiso phase and a subsequent readvance to the Tinley position. Hopefully, this difference can be substantiated by additional analytical data.

Lake Border Advances

Evidence for subsequent activity of the Lake Michigan Lobe that resulted in the deposition of Oak Creek till is not so convincing and therefore will be only briefly outlined in this paper. At least five (post-Tinley) moraines of the Lake Border Morainic System can be recognized in southeastern Wisconsin, but all are not present in a given area. The general features of the Lake Border system were well described by Alden (1918, p. 301), who stated that "although, in large part, these ridges are clearly marked and are distinctly separated, so as to give the peculiar north-south trend to the drainage lines, they are cut through at intervals by streams, and in some places contiguous ridges coalesce, so that there may be differences of opinion as to their exact correlation." Correlation of these ridges with the five named moraines of the Lake Border system in Illinois (Park Ridge, Deerfield, Blodgett, Highland Park, and Zion City) is indeed virtually impossible except for the Highland Park Moraine, which can be traced across the state line.

The number of actual readvances of the ice represented by these five recessional moraines is unknown, but it appears probable that there were at least two. The first is represented by the outermost moraine of the system, which is bordered on the west by a distinct ice-marginal trough floored with outwash sand and gravel. In some places the trough is ditched; in other places it is partially used by underfit natural streams, including segments of the Root and Des Plaines Rivers (fig. 2). The second moraine that appears to represent a distinct retreat and readvance is informally called the Petrifying Springs moraine, which in Kenosha, Racine, and southeastern Milwaukee Counties is the innermost ridge of the Lake Border system (fig. 2). Farther north, in the City of Milwaukee, at least one additional (younger) moraine is present. The Petrifying Springs moraine has the greatest relief and is the most distincve moraine of the system. It correlates with the Highland Park Moraine of northern Illinois.

Analyses of five Oak Creek samples from the outermost Lake Border moraine suggest that the texture of the matrix of the till is similar to the Tinley facies. Analyses of a larger number of samples (17) from the Petrifying Springs moraine south of Milwaukee suggest that the till in this ridge is somewhat coarser grained than that of the Tinley and Lake Border phases, but not so coarse as that of the Valparaiso. The statistical validity of these data has not been tested, and thus it is recognized that these statements of possible differences may be unwarranted.

For a more thorough discussion of the texture and clay mineralogy of the Oak Creek till and its Illinois equivalent (Wadsworth Till Member of the Wedron Formation), the reader is referred to a companion paper in this volume by Hansel (1983).

Kewaunee Formation

Ozaukee Member

Stratigraphically above the Oak Creek Formation is the Ozaukee Member of the Kewaunee Formation (Mickelson and others, 1983). The Ozaukee is one of the eastern Wisconsin red clay tills that were formerly mapped as a single unit called the "Valders till" (Thwaites, 1943; Thwaites and Bertrand, 1957); the Valders till has recently been subdivided into many stratigraphic units based on lithologic characteristics and stratigraphic relations (Evenson, 1973; Mickelson and Evenson, 1975; Acomb and others, 1982; McCartney and Mickelson, 1982; Mickelson and others, 1983).

The Ozaukee is the southernmost and oldest of the late Wisconsinan red clayey tills of the Lake Michigan Lobe, having been deposited about 12 500 to 13 000 years ago. Because of lithologic similarity and because it overlies the Oak Creek Formation, the Ozaukee Member probably correlates with the Shorewood Till Member of the Wedron Formation, which was named and mapped from core samples under Lake Michigan by Lineback and others (1974). The correlation of lake-bottom tills with onshore tills remains somewhat uncertain, despite the acquisition of considerable data on deposits from both environments (Lineback and others, 1974; Acomb, 1978; Acomb and others, 1982; Hansel, 1983).

The Ozaukee Member occurs at the top of the Lake Michigan bluff in a belt that extends from the City of Milwaukee northward through Milwaukee and Ozaukee Counties to about the Sheboygan County line (fig. 2). It extends inland from the lakeshore to Alden's (1918) red-till boundary, which roughly parallels the ice-marginal Milwaukee River. Distinctive end-moraine topography marks the western limit of the unit in some places.

Till of the Ozaukee Member is easily distinguished from all other tills in southeastern Wisconsin by the combination of its fine-grained texture and its reddish color. The till is typically silty clay or silty clay loam; grain-size analyses of the till matrix indicate average composition of 13 percent sand, 47 percent silt, and 40 percent clay (table 1; Acomb and others, 1982). In terms of its mechanical composition, therefore, Ozaukee till is similar to Oak Creek till (table 1), particularly to the Valparaiso facies of Oak Creek till. Its reddish brown (5YR 4/3) to light reddish brown (5YR 6/3) color, however, serves to distinguish it from the yellowish-brown to brown Oak Creek till.

X-ray analyses (Acomb and others, 1982, p. 292-293) indicate that approximately 60 percent of the clay-mineral fraction is illite; the expandable clay minerals and kaolinite plus chlorite both average about 20 percent (table 1). The high illite content is believed to be an important parameter in distinguishing the Ozaukee Member from other members of the Kewaunee Formation farther north (Mickelson and others, 1983), but based on a limited number of analyses of my own samples by H. D. Glass 60 percent illite appears to be somewhat high for average Ozaukee till.

Peoria Loess

In addition to the five rock-stratigraphic units of the Woodfordian Substage described above, deposits of Peoria loess are also present in southeastern Wisconsin (fig. 1). Behind the Woodfordian ice boundary, the loess is relatively thin and difficult to identify. Where present, it is typically between 0.3 and 0.6 m thick, and thus it does not normally extend below the bottom of the solum.

Beyond the Woodfordian moraines, as in southwestern Walworth County and farther west where Peoria loess overlies older tills of the Altonian Substage, the loess blanket is considerably thicker. On many upland surfaces it is typically 1.2 to 1.5 m thick, and in some places it is undoubtedly thicker. Its maximum thickness, which is probably on the east side of the Rock River valley train, has not been determined.

The Peoria loess is not recognized as a formal rock-stratigraphic unit in Wisconsin at this time. Although the bulk of the deposit is considered to be Woodfordian in age, some is no doubt younger, as in Illinois (Willman and Frye, p. 61, fig. 8; p. 65-66).

Lacustrine Deposits

Whereas the Ozaukee Member overlies the Oak Creek Formation along the Lake Michigan shoreline north of Milwaukee, south of Milwaukee the Oak Creek Formation is overlain by various lacustrine and some eolian deposits that range in age from very late Woodfordian to Holocene (fig. 1). The lacustrine sediments include deeper water silt and clay--consisting of both massive and rhythmic deposits, and shallow water or beach sand and gravel. Some of these sediments were deposited in and around glacial Lake Chicago about 12 500 to 10 000 years ago. Younger lake sediments associated with the Algonquin, Nipissing, and Algoma stages are also present, as well as modern shoreline deposits. (Schneider, Edil, and Haas, 1977a,b; Schneider, Sander, and Larsen, 1979).

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A BURIED SANGAMON SOIL IN SOUTHEASTERN WISCONSIN

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ABSTRACT

A truncated paleosol believed to have formed during the Sangamonian Age is well exposed in the highwall of a gravel pit near East Troy in northeastern Walworth County, Wisconsin. If our interpretation is correct, this paper reports the first positive identification of a buried Sangamon Soil in the area of late Wisconsinan glaciation in the State of Wisconsin.

The soil is formed in the upper part of a thick sand and gravel outwash unit and is overlain by calcareous pink loam till that is considered to be the Tiskilwa till of northeast Illinois and southeast Wisconsin. The main horizon of the paleosol is interpreted as the Bt horizon of a well-drained Alfisol (Gray-Brown Podzolic) belonging to the suborder of Udalfs. It is a dark reddish-brown, highly argillic, severely weathered zone in which many of the clasts are in an advanced state of decomposition. In several places the soil has large vertical pendants that hang below the usual base of the soil by as much as a meter. A detailed soil profile description, which includes laboratory data on grain-size distribution and clay-mineral composition, through one such pendant is presented to substantiate our interpretation of the weathered zone as the Sangamon Site.

When the site was first examined a decade ago, the upper part of the paleosol appeared to be developed in two parent materials, the outwash and an overlying thin finer grained deposit interpreted as (Illinoian) till. A thin bed of light yellowish-brown silt, possibly loess of Altonian age, was observed between this older till and the Tiskilwa till above. The upper few centimeters of the silt were darker in color and suggestive of an incipient paleosol (Farmdale?). Enlargement of the pit during the past few years has resulted in removal of the apparently wedge-shaped intermediate units, so that today Tiskilwa till is seen resting directly on the paleosol developed in the outwash.

Near the center of the pit wall the Sangamon Soil reaches the modern surface, and both the soil and overlying Tiskilwa till are absent in the south part of the pit. Here the outwash is overlain by younger sandy-loan till belonging to the New Berlin Formation (equivalent to the Haeger Till Member of Illinois terminology). The contact zone involving the three units is unusual and creates a local stratigraphic problem because the till units abut against each other and New Berlin till actually underlies the Sangamon Soil for a short distance. The relationship is interpreted to be the result of deformation that occurred during deposition of the New Berlin till.

INTRODUCTION

In Walworth County, about 1.5 km southwest of East Troy, the remains of a buried soil are exposed under till in the west-facing high wall of a gravel pit under a continuous deposit of till. The pit is located in the NW corner of Sec. 31, T. 4 N., R. 18 E., just northeast of the overpass on Wisconsin Highway 15 over Townline Road in the town of Spring Prairie. The pit is operated intermittently by B. R. Amon and Sons of Bowers.

The prominent feature of the paleosol is a weathered and oxidized, clay-enriched (argillic Bt) horizon developed in an outwash of cobbly sand and gravel. The soil was truncated and disturbed by overriding glaciers that deposited at least two younger tills. Based on soil characteristics and stratigraphic position, we conclude that this paleosol is the Sangamon Soil.

Buried or relict soil profiles of possible Sangamonian age have been reported from several localities in Wisconsin beyond the late Wisconsinan glacial boundary, mostly in the Driftless Area; the interpretations of most of these sites have been challenged. To our knowledge, the Sangamon Soil has not previously been identified from any site behind the Late Wisconsinan (Woodfordian) boundary. Therefore, if our interpretation of the East Troy site is correct, this paper reports the first identification of the Sangamon Soil in the area of Late Wisconsinan glaciation in tbe State of Wisconsin.

The site was first visited by Schneider in 1972. It was independently discovered, probably in 1973, by David W. Hadley, formerly with the Wisconsin Geological and Natural History Survey. Similar interpretations of the geology were made by Schneider and Hadley, who subsequently examined the site together in 1975. Periodic visits to the site were made by Schneider with his classes between 1975 and 1980. Schneider, Follmer, and Ardith Hansel of the Illinois State Geological Survey studied the site in 1982.

STRATIGRAPHY

The soil is overlain by 1 to 6 m of pink calcareous loam till that is believed to belong to the Tiskilwa Member (Early Woodfordian). The Tiskilwa Member is the upper part of the Zenda Formation in the new Pleistocene lithostratigraphic classification in Wisconsin (Mickelson and others, 1983) and correlates with the Tiskilwa Till Member of the Wedron Formation in Illinois (Willman and Frye, 1970). The pinkish gray to brown color of the till, the grain-size distribution of the matrix (45 percent sand, 34 percent silt, 21 percent clay),* and the clay-mineral composition (24 percent expandable clay, 64 percent illite, 12 percent kaolinite plus chlorite) are typical of Tiskilwa till in southeastern Wisconsin. The till is now known to occur at or near the surface throughout much of central and eastern Walworth County, especially in a belt 11 to 18 km wide from the Illinois state line northward to the Kettle Interlobate Moraine (Schneider, 1983). It has been observed at many sites near the East Troy pit and was well exposed southwest of the pit a few years ago during construction of new Wisconsin Highway 15.

The soil is formed in the upper part of a thick unit of well-stratified outwash sand and gravel with many cobbles in the upper part. The thickness of the outwash exposed in the pit face is estimated to be about 15 m.

* Grain-size boundaries used in this paper are 2 mm, 0.0625 mm, 0.004 mm and percentages are based on the less-than-2 mm fraction. Clay mineral identifications were made by H. D. Glass from X-ray diffraction data using oriented aggregate techniques on the less-than-0.002 mm material.

A power-auger hole (Wisconsin Geological and Natural History Survey Boring ET-2) was drilled below the floor of the pit to a depth of more than 22 m without encountering bedrock; the deposits consisted mostly of well-sorted sand with some interbedded gravel layers. Some workers have suggested that the outwash here was deposited near the axis of the preglacial Troy Valley, but from a recent bedrock topography map prepared by Green (1968, fig. 2), it appears that the site more likely is near the break in slope between the upland surface and the valley wall of a tributary to the main Troy Valley.

Little information is available to judge the age of the outwash. Beyond the outer margin of the overlying till, the surficial deposits are mapped as Early Wisconsinan (Frye, Willman, and Black, 1965) or Illinoian (Alden, 1918). Outwash deposits older than Wisconsinan were recognized by Borman (1977) in Walworth County, but he did not identify any stratigraphic units. South of Walworth County in Boone County, Illinois, Berg, Kempton, and Stecyk (1981) described an Illinoian outwash that could be related to this site, but the correlations at this time are circumstantial. The highest level terrace mapped by Anderson (1967) along the Rock River near Rockford is likely related to this site. This terrace is covered by Wisconsinan loess and contains about one meter of highly weathered, reddish brown gravel over about 6 m of unweathered gravel. We conclude that the terrace described by Anderson is Illinoian and was weathered during the Sangamonian. Therefore, considering the regional stratigraphic relations, the East Troy outwash is assigned to the Illinoian Stage.

DESCRIPTION AND INTERPRETATION OF THE PALEOSOL

At times during pit operations, the soil has been continuously exposed for a lateral distance of about 50 m. It appears as a leached dark reddish-brown horizontal layer about 1 m thick. The main body of the soil is a weathered, clayey Bt horizon developed in cobbly sandy gravel. The Bt is dark reddish brown and strongly contrasts with the yellowish-brown gravel below and the pinkish-brown till above. In places the soil has large vertical pendants, whose tapered ends extend below the usual base of the soil by as much as a meter (fig. 1). The top of the soil is truncated at all places observed in 1982, which suggests either proglacial fluvial scour or the direct effects of the overriding glacier. Small-scale shear is evident in places where paleosolic material (Bt) has been sheared or injected into the overlying calcareous till. The displaced material commonly pinches out along a thrust plane and appears now as a low-angle joint. In other places the paleosolic material appears interstratified with the till in a contact zone up to 1 m thick.

A soil profile with the largest pendant exposed in 1982 in the northern part of the pit was selected for study. The major features are sketched on figure 1. An attempt to discriminate pedologic boundaries from geologic boundaries was made because they are commonly confused. Commonly a stratigraphic boundary predetermines the position of a pedologic boundary, but in other cases the boundaries are independent of each other. The main pedologic boundary in the soil here is the base of the Bt horizon, shown as a heavy line on figure 1. An excellent example of cross-cutting relationships is illustrated by the layer of fine gravel. This layer passes through the pendant. Near the middle of the pendant the layer sags about 5 cm, which is evidence for solution collapse.

The Bt is a zone of excessive accumulation of reddish-brown clay with accessory features such as preponderant diffuse iron stains and discrete manganese stains. Selected details are described in table 1. So much clay has accumulated in the Bt that the sand,

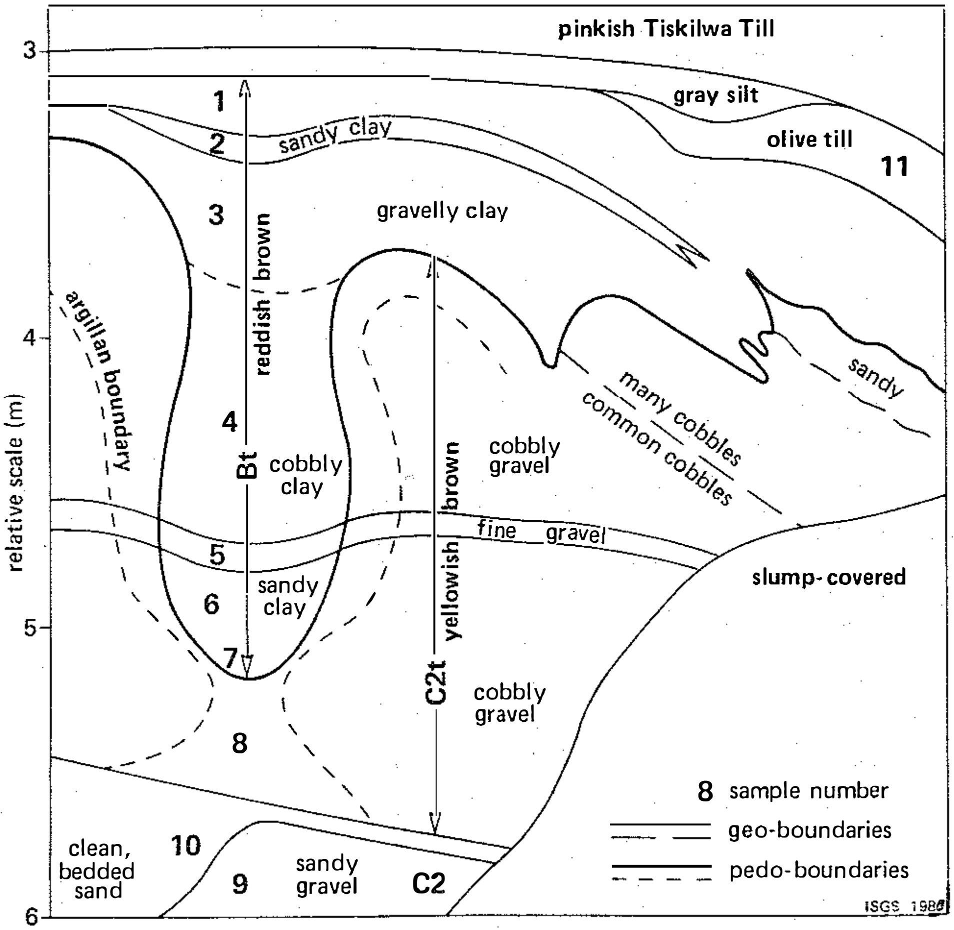

FIGURE 1.--Sketch of part of high wall of pit showing major features of buried soil.

gravel, and cobbles are totally enveloped in layers and masses of translocated clay (argillans). During formation, pedoturbation and desiccation cracking continually opened up avenues for continued soil-water movement and clay accumulation.

Surrounding the pendant is a diffuse zone of localized clay enrichment that dissipates laterally away from the pendant into the calcareous gravel (C2t). The outer margin of this zone is shown on figure 1 with a short dashed line. This zone appears to be constricted near the base of the pendant, but below it appears to fan out. The outer margin is very difficult to determine because of the discontinuous nature of the clay accumulation, which seems to occur in a random pattern of enrichment. However, this penomenon is clearly related to the Bt development because it is adjacent to the Bt horizon and disappears with depth.

At the contact with the clean bedded sand, the argillans abruptly stop and clay-free iron stains continue into the upper few centimeters. Below and to the left on figure 1 the sand is clean and gray (gleyed). Argillans reappear in the sandy gravel at the base as though they went around the clean sand. The circumstances suggest that the sand formed a hydraulic discontinuity and remained wetter than the surrounding gravel. The staining and argillan patterns indicate a direction of soil-water movement. Funneling may have occurred in the upper Bt. Leaching water appears to break broken through the Bt boundary and fanned out below the pendant.

Table 1. Sangamon Soil profile description at East Troy Gravel Pit

Geologic Unit	Sample no.	Horizon	Depth (cm)	Description
Tiskilwa till	-	C2	0-290+	7.5YR 5/4 loam; few stains, jointed; few secondary carbonates; dolomitic.
silt	-	C1g	290-300	5Y 5/2 silt loam; few iron stains, pinches out to right above Sample 11.
till	11	C1g	300-340	2.5Y 5/4 loam with common 5/6 mottles; stratified in places with layers of Bt material; leached; basal deformation zone of meltout till(?).
Outwash	1	Bt1	300-340	7YR 5/6 gravelly sandy clay loam; common red and dark stains; weakly cemented, traces secondary carbonates along joints; leached; eroded upper surface.
"	2	Bt2	340-350	7YR 5/8 loamy sand lense; uniform.
"	3	Bt3	350-410	6YR 4/4 to 5/6 gravelly sandy clay loam; few 2.5YR 3/4 and 2/1 stains; many argillans; many rotten igneous and sedimentary cobbles; traces of carbonates.
"	4	Bt4	410-450	5YR 3/3 gravelly clay, many thick masses of argillans, some slickensided; some large areas of manganese staining; many rotten rocks 1 to 10 cm in diameter; traces of carbonates.
"	5	Bt5	450-460	5YR 3/3 gravelly sandy clay lense; coarse fraction better sorted than adjacent horizons; sags about 5 cm in middle of pendant, leached.
"	6	Bt6	460-490	5YR 3/3 gravelly sandy clay loam; poorly sorted; fewer cobbles, nearly all hard; leached.
"	7	Bt7	490-510	5YR 3/3 to 4/4 gravelly sandy loam; more color and textural variation; friable; a decrease in argillans and stains cause a color boundary at base where uncoated coarse fragments dominate color appearance; base of beta horizon pendant.
"	8	C2t	510-550	Yellow, gray and brown gravelly sandy loam; partly weathered gravel dominated by carbonates, many soft; weakly cemented; common 5YR 4/4 argillans around pendant that decrease away to form a discontinuous boundary with clean bedded sand lense; argillans reappear in sandy gravel at base of exposure.
"	9	"	550-580	
"	10	"	540-580	

Comments:

1. This profile contains the main part of a truncated Sangamon Soil that has the morphology of a Fox-like soil with an overdeveloped Bt pendant. Classification: best fit is Typic Paleudalf.

2. Bt horizons 3 to 6 in the exposure are very hard and coarsely crazed by desiccation. Natural soil structures are confounded with exposure-induced cracking. Iron staining is essentially continuous, but redder in places, and dominates matrix color. Argillans appear to diffuse away from the pendant.

3. Sampled from the northwest wall of a gravel pit in the northwest corner of Sec. 31, T. 4 N., R. 18 E., Walworth County.

Table 2. Particle size and clay mineral data of Sangamon Soil profile at East Troy Gravel Pit

Sample Number	Horizon	Depth (cm)	Sand[1] (%)	Silt[1] (%)	Clay[1] (%)	Exp[2] (%)	I[3] (%)	K + C[4] (%)
11	C2g	300-340	54	28	18	38	45	17
1	Bt1	300-340	56	15	29	29	52	19
2	Bt2	340-350	84	2	14	--	--	--
3	Bt3	350-410	64	7	29	--	--	--
4	Bt4	410-450	23	29	48	--	--	--
5	Bt5	450-460	52	10	38	28	58	14
6	Bt6	460-490	55	8	37	26	54	20
7	Bt7	490-510	76	3	21	--	--	--
8	C2t	510-550	64	16	20	26	57	17
9	C2t	550-580	70	18	12	32	49	18
10	C2g	540-580	--	--	--	16	66	18

1. Weight percent of less than 2 μm fraction; sand - 2.0 to 0.62 mm, silt - 0.62 to 0.002 mm, clay - less than 0.002 mm.

2. Exp - expandable clay minerals (17Å, glycolated).

3. I - illite (mica, 10Å).

4. K + C - kaolinite and chlorite (7Å).

Other geologic boundaries in the profile control or at least are coincident with weathering boundaries. The material below the Bt horizon is yellowish-brown, calcareous cobbly gravel. Most parts seem to contain about 50 percent limestone and dolomite cobbles. This zone, which shows some alteration, some argillans, and yet contains primary carbonate minerals is designated a C2t horizon. Many cobbles up to 10 cm in diameter are in the C2t and seem to disappear in the pendant. Near the middle of figure 1, above the final gravel lens, the amount and orientation of the cobbles delineate a subtle boundary. More cobbles are present above the boundary which represents a change in the depositional environment. Weathering and clay accumulation follow this geologic boundary to the left of and above the small pendant, but depart at the pendant where the Bt boundary cuts up across the "many cobbles" layer. A more sandy layer occurs stratigraphically above and to the right and appears to be detached from the "sandy clay" layer in the Bt. This suggests early detachment, perhaps by slump, during parent-material formation, followed by the development of the soil.

At the sampling location, the soil is abruptly truncated by a gray silt. No interstratification is present but the silt pinches out to the right above olive-brown loam till that is interstratified with Bt material. The till seems to be related to the overlying Tiskilwa till, as if it is a basal deformation zone of the Tiskilwa. However, the silt is not deformed and appears to be a fluvial deposit on an erosion surface. A possibility is that the olive till was deposited by an early advance of the ice, then exposed to glaciofluvial erosion during a minor retreat of the glacier. Then, the main body of Tiskilwa till was deposited during a subsequent advance.

CLASSIFICATION OF THE PALEOSOL

The best modern soil analogs of this buried soil are the deep phases of the Fox and Ockley Series, which are both Alfisols. At present, Fox is defined as having a solum (A and B) thickness of less than 1 m, and Ockley has a solum thickness up to 1.5 m. To classify a paleosol according to modern soil taxonomy is difficult because the actual climatic and chemical parameters during formation must be estimated. Considering the morphological expression alone, this soil can be considered a Udalf or in older soil classification terms, it is similar to a reddish, clayey Gray-Brown Podzolic of the Midwest or a minimal Red-Yellow Podzolic of the Tennessee region.

Particle-size distribution and clay-mineral data (table 2) were determined on samples collected through the pendant as shown on figure 1 in order to aid our attempts to classify the soil. Although the presence or absence of pendants is secondary in the classification of soils of this type, we think that this large pendant is the most interesting part of the soil-stratigraphic unit exposed in the pit wall.

The lack of an A horizon presents an obstacle, so we attempted to reconstruct the nature of the original soil. In doing this, the B horizon provides the clues--features that are dependent on A-B horizon relationships. All of the subdivisions of the Bt horizon contain evidence of illuviation, (thick continuous clay skins or argillans). The variation in sand, silt and clay contents reflects the original stratification of the outwash. The clay of the upper Bt is similar to the Fox and Ockley series, but the large size of the pendant suggests development that is greater than what is considered to be normal for these soil series. Many cobbles up to about 10 cm in diameter in the Bt are in an advanced stage of decomposition and can be cut with a knife. Most of the cobbles are igneous and sedimentary (silty) types that also might have contributed to the clay content upon weathering, but the in-situ clay could not be identified because of the large amount of argillans.

The large amount of illuvial clay suggests that this soil belongs to the Alfisol Order, although Mollisol and Ultisol options are possible. The dark color of the argillans suggests that the original epipedon was rich in humus, as in a Mollisol, but the color of the lower half of the Bt closely matches the type concept of the Ockley Series, a Typic Hapludalf. A forest or grassland origin is not interpretable from the morphology, but other parameters, not measured in this study, such as the composition of the contained humic acids, could theoretically be used to differentiate the dominant sources of the humic material.

The large size of the pendant suggests the more intense or longer weathering conceptually associated with Ultisols rather than Alfisols. However, the clay-mineral data indicate that substantial amounts of illite are still present. One of the requirements of an Ultisol is that less than 10 percent of the weatherable minerals remain in the 20 to 200 µm fraction of the Bt horizon (Soil Survey Staff, 1975). Because the illite was determined from the less-than-2 µ fraction, even less weathering would be expected in the coarser fractions. Therefore, the type of weathering indicated by the clay mineral data places this soil into the range of Alfisols. Samples with no clay mineral results presented in table 2 were analyzed, but clay-mineral species were not resolved by the no-pretreatment method employed. This appears to be caused by the abundant iron, which interferes with the x-ray diffraction method for measuring clay minerals. The method used by the Illinois State Geological Survey is one that is routinely employed for distinguishing stratigraphic boundaries and the correlation of material units. In view of this constraint, the unresolved x-ray diffraction peaks indicate a moderately to strongly weathered, oxidized material.

Considering all available information, the best fit classification for the profile is a Typic Paleudalf. A Paleudalf is distinguished from a Hapludalf mainly on the basis of clay distribution. A Paleudalf as described by the Soil Survey Staff (1975) must meet the requirement that the clay content does not decrease from the maximum by more than 20 percent within a depth of 1.5 m below the soil surface. A Udalf that decreases in clay content, more than that is a Hapludalf. At the other locations where the Bt is about a meter thick, a Hapludalf classification seems best in spite of the redness which favors the Paleudalf interpretation.

In reconstruction of the probable A and E horizons, it would be expected to be sandy because its parent material was probably outwash. Modern equivalents of Paleudalfs that have been described (Soil Survey Staff, 1975) on sandy parent material on the coastal plains in Texas have sandy epipedons that are about 1 m thick. Where the epipedon is sandy (loamy sand) the profile is classified as an Arenic Paleudalf. If our pendant profile here had less sand in the epipedon, it would remain in the taxon of a Typic Paleudalf. However, one must rememeber that this is a borrowed classification from a system for living soils. The soil features described here are the remains of a fossil soil.

LOCAL STRATIGRAPHIC CORRELATION PROBLEMS

The Sangamon Soil rises southward from the described profile (fig. 1) and reaches the ground surface near the center of the pit wall (fig. 2). Both the soil and the overlying Tiskilwa till are absent in the southern part of the pit, and they terminate in a way that creates a local stratigraphic problem. Beyond the termination, the gravel is overlain by calcareous yellowish-brown pebbly sandy loam till of the New Berlin Formation (Mickelson and others, 1983). The New Berlin till was deposited by the Delavan Sublobe of the Lake Michigan Lobe (Alden, 1904, 1918; Schneider, 1982) in Late Woodfordian time. It is the surface till in the immediate area of the East Troy pit and throughout much of southeast Wisconsin, mostly in Walworth and Waukesha Counties. It also covers parts of Kenosha, Racine, Milwaukee, Washington, and Ozaukee Counties. New Berlin till is found behind (northeast of) the Darien Moraine and between the Kettle Interlobate Moraine on the west and the Valparaiso Moraine or its equivalent on the east. The New Berlin till is about equivalent to the Haeger Till Member of the Wedron Formation in Illinois (Willman and Frye, 1970).

The New Berlin till is distinguished from the Tiskilwa till by its lighter and yellowish-brown color, greater stone content, and coarser matrix. Results of particle-size analyses of three samples of New Berlin till from the East Troy pit average 62 percent sand, 27 percent silt, and 11 percent clay. Results of clay-mineral analyses of five samples of New Berlin till from the East Troy pit average 20 percent expandable clay minerals, 66 percent illite, and 14 percent kaolinite plus chlorite.

Near the center of the pit wall the two tills are in contact with each other in an unusual way (fig. 2). The stratigraphic relationships between the tills and between the New Berlin till and the paleosol are unclear. The tills abut against each other, and the New Berlin till underlies the paleosol for a distance of about 1 m. The age relationship of the Tiskilwa till and the New Berlin till is well established by regional relations and by many stratigraphic sections that show the New Berlin Formation ovelying the Tiskilwa Member of the Zenda Formation. Thus, there is no question about the relative age of the tills, although the relationship cannot be demonstrated in the East Troy pit. We interpret the relationship seen here as the result of deformation produced by the bulldozing action of the ice that deposited the New Berlin till. Although the mechanics are not understood, the snout of the advancing ice apparently shoved and lifted the inclined part of the Sangamon Soil and overlying Tiskilwa till and injected a mass of basal New Berlin till into and below the paleosol (fig. 2). In that part of the pit south of the contact zone, the Sangamon Soil and Tiskilwa till were completely eroded before basal New Berlin till was plastered on top of the outwash sequence. Less than a kilometer to the south, however, 5 m (exposed) of Tiskilwa till is overlain sharply by 3 m of New Berlin sand and gravel.

When this site was examined in 1972 and 1975, additional stratigraphic units were present between the paleosol and the overlying pink till. The latter was observed to overlie a thin bed of light yellow calcareous silt (loess?), the upper few centimeters of which were darker in color and suggestive of a faint A1 horizon of an incipient paleosol (Farmdale?). Although Altonian loess has not been previously identified in southeastern Wisconsin, the silt is possibly equivalent to the Roxana Silt of Illinois (Frye and Willman, 1960; Willman and Frye, 1970).

The silt either rested upon a stone line (Schneider's interpretation) or contained a concentration of cobbles at its base (Hadley's interpretation). In either case, this stone concentration marked the top of the paleosol. The upper part of the paleosol, although

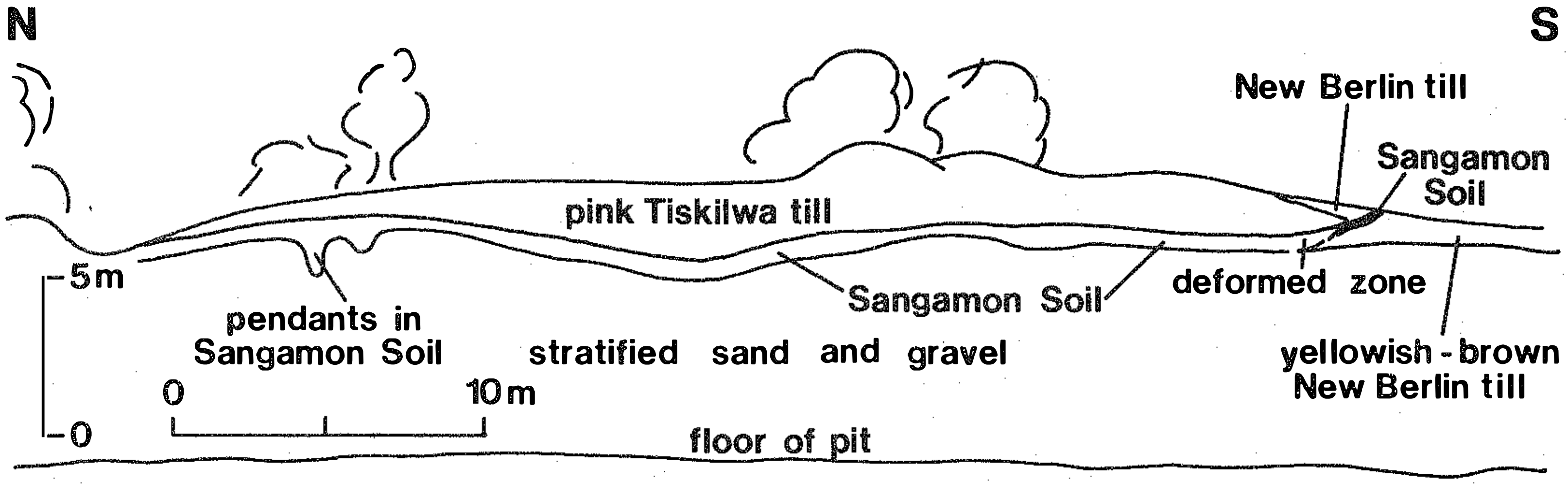

FIGURE 2.--North-south sketch of part of the East Troy gravel pit as seen in 1982. The Sangamon Soil is continuous across the exposure, as shown, but is partially concealed by slump and slope wash. Modern soil profile (not shown) is at the sketched surface in some places, but in other places it has been removed or truncated by mining operations. Height of pit wall is about 10 m; approximate length of section is 50 m.

similar in most of its characteristics to that below, contained fewer stones and had more silt; it resembled a strongly developed B horizon developed from till rather than gravel. Both Schneider and Hadley interpreted this to be a two-material profile, with the upper part of the B horizon having formed from till and the lower part from gravel. However, the geologic contact between the gravel and the till, if present, was masked by pedogenesis; both parent materials were weathered by the same soil-forming episode.

Unfortunately, these additional stratigraphic units have not been visible in recent years. Pit enlargement during the past 5 or 6 years has resulted in the removal of the weathered till, the stone line, and the overlying silt with its possible incipient soil; thus, the pink Tiskilwa till is now seen in direct contact with the paleosol. Apparently the sand and gravel unit was overlapped from the west by a wedge of till and a thin layer of silt, both of which have been removed as mining operations have moved the pit face eastward.

Neither the Illinoian till (weathered or unweathered) nor the younger silt are now exposed elsewhere in the pit, and neither the till, the paleosol, nor the silt have been identified at any other site in southeast Wisconsin. Fortunately, however, samples of both the till and the silt were collected from the East Troy site in 1977. Analyses of these samples seem to confirm the field interpretations.

CONCLUSIONS

The exposure at the East Troy pit reveals stratigraphic relationships that have been suspected to exist for some time, probably since Alden's report in 1918 or longer, but they have not been confirmed until now. Because the Sangamon Soil and other pre-Woodfordian features are widespread beyond the Wisconsinan border, it follows that they should occur under Late Wisconsinan deposits where spared from glacial and other causes of erosion.

The fragmentary information developed from the study of this site leads to the conclusion that the weathered, clayey paleosol exposed in the wall of the pit is the Sangamon Soil. The paleosol is developed in a coarse cobbly outwash that is judged to be Illinoian in age. Morphology and composition of the overlying unweathered till indicate that it can be identified as the Tiskilwa till, which was deposited by an early glacial advance of Woodfordian Age. The confidence of this identification and the assumption that the paleosol represents the last interglacial age or the last time during which a warm-climate soil could have formed in this area form the main arguments for this interpretation. The relation of the Sangamon Soil and Tiskilwa till to the younger New Berlin till at this exposure creates some confusion but can be explained as a local anomaly caused by glacial deformation. It appears that New Berlin till was down thrusted through Tiskilwa till into the Sangamon Soil at the only place where the two tills are in contact at this site.

ACKNOWLEDGEMENTS

We wish to express our thanks to Richard Amon of B. R. Amon and Sons, operator of the pit, for permission to study the site. Schneider's joint visits to the Amon pit and other exposures in Walworth County with David Hadley contributed much to our understanding of the site. Analytical data presented in this paper was provided by the Illinois State Geological Survey; the clay-mineral identifications were made by H. D. Glass, and the particle-size analyses were run by R. Bianchini. The manuscript was reviewed by Lee Clayton, David Mickelson, and Dan Muhs.

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FABRIC AND DEPOSITIONAL STRUCTURES IN DRUMLINS NEAR WAUKESHA, WISCONSIN

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ABSTRACT

Deep gravel-pit exposures reveal the distribution and structure of till and underlying sand and gravel in drumlins near Waukesha, Wisconsin. The subglacial sediment is interpreted to have moved laterally into the drumlin sites because the till thickens from the margin to the core of the drumlins, the stone orientation in the till is perpendicular and oblique to ice flow on the drumlin margins, and recumbent isoclinal folds occur in sand on the drumlin margins with axes parallel to the drumlin axes. The resulting accumulations of sediment presented obstacles to ice flow and were streamlined into the minimum-drag drumlin shape by erosion on the margins and by remolding of material in the core of the drumlins. These drumlin nuclei may have formed at spots where there was low normal stress on the bed due to thin ice. The subglacial sediment became mobile as a result of high pore pressure that may have formed at spots where there was low normal stress on the bed due to thin ice. The subglacial sediment became mobile as a result of high pore pressure that may have developed as groundwater and subglacial meltwater were trapped behind a frozen bed at the ice margin. However, under certain conditions, lateral sediment flow might also have occurred if the sediment was frozen.

INTRODUCTION

This paper describes the distribution and fabric of till and the structure of sand and gravel exposed in gravel pits in drumlins near Waukesha, Wisconsin. Inferences about the stresses on and strength of the subglacial material during drumlin formation are then drawn from these observations. This study is an expansion and continuation of the work of Whittecar (1976) and Whittecar and Mickelson (1977, 1979), who first described and interpreted the till stratigraphy and deformational structures in the drumlins. Previous workers in this area include Alden (1905, 1918) who first described the morphology and regional distribution of the drumlins, and Evenson (1971), who measured fabric in several drumlins as part of a general study on the origin of till fabric.

Two drumlin fields occur in southeastern Wisconsin: a small field near Waukesha formed by ice of the Lake Michigan Lobe, and a large, 90-km wide arcuate belt of drumlins behind the outermost end moraine formed by the ice of the Green Bay Lobe (fig. 1). For this study, nine drumlins in the Waukesha field and two in the Green Bay Lobe field were examined (fig. 1). Three of these drumlins are field-trip stops described by Mickelson and others (1983), (sites 2, 5, and 10 on fig. 1). Based on the correlation of the drumlin-forming Horicon and New Berlin tills with the Haeger Till Member in Illinois, both the Waukesha and Green Bay Lobe drumlins are thought to have formed during advance of ice to the Darien, Johnstown, and West Chicago Moraines approximately 14 500 B. P. (Whittecar and Mickelson, 1979). The Waukesha drumlins are clustered on uplands (Whittecar, 1976), are commonly

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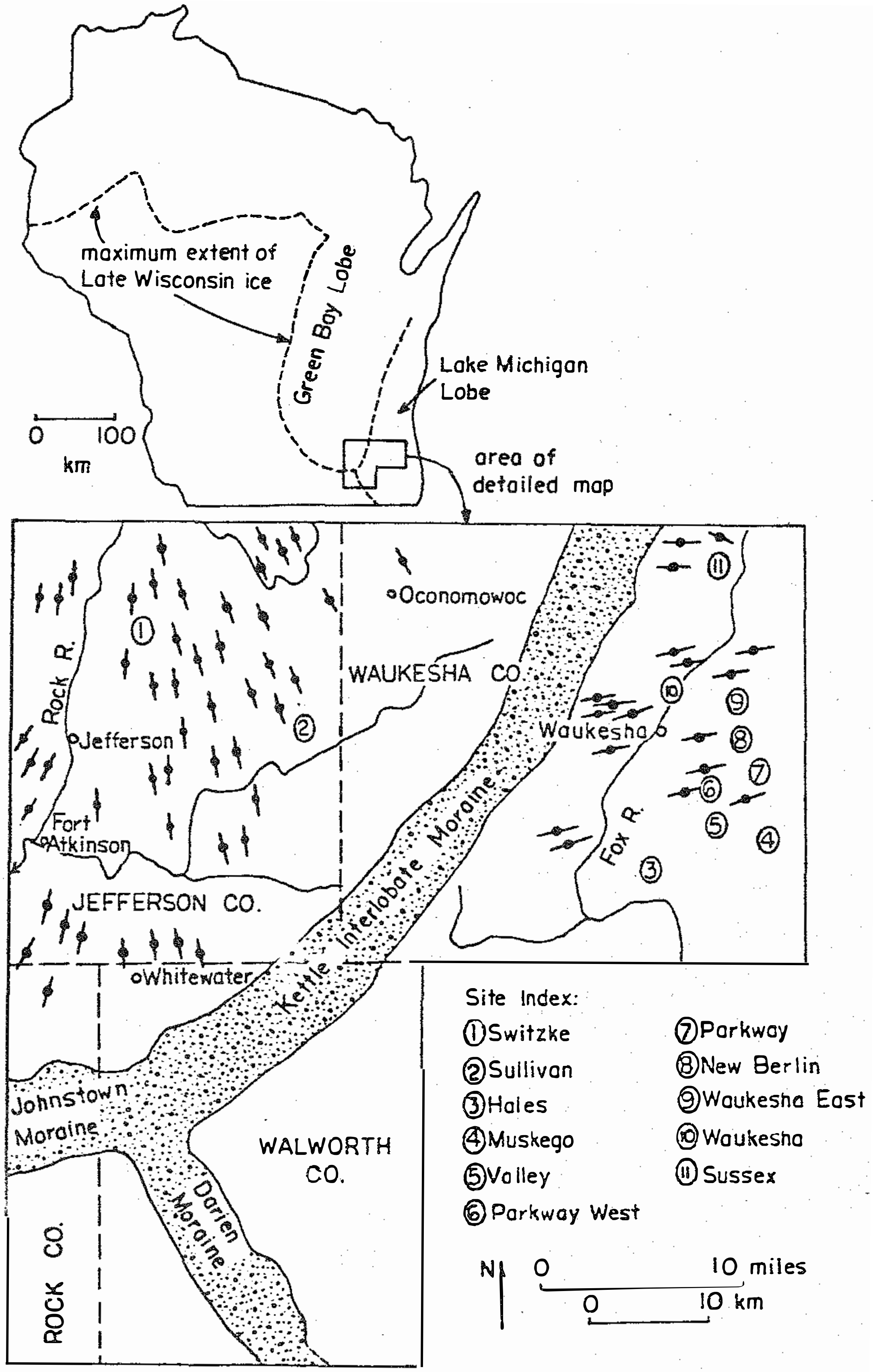


FIGURE 1.--Map of Wisconsin and more detailed map showing location of drumlin trends, prominent moraines, modern drainage, and sites examined.

overlapping or composite in form, and, in places, are gradational to or superimposed on linear ridges that parallel the drumlin axes. The Green Bay Lobe drumlins are generally longer and narrower than the Waukesha drumlins (Mills, 1972, 1980), and they are discrete hills with a less marked tendency to cluster on uplands.

DISPOSITION OF TILL IN THE DRUMLINS

Both the Green Bay Lobe and the Waukesha drumlins are at least partially cored and carpeted with very pale brown (10YR 7/4) sandy loam or loam till. In places till near the surface of the drumlin is enriched in sand and contains stratified sandy and pebbly lenses, suggesting that patches of supraglacial debris were let down atop the drumlins during final melting, but the bulk of the till in the drumlins has a uniform, well-compacted matrix and was probably deposited subglacially. In all but one of the drumlins where the base of the till is exposed, the basal contact of the till dips downard and the surface rises as one proceeds from the margin to the core of the drumlin, thus defining a pod-shaped body of till that is thickest beneath the drumlin crest. Figure 2 summarizes thickness measurements in five drumlins and demonstrated thickening of the till toward the center of the drumlins. This pattern suggests that till accumulated preferentially at the drumlin sites. In a few places the basal till can be separated into a lower, deformed unit of basal till and an upper, undeformed basal till unit that conforms to the drumlin shape, suggesting that there were two episodes of subglacial deposition during the drumlin-forming glaciation--possibly one during ice advance and the other during retreat of the ice--separated by a period of erosion, deformation, and drumlin formation (Whittecar and Mickelson, 1977).

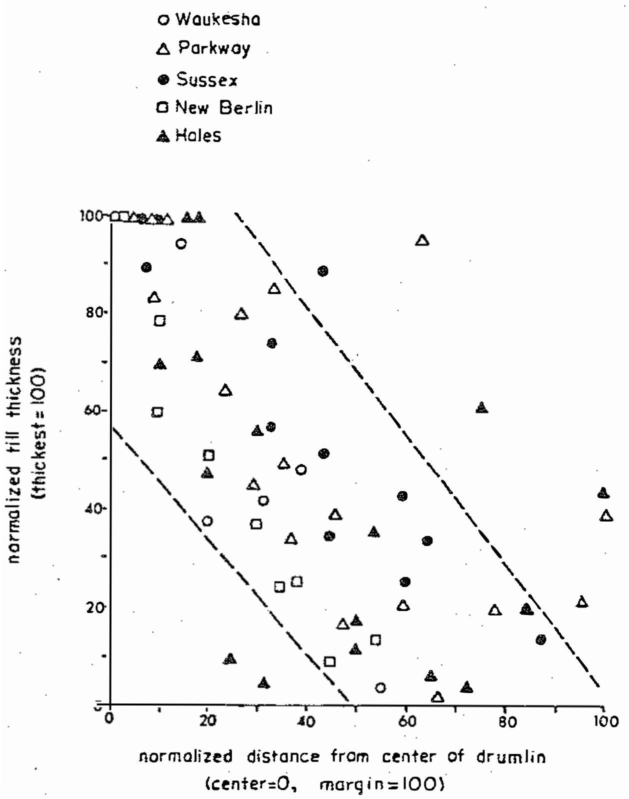


FIGURE 2.--Summary of till thickness distribution of five drumlins, indicating thickening of till towards drumlin cores.

TILL FABRIC

In order to investigate the structure of the drumlin-forming till, fabric was measured at 84 sites in ten pits. For each fabric measurement, bearing and plunge of 25, 30, or 50 pebbles with long axis to intermediate axis ratios of 3:2 or greater was determined using a Brunton compass. Most pebbles measured were dolomite, usually prolate ellipsoids in shape.

The origin of till fabric has been the subject of a number of papers. In theory, elongate particles immersed in a flowing medium (whether it be water, ice, or viscous sediment) will orient to attain a position of minimum torque. Rusnak (1957) presents the following equation for the torque (T) on a particle in terms of the fluid density (ρ), fluid velocity (μ), length of the long (a) and intermediate (b) axes of the particle, and the angle (β) between the a-axis of the particle and the mean velocity vector:

$$T = -\pi\rho(a^2 - b^2)\ \mu^2 \sin\beta \cos\beta.$$

The torque goes to zero--indicating a stable position--when $\beta = \pi$ (that is, long axis transverse flow) and when $\beta = \pi$ (that is, when the long axis is parallel to flow [parallel]).

For a lone particle lying parallel to flow, slight velocity fluctuations in the fluid will tend to rotate the particle into a transverse alignment; thus, the transverse position is more stable. But if a number of particles impinge on each other in the fluid the transverse orientation gives rise to frequent collisions, and the longitudinal orientation is more stable. Thus, in a pebble-rich material such as till or debris-laden ice a longitudinal orientation would be expected to be the stable condition and therefore fabric maxima should indicate the direction of movement of the ice or of viscous till. However, transverse orientations in debris-rich material have been described in areas of compressive flow where fluid above and behind the particle is moving faster than fluid below and in front. For example, transverse fabric is observed on the margins of debris flows and in sheared-up debris bands in ice (Boulton, 1971). Possibly this transverse fabric is produced by the velocity gradient set up across the up-flow and down-flow ends of a particle in longitudinal orientation when it enters a compressive-flow regime. Fluid moving against the up-flow end of the particle will have a slightly higher velocity than fluid moving at the down-flow end. Any slight fluctuation in the flow direction will thus set up a torque tending to rotate the up-flow end until a transverse orientation is attained and there is no appreciable velocity gradient across the particle. In general, then, longitudinal fabric forms in debris-rich flow and transverse fabric forms in compressive or debris-poor flow.

The deep exposures available in the Waukesha area afforded a rare opportunity to measure till fabric in complete drumlin cross sections. Fabric was measured at depths ranging from 2 to 39 m below the surface. At eleven sites where gullies were eroded into the pit walls fabric was measured at several depths to determine vertical as well as lateral variability within the drumlin. Figure 3, and the maps for Stops 1 and 3 in Mickelson and others (1983), show the location of structural data and lower-hemisphere equal-area projections of fabric measurements.

As can be seen on the maps, most of the fabric measurements have maxima that are parallel to the drumlin axes, but measurements having maxima perpendicular and oblique to ice flow are not uncommon (fig. 3, and Stop 6). The perpendicular fabric measurements tend to occur between the margin and core of the drumlins at depths greater than 6 m, and where overlying fabric can be measured (for example, at Waukesha), it is parallel to ice flow. The measurements that are perpendicular to ice flow are in uniform basal till that is clearly traceable to, and is not visibly or analytically different from, till having fabric parallel to ice flow.

Given its position in the drumlins, it is unlikely that the fabric that is perpendicular to ice flow is a transverse fabric produced by compressive flow in the ice itself or by compressive conditions transmitted from the ice into the underlying till. In accordance with Bernoulli's Theorem, fluids will experience increased pressure and decreased velocity (a compressive regime) on the up-flow end of an obstacle but on the sides and down-flow end

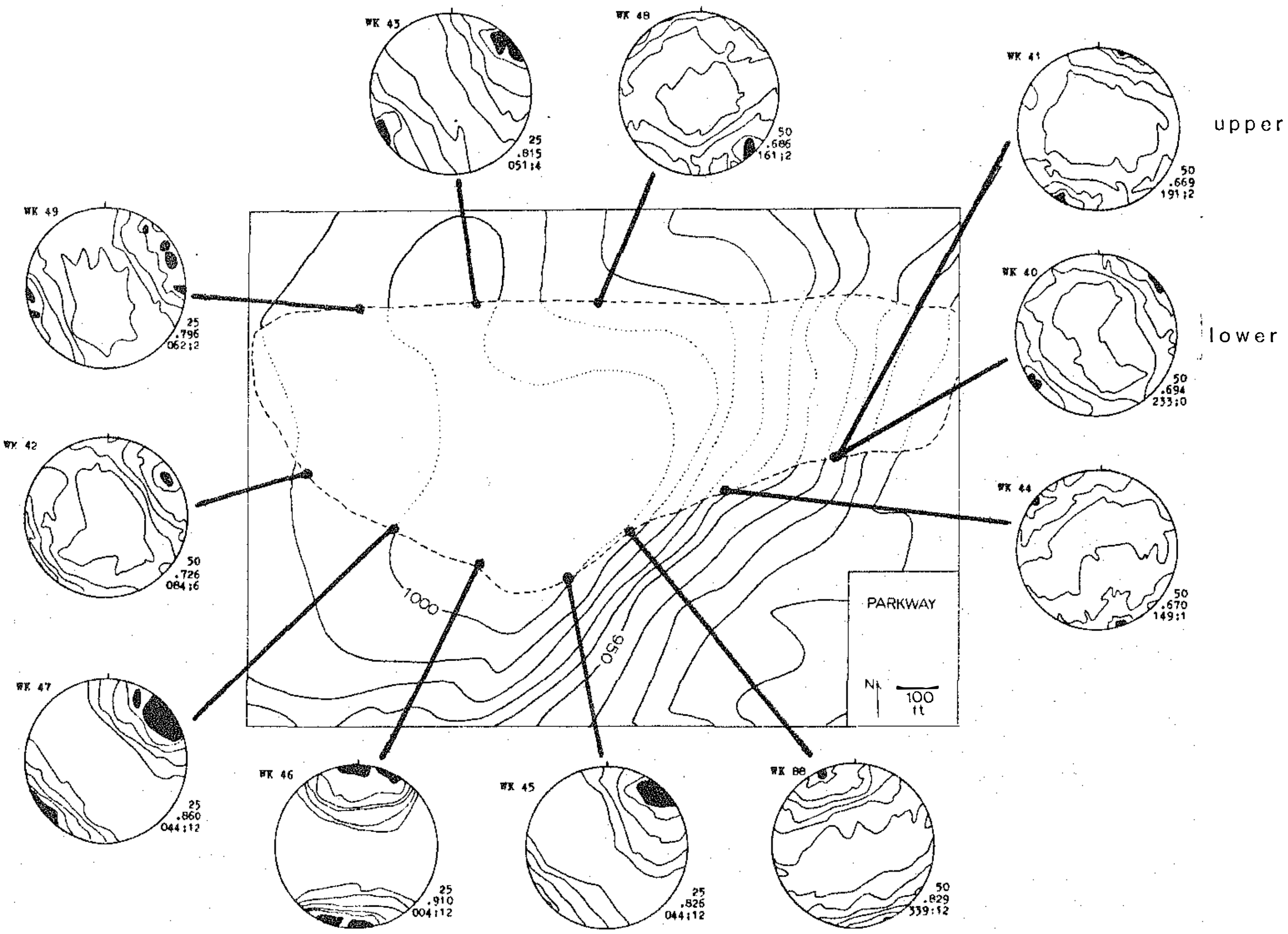


FIGURE 3.--Parkway pit map with fabric and structural data. Note perpendicular fabric (WK48, WK44, WK88).

of the obstacle pressure drops, velocity increases, and extending flow results (see also Savage, 1968). Ice flowing around a drumlin, then, would not be under compressive flow at the marginal position in which the fabric perpendicular to ice flow is commonly found.

Another intepretation is that the fabric that is perpendicular ice flow is longitudinal fabric formed by lateral flow of remobilized till toward the drumlin site rather than fabric created by shear or deposition from flowing ice. This remobilization fabric would then be similar in origin to the squeeze-up fabric in flutes described by Boulton (1976). Such fabric, as the product of flow within previously-deposited till, may be wholly independent of the ice flow direction. Furthermore, the observed coincidence of fabric perpendicular and oblique to ice flow on the drumlin margins with thickening of the till towards the core of the drumlins is complementary evidence for movement of till into the drumlin.

Fabric perpendicular to ice flow was not found in the Valley pit (Stop 3 in Mickelson and others, 1983). This pit was excavated in a ridge that trends parallel to ice flow and is more elongate than the other drumlins examined. In addition, present exposures do not reveal appreciable thickening of the upper till in the core as in the other drumlins, but some thickening was noted in the past (D. M. Mickelson, personal communication, 1982). These observations suggest that there was little referred accumulation of till at the Valley pit (and thus no transverse fabric) and that the ridge is primarily an erosional feature rather than a streamlined depositional feature. Alternatively, the large amount of excavation in the Valley pit may have removed till sections with transverse fabric.

Measurements having maxima parallel to ice flow are more common and are found in the cores and on the margins near the surface of the drumlins. Parallelism with ice flow suggests that such fabric is primarily longitudinal fabric produced during original deposition rather than a remobilization fabric. This deposition, however, was probably not synchronous with drumlin formation, because, if wide-spread deposition of till occurs primarily in a zone near the ice margin, as suggested by many authors (for example, Sugden and John, 1976; West, 1977; and Whittecar and Mickelson, 1979), and if drumlins are formed up-ice from this zone of deposition (Whittecar and Mickelson, 1979), it is unlikely that primary deposition from ice at the time of drumlin formation was responsible for the bulk of the till in the drumlin or for the fabric of that till. Instead, the fabric parallel to ice flow may have been produced either during predrumlin or postdrumlin subglacial deposition, or it may be postdepositional fabric imprinted during shearing of till by ice moving over and around the drumlin. This latter possibility is particularly applicable to fabric paralalel to ice flow near the surface that overlies fabric perpendicular to ice flow (for example, at Waukesha).

STRUCTURE OF THE SAND AND GRAVEL

Thick sand and gravel occurs beneath the till in the drumlins. It is predominantly either horizontally bedded or tilted and truncated by the till. However, intense deformation is not unusual, especially in sand. This deformation is of three types: recumbent isoclinal folds, upright isoclinal to open folds, and clastic dikes. Faults, although described by Whittecar (1976), were not observed during this study.

The recumbent isoclinal folds occur between the edge and core of the drumlins, usually under relatively thin till (1.5 to 6 m thick). Axes of these folds are consistent at a given location and tend to be either nearly perpendicular to the drumlin axis or nearly parallel to the axis. Where the folds occur in sand, amplitudes are on the order of 0.3 to 1 m and wavelengths are usually less than 0.6 m. In gravel, amplitudes are more than 3 m and wavelengths are about 1.5 to 3 m. This difference in size is due both to the thicker bedding in the gravel and to the greater angle of internal friction of the gravel (both in the dry and frozen state). The greater angle of internal friction of the gravel imparts a greater shear strength than that of sand and hinders internal deformation, thereby preventing small-amplitude folds.

The recumbent folds with axes perpendicular to ice flow probably are drag folds produced by shear from overriding ice. Recumbent folds with axes parallel to the drumlin axis are probably not the result of drag from overriding ice. Instead, these folds may be similar to recumbent folds that have been observed and experimentally produced in liquefied sand.

Williams (1960) observed that loosely packed fine sand and silt collapses when sheared. If such sediment is saturated, confined, and then sheared, it liquefies; that is, its shear strength drops as the loose packing disintegrates and the pore fluid assumes the load. Liquefaction, in turn, allows flow when an external force is applied (as, for example, by unequal vertical loading). Flow is laminar, and recumbent folds develop as manifestations of flowing bands moving at different velocities. Fold axes are perpendicular to the flow direction. Similar behavior is described by McKee and others (1962) for a sand layer confined by silt strata. High pore pressure in the sand led to recumbent folds when a horizontal total head gradient was applied across the sand layer.

Applying these observations to the recumbent folds with axes parallel to the drumlin axes suggests that they formed by flow of liquefied sediment into the drumlin either in response to a greater weight of ice in the interdrumlin areas or to flow of water through the sediment towards the drumlin. The parallelism of the fold axes with ice flow rules out drag from overriding ice, and the regularity of the folds and lack of thinning or thickening of the beds rules out downslope slump. Sites where fold axes have oblique or ambiguous orientations with respect to the drumlin axis may have undergone two folding episodes: an original set of folds was produced by flow towards the drumlin and a later set was produced by ice drag, resulting in a deformational pattern similar to that described by Boulton (1976) in modern flutes.

Upright folds are less common, though more spectacular, than the recumbent folds. They occur singly and are of much larger amplitude (as much as 12 m) than the recumbent folds, suggesting the presence of a larger-scale stress field. These folds are composed of sand, gravel, and till layers and are found both on the margin and in the core of the drumlins. Axes of these folds are both parallel and perpendicular to ice flow.

The origin of these upright folds is more problematic than that of the recumbent folds because no clear analog exists in nonglacial sediment. Those folds having axes perpendicular to ice flow may be drag folds that did not become overturned and were later truncated by erosion. The marginal folds with axes parallel to ice flow are probably not related to the ice flow, and the presence of silt, gravel, and thin till layers, as well as their upright, large-amplitude geometry and isolated occurrence, rules out liquefied sediment flow because horizontal flow of liquefied sediment would not produce upright folds involving several sediment layers folded concordantly. One possibility is that they are compressive folds produced by the weight of ice in the interdrumlin areas acting laterally against the drumlin margin. Under these conditions, upright marginal folds of large amplitude might be formed locally, especially if high pore pressure lowers the yield strength of the sediment so as to induce ductile deformation.

Clastic dikes are vertical bodies of layered sand and, in some cases, gravel and till, which intrude upward into and, at places, through the upper till. They generally occur in the drumlin cores and commonly trend parallel to the drumlin axis, although several dikes described by Whittecar (1976) are perpendicular to the drumlin axis. Dike widths range from 1 to 9 m; vertical dimensions are more obscure because the bottoms of the dikes are rarely exposed. Minimum vertical dimensions range from 1.5 to 6 m. At two sites where longitudinal dimensions could be observed, the dikes were linear and tabular in shape, although Whittecar (1976) described several dikes that are domes or doubly-plunging antiforms.

Till fabric was measured in and near the dikes at two locations. Fabric in the intruded till near the margins of the dikes does not show steepened plunge but does tend to be reoriented towards the dike. Fabric in till in the dikes or immediately next to the dikes does show steepened plunge. These findings suggest that the till enclosing the clastic dike did not deform in concert with the material in the dike but rather acted as a rigid layer into and through which the underlying sediment intruded.

A striking feature of the clastic dikes is the preservation of primary stratification. Stratification, defined by interbedded layers of varying grain size, is always continuous, parallel to the dike walls, and only rarely interrupted by isolated, small-scale intrafolial isoclinal folds (with axes parallel to the dike). At several sites this stratification is traceable laterally to horizontal strata, indicating that it is primary stratification and not flow-banding.

Stratification is not commonly observed in dikes in sedimentary rock (Potter and Pettijohn, 1977), and, where it has been described (Waterson, 1950; Peterson, 1968), it is interpreted as an intrusion phenomenon rather than as primary depositional layering. This absence of primary bedding in dikes in sedimentary rock is perhaps the result of turbulent flow during injection or of the massive or thickly bedded character of the source beds. Presumably, however, there is a continuum from low-viscosity, rapid-injection density-inversion structures such as clastic dikes in which turbulent flow occurs and bedding is not preserved, to high-viscosity, diapiric density-inversion structures such as salt domes or load structures in which laminar flow occurs and bedding is preserved. The fact that bedding is preserved in the drumlin dikes, then, is indicative of a laminar, diapiric rise of low-density, liquefied sediment into a denser, rigid till cap. The presence of thin layers of till and gravel (which do not readily undergo liquefaction) in the dikes perhaps indicates either that movement of the enclosing liquefied sand was capable of deforming the interstratified till and gravel or that gravel and till strata were penetrated and upwarped by the upwelling sand (Whittecar, 1976).

BEHAVIOR OF THE SUBLACIAL MATERIAL

The fabric pattern in the till and the folds and dikes in the sand and gravel are indicative of ductile deformation but give no direct indication of whether the sediment was wet or frozen or of the origin of the stresses responsible for deformation. In the case

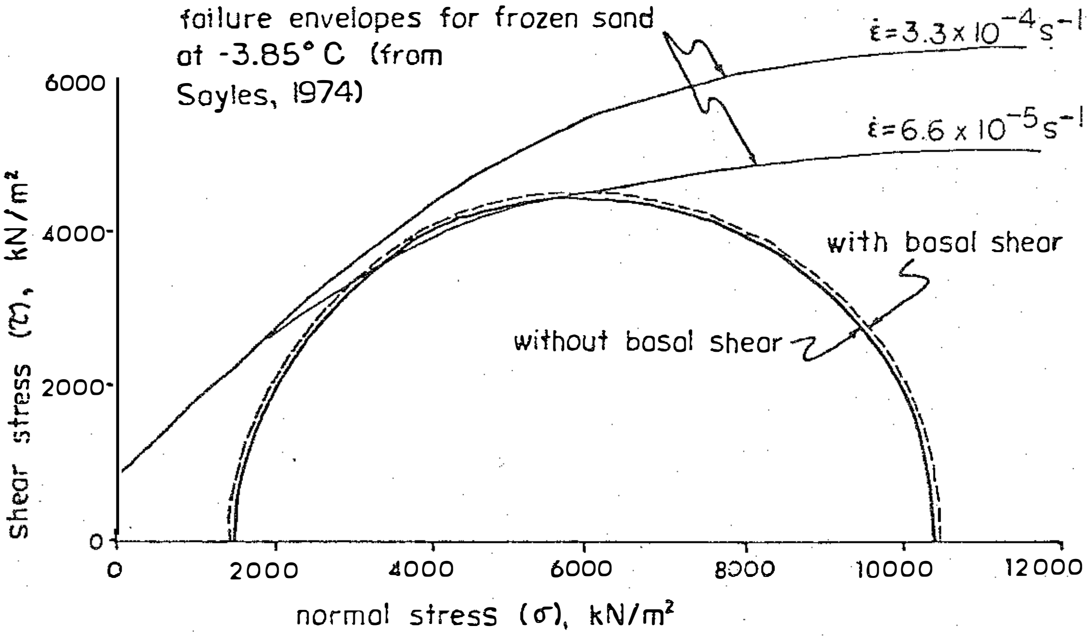


FIGURE 4.--Mohr circle for subglacial stress conditions at Waukesha during maximum extent of ice, assuming an Antarctic-type ice surface profile, a temperature of approximately -5°C, and Poisson's Ratio for frozen sandy till of 0.10.

of wet-sediment deformation, high pore pressure is necessary in order to lower the shear strength of the material to the point where the observed ductile deformation becomes possible. The effect of pore pressure is expressed by the Mohr-Coulomb equation:

$$\tau = C + (\sigma_n - \mu) \tan \phi,$$

where τ = shear strength, C = cohesion, σ_n = normal stress, μ = pore pressure, and ϕ = angle of internal friction. As the equation indicates, increases in pore pressure that are not countered by equivalent increases in normal stress (in this case, the weight of overlying ice) lower the shear strength. In subglacial sediment beneath a temperate glacier (or a sufficiently thick polar glacier), abundant water would be expected due not only to basal melting, but also to compaction and dewatering of fine-grained sediment by ice advance (Vaiden and others, 1982) and by blockage by permafrost of preglacial groundwater discharge areas (Mickelson and Clayton, 1981). If this water is trapped by underlying aquitards (Moran, 1971) and, perhaps, by freezing of the glacier onto its bed at the margin, high pore pressure would develop and sediment (especially the sand and silt subject to liquefaction) would become mobile.

However, ductile deformation could also have occurred if the sediments were frozen. Using an Antarctic-type ice-surface profile, and assuming a basal temperature of approximately -5°C based on findings reported by Tsytovich (1975) and a Poisson's Ratio (the ratio of transverse to longitudinal strain for a material) of 0.10 for the frozen sandy till at Waukesha, the stress conditions during the maximum extent of the drumlin-forming glaciation can be reconstructed (Stanford, 1982). Comparing the resulting Mohr circle for the postulated stress conditions with failure envelopes derived from triaxial compression tests on frozen sand performed at slow strain rates by Sayles (1974) indicates that the long-term yield strength of the frozen sandy till would have been exceeded (fig. 4), and deformation might have ensued. In addition, strain rates slower than the 6.6×10^{-5} s^{-1} of Sayles would be expected beneath the ice; this would further reduce the long-term resistance of the material to deformation.

Given the possibility of frozen deformation, though, it is still not clear whether the large viscosity contrast implied by the observed intrusion of the clastic dikes into a rigid till would be possible with frozen material. Furthermore, the strength of frozen material increases rapidly as temperatures drop (Sayles and Haines, 1974; Tsytovich, 1975; Haynes and Karalius, 1977), and stress on the material drops as the ice-surface profile becomes more gentle. In summary, then, although it is possible that either wet or frozen sediment would have been mobile beneath the ice at Waukesha, the observed structures seem to indicate high pore pressure and wet conditions.

GENESIS OF THE DRUMLINS

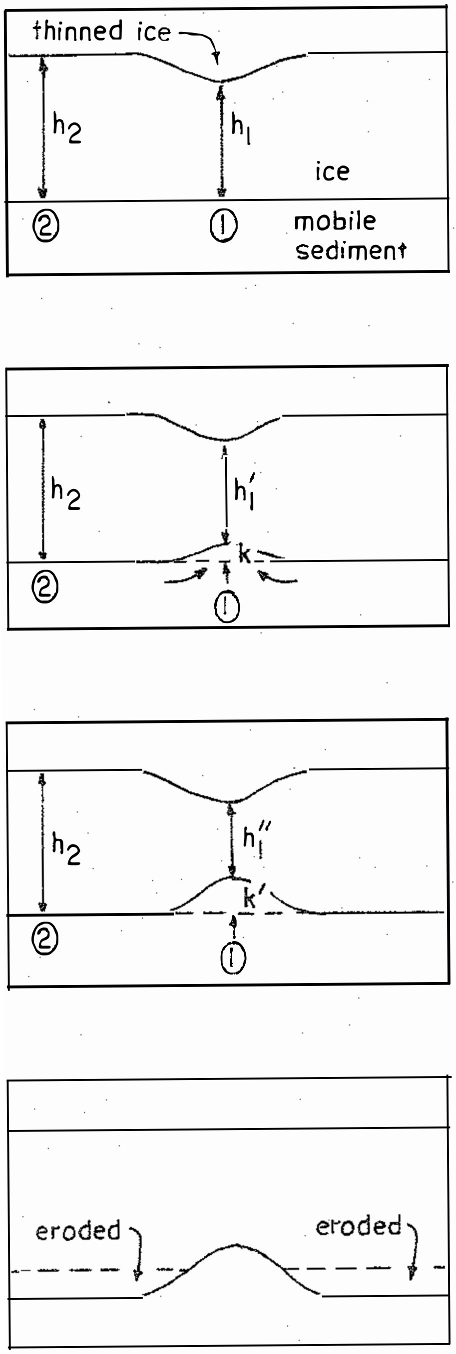
Drumlins are streamlined subglacial landforms that present minimum drag to ice flow around an obstacle (Chorley, 1959). As such, two questions seem pertinent to the origin of drumlins: (1) How was the obstacle produced, and (2) How was streamlining achieved? As emphasized by Boulton (1976), drumlins are morphologically-defined landforms, and, because a number of processes may produce similar or identical morphologies, there need not be a single origin for all drumlins. Thus, there are no doubt several correct answers to the above questions, and any postulated origin for drumlins applies, of necessity, to a specific set of drumlins.

With this limitation in mind, we suggest the following sequence of events in the formation of the drumlins in southeastern Wisconsin (modified from Whittecar and Mickelson, 1979):

(1) Basal till was deposited in a marginal zone as the ice advances, resulting in a sheet of till blanketing the pre-advance topography.

(2) Till and underlying sand and gravel--if mobile--flowed laterally into sites on the bed, beneath the thinnest ice [for example, perhaps below a crevassed area.] At these sites, the normal stress on the bed is lower than on surrounding parts of the bed. Lateral flow of sediment continues until the weight distribution above an arbitrary horizon is equalized, that is, when the thinned ice column is compensated by a thickened sediment column (fig. 5, panels 1 to 3). The observed thickening of the till from the margin to the core of the drumlins is evidence for accumulation of sediment at the drumlin site, and the observed presence of till pebbles that are perpendicular to ice flow and of recumbent folds in sand with axes parallel to ice flow in the margins of the drumlin is evidence for lateral sediment flow towards the drumlin site. The sediment accumulations that resulted from this flow are drumlin nuclei: they were obstacles to ice flow, and consist of sediment that could be shaped by erosion and remolded into a streamlined form.

If the sediment were completely frozen, flow occurred only under special combinations of ice thickness, temperature, strain rate, and ice content. However, if the sediment were unfrozen or partially frozen, increases in pore pressure that were not matched by equivalent increases in normal stress reduced the effective stress, lowered the shear strength, and readily enhanced sediment mobility. Such increases in pore pressure could be produced by rapid loading and compaction of slowly drained or undrained sediment due to ice advance (Vaiden and others, 1982) and by blockage of preglacial groundwater discharge areas by ice. Drainage of the subglacial water, in turn, would be impaired or halted by aquitards (Clayton and Moran, 1974) and by freezing of the glacier onto a permafrost bed at the margin (Mickelson and Clayton, 1981). Thus, advance of ice over water-bearing sediment, in conjunction with a frozen margin and



1. Prior to lateral flow of sediment.

$$\sigma_1 = \gamma_{ice}\ h_1$$
$$\sigma_2 = \gamma_{ice}\ h_2$$
$$h_1 < h_2$$
$$\therefore \sigma_1 < \sigma_2$$

2. Initiation of lateral sediment flow.

$$\sigma_1 = \gamma_{ice}\ h_1' + \gamma_{sediment}\ k$$
$$\sigma_2 = \gamma_{ice}\ h_2$$
$$\gamma_{sediment} > \gamma_{ice}\ ,\ h_1' < h_1$$

$\therefore$ σ_1 approaches σ_2 in magnitude as flow continues.

3. Termination of lateral sediment flow.

$$\sigma_1 = \gamma_{ice}\ h_1'' + \gamma_{sediment}\ k'$$
$$\sigma_2 = \gamma_{ice}\ h_2$$
$$k' > k \text{ such that } \sigma_1 = \sigma_2$$

$\therefore$ Flow stops because there is no stress gradient.

4. Definition of drumlin by erosion and remolding of the sediment accumulation into a streamlined shape.

FIGURE 5.--Schematic illustration of drumlin formation near Waukesha.

aquitards surrounding the sediment, induced abnormally elevated (excess) pore pressure in the sediment and thereby created conditions favorable for drumlin nucleation.

(3) The accumulation of material in these proto-drumlin sites was an obstruction to ice flow, and flowlines were diverted around the obstacle. Streamlining of the obstruction into the minimum-drag drumlin shape was achieved by remolding and erosion (fig. 5, panel 4). Till in the center of the drumlin flowed into a streamlined shape in response to shear transmitted from overriding ice seeking a flow pattern of minimum drag. More rapid flow (and possibly frozen-bed conditions) on the drumlin flanks and interdrumlin areas promoted extensive erosion of the till and underlying outwash from these areas, also emphasizing the streamlined form. The observed truncation of the till and bedded sand and gravel at the drumlin flanks indicates extensive erosion of interdrumlin areas, and the prevalence of till fabric oriented parallel to ice flow, especially close to the drumlin surface above fabric oriented perpendicular to ice flow, may reflect local remolding from overriding ice.

(4) Next, another basal till was deposited as a carpet over the drumlinized topography, either during retreat of the ice margin or under thick ice shortly after formation of the drumlins.

(5) Lastly, a discontinuous blanket of supraglacial till was deposited on the landscape during final melting of the ice.

On a regional scale, the occurrence of drumlins in a belt parallel to the ice margin may mark the location of a zone of ice that was partially frozen to the bed. This zone, in turn, marks the transition from a frozen bed at the margin to an unfrozen bed farther upglacier. On the basis of geomorphologic evidence, Mickelson and Clayton (1981) argue that a frozen bed was present at the margin of the Green Bay Lobe and the northern Lake Michigan Lobe during Late Wisconsinan time. As mentioned above, this might allow high pore pressure to develop in unfrozen-bed areas behind the margin. Erosion would occur in areas where ice under compressive flow was freezing-on to the bed and thereby lifting material off the bed. These observations suggest that the drumlins may have formed in the unfrozen-bed portions of the partially-frozen zone where mobile sediment was present and that interdrumlin areas where extensive erosion has occurred may represent frozen-bed portions of the partially-frozen zone.

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