Re-examination of Quaternary Bluff Stratigraphy, Southeast Wisconsin

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ABSTRACT

Seven lithostratigraphic units from six ice advances are present within the Oak Creek Formation along Lake Michigan bluffs in southeastern Wisconsin, whereas only three till units were previously recognized. Two of the units are fine-grained glacial diamicton, apparently deposited into standing water, and five are till. To the north, each unit rises within the bluff and is successively truncated, exposing progressively older units at or near the bluff top.

Each till has a unique and consistent combination of color, texture and clay mineralogy. The characteristics of the oldest till are identical to the Shorewood till defined beneath Lake Michigan and is present in the bluff along the same reach delineated offshore for the Shorewood till. Based upon these similarities, the Shorewood till is provisionally correlated to the oldest Oak Creek till.

INTRODUCTION

Few geologists have studied the Pleistocene stratigraphic sequence in southeastern Wisconsin (fig. 1); Few, in particular, have studied the sequence exposed in the Lake Michigan bluffs. The first such study began in the mid-1970s when rising lake levels accelerated bluff erosion and sparked a comprehensive coastal inventory. As part of that inventory various geologists completed the first study on the lake-bluff stratigraphy. Results were compiled into a report with county by county appendices (Mickelson and others, 1977). In addition, Klauk (1978) and Acomb (1978) prepared theses as part of the study.

Results in the Mickelson and others (1977) study include identification of three formations. From oldest to youngest they were informally named till 1, 2 and 3; formally they are now the New Berlin, Oak Creek, and Kewaunee Formations, respectively (table 1; Mickelson and others, 1984). Each formation consists of multiple till units, however, only the Kewaunee Formation is formally subdivided. The oldest Kewaunee Formation Member (3a in Mickelson and others, 1977) is the only member present in this study area and is now known as the Ozaukee Member of the Kewaunee Formation.

One major aspect of the 1977 report can be revised; more than three Oak Creek till units are present in the bluff. This first became apparent during 1987, when record high lake levels coincided with a lack of ice armoring during an unusually mild winter. This resulted in erosion which exposed the most complete section probably ever seen along the shoreline. At numerous sites four distinct Oak Creek till units were unmistakably exposed in the bluff.

PROCEDURES

Field Sampling

Our major objective was to reinvestigate the sequence of Oak Creek till exposed in the Lake Michigan bluffs. Along one three-kilometer section (sections 25 and 36, fig. 2b) differentiation was simple; four tills were clearly superposed, separated from each other by stratified sediment or a boulder lag or both. To help trace and correlate the till units laterally, each was sampled along the three-kilometer section to establish characteristic parameters for unoxidized color, matrix texture and clay mineralogy. At each location samples were collected over a vertical and lateral distance of three to four meters or as thickness permitted. Mapping was then extended to both the north and south. In all cases care was exercised to collect only in-place material, and oxidized samples were avoided for color and clay mineral analysis.

Textural Analysis

The percentage of sand, silt and clay in the sample matrix was determined using the total hydrometer method of Boyoucos (1962). Textural percentages determined using the Boyoucos method are not di-

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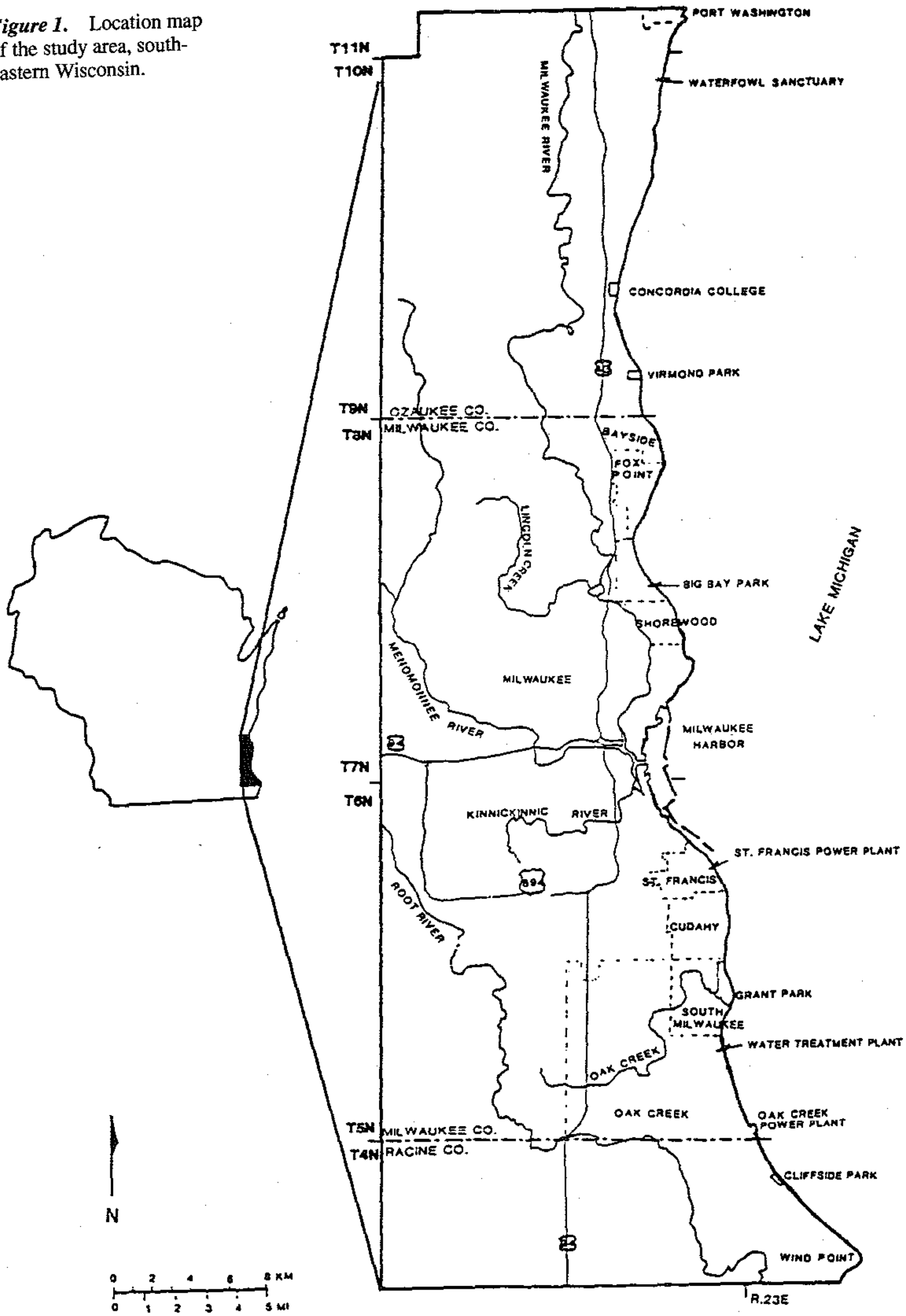


Figure 1. Location map of the study area, southeastern Wisconsin.

Table 1. Synopsis of glacial stratigraphy, southeastern Wisconsin.

Mickelson and others, 1977	Schneider, 1983	Illinois	This study
Till 3A	Ozaukee Mbr. Kewaunee Fm.	Shorewood (Offshore)	Ozaukee Mbr. Kewaunee Fm.
Till 2 (a,b,c)	Oak Creek Fm. (1,2,3)	Wadsworth Mbr. Wedron Fm.	Oak Creek Fm. (1,2,3,4,5)
Till 1 (a,b)	New Berlin Fm. (1,2)	Haeger Till Mbr. Wedron Fm.	New Berlin Fm. (1,2)

rectly comparable to those obtained using different procedures. This method is rapid and convenient for processing large numbers of samples, but differs from other hydrometer methods in that a larger sample (50 grams as opposed to 10-15 grams) is used. The sand fraction is also determined from a hydrometer reading, and not from sieving. The sand/silt boundary was 0.05 mm, because stable hydrometer readings could not be obtained for the usual 0.062 mm boundary.

Most previous studies in southeast Wisconsin used either the sieve and pipette technique, or determined clay percentage with the Boyoucos method, and determined sand percentage by sieving. Sieve and pipette analyses were conducted on 16 duplicate samples following procedures outlined in Walter and others (1978). The hydrometer sand values were, on average, 6% greater than the duplicate sieved samples, with no apparent dependence on clay or sand percentage. The deviation in clay percentage, however, is not as simple. A second order polynomial-fit between clay percents from the Boyoucos method and corresponding deviations from the pipette method gives the equation:

$$\text{Pipette\%} = \text{Hydrometer\%} + 1.0 - .16(\text{Hydrometer \%}) + 5.2 \times 10^{-3} (\text{Hydrometer\%})^2$$

for converting Boyoucos to pipette clay percentage. Details are available in Borucki (1988).

Clay Mineral Analysis

The semi-quantitative method of clay mineral analysis by H.D. Glass was used in this study. The method is termed "semi-quantitative" in that the clay minerals are lumped into three broad categories, expandable clay, illite and kaolinite + chlorite. The percentages of each category are not deemed highly accurate, but they are very precise and diagnostic as demonstrated by Hallberg and others (1978) who documented the procedures and achieved standard deviations of approximately three percent in each fraction from duplicate samples. The technique is proven useful for stratigraphic differentiation of individual till units over wide areas (see for example Wikham and others, 1988; Hallberg, 1980). In southeastern Wisconsin, the method was previously used by Acomb (1978) and Acomb and others (1982) for bluff stratigraphy, and by Schneider (1983) and Hansel (1983) for inland localities. Duplicate samples (13) were sent to the Illinois State Geological Survey for analysis. The average deviation in each clay fraction was less than 1% (see Borucki, 1988).

RESULTS

General

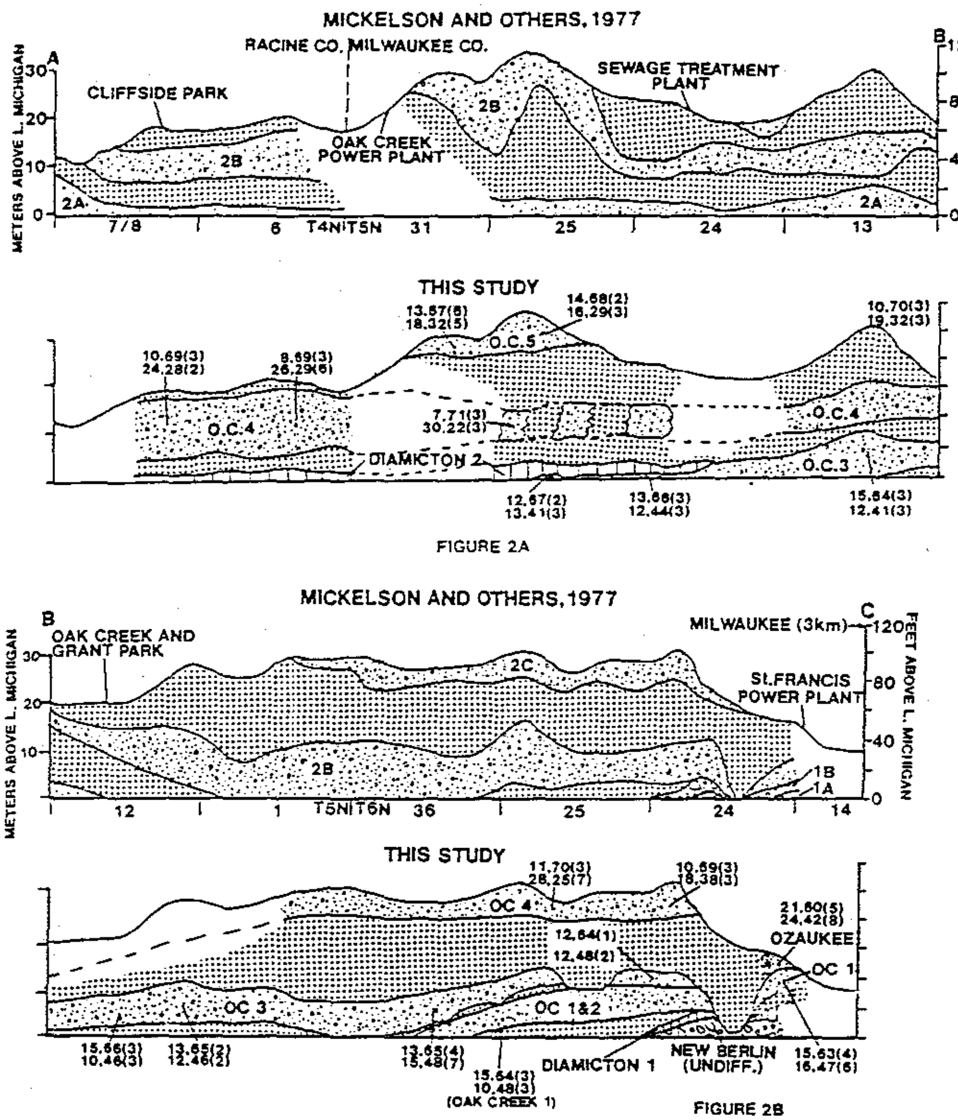
Field mapping in combination with the laboratory analyses identified five Oak Creek till units and two stratified glacial diamicton units in the Lake Michigan bluffs. Their distribution and laboratory characteristics are found in figures 2 and 3 and table 2. All of the (sometimes) complex thickness variations are not shown on the figures, but rather general values and trends are shown, because the bluffs erode through time, and thicknesses invariably change in the new exposures. The primary purpose is to show the general stratigraphic relations among the different tills and diamicton.

As in the original survey numerous gaps in exposure were encountered. Differentiation between major and inconsequential gaps is subjective, but the gaps shown in figures 2 and 3 are those which we believe could be reasonably deemed to introduce uncertainty in lateral correlation. Each unit, oldest to youngest, is sequentially discussed below.

Diamicton 1

The oldest mappable unit within the Oak Creek Formation is a deposit of uncertain origin. Schneider and Need (1985, p. 55) described this unit at the St. Francis Power Plant (fig. 2B) stating : "The basal part of the Oak Creek Formation is commonly a water-laid diamicton." This diamicton is found wherever the underlying New Berlin is itself exposed, at least as far north as Port Washington (fig. 2b, 3a-3c). The diamicton is

Figure 2. Comparison of bluff stratigraphy south of Milwaukee between this study and Mickelson and others (1977). Bluff elevations are taken from Mickelson and others (1977). Numbers along the bottom of the upper profile are one mile sections. Selected general sampling locations and average composition for the Oak Creek till units are shown as space permits.
Abbreviations:
O.C. 1 - Oak Creek 1
O.C. 2 - Oak Creek 2
O.C. 3 - Oak Creek 3
O.C. 4 - Oak Creek 4
O.C. 5 - Oak Creek 5



Explanation for figures 2 and 3

15 . 64 (3) %expandables % illite (number of samples analyzed)
10 . 48 (4) %sand %clay (number of samples analyzed)

UNDIFFERENTIATED LAKE SEDIMENT
FINE GRAINED GLACIAL DIAMICTON
FINE GRAINED TILL
COARSE GRAINED TILL

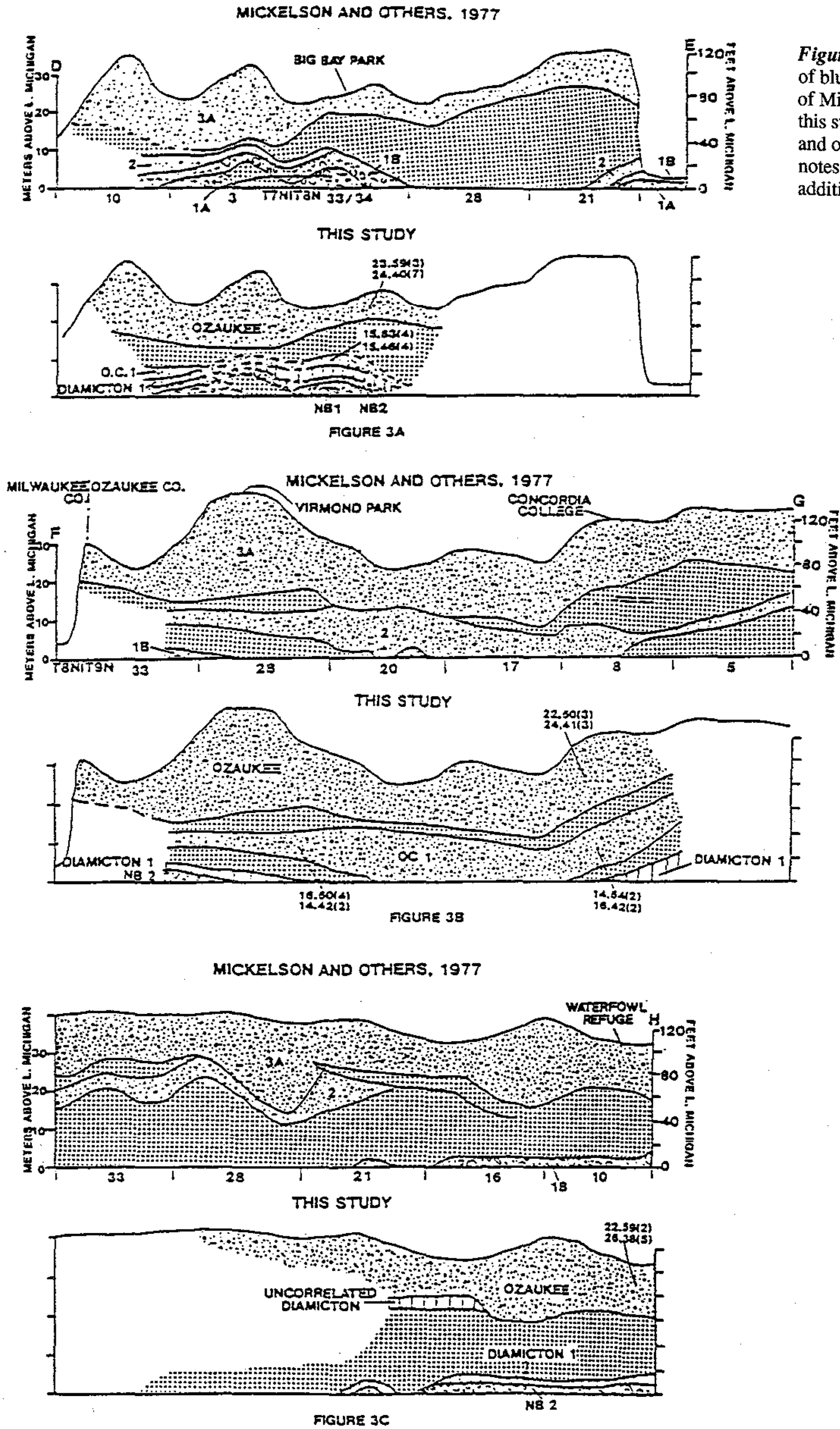


Figure 3. Comparison of bluff stratigraphy north of Milwaukee between this study and Mickelson and others (1977). See notes on figure 2 for additional descriptions.

Table 2. Mean composition of glacial units in Lake Michigan bluffs, southeastern Wisconsin. Textural percents determined by the Bouyoucos (1962) method using sand/silt and silt/clay boundaries of 0.05 mm and 0.002 mm, respectively. X = arithmetic mean (S) = standard deviation in percent, [N] = number of samples.

BLUFF UNIT	TEXTURE							CLAY MINERALOGY							MUNSELL COLOR (DRY)
	Sand		Silt		Clay			Expandables		Illite		Kaolinite + Chlorite			
	X	(S)	X	(S)	X	(S)	[N]	X	(S)	X	(S)	X	(S)	[N]	
Ozaukee	23	(5.9)	36	(3.8)	41	(3.1)	[26]	22	(2.2)	59	(2.6)	19	(1.9)	[16]	Lt. Reddish Brown, 5YR
Oak Creek 5	19	(3.8)	52	(2.1)	29	(3.7)	[11]	14	(.9)	67	(1.4)	19	(2.2)	[9]	Lt. - Dk. Gray, 10YR
Oak Creek 4	22	(5.8)	47	(3.0)	31	(5.3)	[36]	10	(2.2)	69	(2.0)	21	2.0)	[28]	Lt. - Dk. Gray, 10YR
Diamicton 2	13	(8.7)	45	(3.9)	42	(10.5)	[8]	13	(2.4)	66	(2.7)	21	(0.9)	[8]	Lt. Gray, 10YR
Oak Creek 3	13	(2.4)	42	(3.6)	45	(3.8)	[22]	13	(1.7)	65	(1.5)	22	(1.6)	[20]	Lt. Gray-Pinkish Gray,10YR- 5YR
Oak Creek 2	40	(3.8)	34	(3.1)	26	(6.4)	[9]	18	(3.0)	60	(1.8)	22	(2.2)	[10]	Pink - Pinkish Gray, 5YR
Oak Creek 1 (Total)	14	(2.8)	40	(3.3)	46	(3.4)	[19]	16	(1.7)	62	(2.5)	22	(1.9)	[15]	Pinkish Gray, 5YR
Oak Creek 1 (N. of Milwaukee)	15	(1.5)	41	(2.5)	44	(2.2)	[8]	15	(1.6)	62	(2.3)	22	(2.0)	[10]	Pinkish Gray, 5YR
Oak Creek 1 (S. of Milwaukee)	13	(3.1)	39	(3.5)	48	(3.3)	[11]	16	(1.7)	62	(3.1)	22	(1.5)	[5]	Pinkish Gray, 5YR
Diamicton 1	19	(12.9)	42	(7.0)	39	(11.4)	[20]	14	(4.5)	65	(4.8)	21	(2.0)	[19]	Dk. Gray, 10YR
New Berlin 2	30	(5.0)	45	(6.0)	25	(7.1)	[12]	18	(3.2)	63	(3.0)	19	(1.3)	[8]	————
New Berlin 1	57	(5.4)	30	(2.3)	13	(4.3)	[5]	—	—	—	—	—	—	—	————

consistently 1.5 to 2.5 meters thick, but the nature of both contacts is variable. The lower ranges from a sharp contact directly above the New Berlin Formation to a gradational change from laminated to bedded sediment which overlies the New Berlin Formation. The upper contact is usually gradational to laminated silt and clay, but locally this same transition is abrupt. The texture and clay mineralogy are quite variable compared with the till (table 2). However, there is an apparent trend towards greater consistency in the upper parts where the deposit is characterized by the mean values in texture (table 2), but a higher illite and lower expandable clay content (approximately 70% and 10%, respectively) than average. The dark gray (10YR) color and high illite percentage are typical of the Oak Creek Formation, but the sedimentologic origin of this oldest Oak Creek deposit is uncertain. Although locally it appears massive and to be a till, close inspection invariably discloses a crude stratification (fig. 4). Therefore, the non-genetic term "diamicton" is applied to exposures of this unit in the bluff.

Oak Creek 1 and 2 tills

The oldest definite till is here termed Oak Creek 1. It is distinguished by its pinkish gray (5YR) hue, finer texture and lower illite percentage than overlying Oak Creek till (table 2). The lower contact is abrupt, overlying stratified sediment above diamicton 1. The same sequence was previously reported at the St. Francis Power Plant by Christensen and Schneider (1984). Oak Creek till north of Milwaukee is identical in color, texture and clay mineralogy and vertical stratigraphic sequence to the Oak Creek 1 unit south of Milwaukee (table 2, figs. 2, 3). Therefore, all Oak Creek till north of Milwaukee is correlated to the Oak Creek 1 till.

Because of the color similarity between the pinkish Oak Creek 1 and 2 till units which are in strong contrast to the gray underlying and overlying units, and because the contact between the two is difficult to trace, the Oak Creek 1 and 2 tills units are undifferentiated south of Milwaukee. The two till units do, however, contain subtle differences in clay mineralogy and marked differences in texture (table 2).

The Oak Creek 2 till is only present south of Milwaukee, where the Oak Creek 1 till is occasionally absent or beneath lake level. Consideration must be given to whether the Oak Creek 1 and 2 till units are really distinct or whether they are different facies deposits of the same glacial advance. Might the Oak Creek 2 till be a supraglacial deposit overlying a basal Oak Creek 1 till, and might this origin account for the difference in texture and apparent patchy occurrence of the Oak Creek 1 till south of Milwaukee? Several observations are inconsistent with a supraglacial origin of the Oak Creek 2 till:

1. Both units have extremely uniform textures.

2. Neither unit contains interbedded stratified material, flow, or deformation structures, although locally a cobbly diamicton with flow structure interbedded with stratified sediments overlies the Oak Creek 2 till.

Both units appear to be basal till. Another question might be whether the Oak Creek 1 till is merely a basal contamination of the sandier Oak Creek 2 till? While we can not discount this possibility entirely, several observations are inconsistent with it also:

1. Where exposed, the contact is usually abrupt and planar, not gradational.

2. Discrete inclusions of the Oak Creek 1 till are present in the basal few feet of the Oak Creek 2 till, but no inclusions of the Oak Creek 2 till have been found within the Oak Creek 1 till.

3. Locally, the units are separated by laminated silt.

We conclude that the two units are deposits from two separate glacial advances.

Oak Creek 3 till and diamicton 2

The Oak Creek 3 till is traceable from south of the St. Francis Power Plant to within 2 kilometers of the Milwaukee/Racine County line (figs. 2a, 2b). The till is separated from the undifferentiated Oak Creek 1 and 2 tills by coarse stratified sediment or boulder pavement. Matrix texture is similar to the Oak Creek 1 till (table 2), but the color and clay mineralogy are clearly different and distinguishable.

From section 24 (fig. 2a) southward the Oak Creek 3 till has a diffuse, undulating upper contact with a second, fine-grained diamicton, here termed diamicton 2. Diamicton 2 is variable in thickness, crudely bedded, and contains abundant flow and deformation structures such as folded silt laminae (fig. 5). Where it is best exposed 1.5 km north of the Racine-Milwaukee County line, its thickness ranges from one

Figure 4. Diamicton 1 overlying New Berlin 2 Till. Contact is at hammer. Note crude stratification in diamicton. Photo taken at Virmond Park, figure 1, figure 2B, section 28.

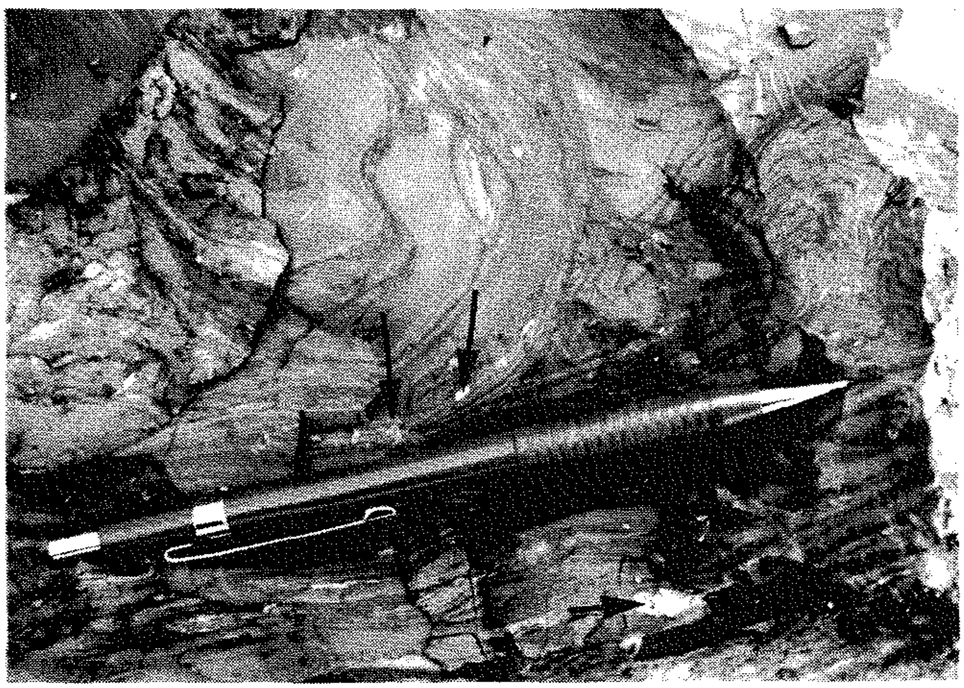


Figure 5. Folded and contorted laminae in Diamicton 2. Arrows point to unconsolidated rip-up clasts. Photo taken 1.5 miles north of the Oak Creek Power Plant (figure 1, figure 2A, section 25).

to six meters. Its texture is similar, but more variable than the Oak Creek 3 till, and the clay mineralogy is identical (table 2). The upper contact is gradational to laminated silt and clay. The similarity in clay mineralogy and the diffuse lower contact are evidence that the origin of diamicton 2 is closely related to the Oak Creek 3 till. The genetic origin of diamicton 2 is discussed in more detail below.

Oak Creek 4 till

The Oak Creek 4 till is easily traced in the upper six meters of the bluff from south of the St. Francis Power Plant (Fig. 2b) to north of Grant Park (fig. 2b). It has a distinctly coarser texture than the underlying Oak Creek 1 and 3 till units, and is also set apart by its higher illite/lower expandable clay percentages (69%, 10%) (Table 2). Another unique characteristic is the variability in matrix texture compared with other till. Samples taken within three meters of each other commonly vary by 8% or more in each size fraction. The continuous exposure at the bluff top ends in the vicinity of Grant Park (fig. 2b), however, south of the park an identical till is present in the mid-bluff (fig. 2a). Southward from section 13 (Fig 2a) the Oak Creek 4 till is even more difficult to trace. There, the occurrence is patchy, and the entire section above diamicton 2 and below Oak Creek 5 till is chaotic.

South of the 1.5 km gap in exposure at the Milwaukee/Racine County line (fig. 2a), the deposits are no longer chaotic and a continuous till from the mid-to-upper parts of the bluff is again present. Because of the identical vertical sequence above diamicton 2, and identical clay mineralogy and texture - including textural variability - this till is again correlated to the Oak Creek 4 till.

Oak Creek 5 till

The Oak Creek 5 till caps the upper four to five meters of bluff from north of the Oak Creek Power Plant, northward to the central part of section 25 (fig. 2a). It is the same till described capping the bluff by Schneider (Mickelson and others, 1984) at the Oak Creek type section 1.5 km north of the Oak Creek Power Plant. Oak Creek 5 till has a similar average texture to the Oak Creek 4 Till, but averages 14% expandable clay and 67% illite; not a single sample contained less than 10% expandable clay and more than 70% illite, characteristics of the Oak Creek 4 till. The Oak Creek 5 till overlies the chaotic sediment described above, which in turn overlies a patchy occurrence of a 70% illite till, the Oak Creek 4 till. To the north, the Oak Creek 5 till is easily traced at the top of the bluff to a point in the northern half of section 25 beyond which it is not present.

DISCUSSION AND IMPLICATIONS

Glacial Diamicton

Three Oak Creek till units were described in the Mickelson and others (1977) study. All intervening sediment was undifferentiated. Not only are there five Oak Creek till units, but two mappable diamictons are included within the undifferentiated sediment. The diamicton units resemble till in many respects, but contain crude stratification. There are two explanations for the genesis of such diamicton. The first is that the stratification was produced by a series of mass flows emanating from the glacier margin (Hartshorn, 1958; Boulton, 1968). Dreimanis (1976) and Evenson and others (1977) extended this mechanism to flows into proglacial lakes and each modified the terrestrial term flow till to the analogous terms waterlaid till and subaqueous flow till. May (1977) subsequently proposed the term lacustrotill. Gibbard (1980) and Hicock and others (1981), however, retained versions of the term flow till. Regardless of nomenclature, the identifying characteristics include a crude, but deformed stratification, abundant evidence of flowage such as flow noses, roll-up structures and inclusions of unconsolidated silt rip-up clasts, and widely variable thickness. All of these attributes characterize diamicton 2, so we interpret it as the product of a series of mass flows. Because it has identical mean textural and clay mineral properties as the underlying Oak Creek 3 till, it was probably deposited during the same ice advance. But, because it commonly grades upward into laminated lacustrine silt, the flows were deposited into standing water during glacial retreat. A similar, but more detailed, description and interpretation of diamicton 2 was given by Jung and Powell (1985) for exposures on either side of the Oak Creek Power Plant (R.D. Powell, verbal communication, 1989).

The second explanation for stratified diamicton attributes deposition to basal melt-out beneath an ungrounded ice sheet (May,1977; Gibbard, 1980). Such deposits would have few, if any, flow structures, would be more constant in thickness, and would be vertically gradational into an unstratified till, deposited as grounded ice overrode deposits from the floating ice shelf. Most of these attributes characterize diamicton 1, but there is no conclusive evidence for a vertical transition into a true till. The upper part of diamicton 1 has a greater consistency in texture and clay mineralogy, possibly indicating less reworking, but it too appears crudely stratified. Therefore, although diamicton 1 was probably deposited into water, perhaps by melt-out beneath a floating ice margin, conclusive evidence is lacking and its genetic origin is still in doubt.

Till Sequence

The pattern exposed in the southeast Wisconsin lake bluffs is counter to the regional trend. The general pattern of Lake Michigan Lobe Woodfordian deposits is described as shingled (Johnson and Hansel, 1986) with older till thinning and pinching out to the north beneath younger tills. However, the pre-Ozaukee pattern (fig. 2 and 3) is the reverse of this normal sequence. To the north, younger units are progressively truncated, successively uncovering older units. Two different mechanisms, non-deposition or erosion, may account for this pattern. Non-deposition would result if successively younger ice advances flowed farther south down the Lake Michigan basin - much as a valley glacier - before spilling out of the basin and depositing younger till in the vicinity of the present shoreline. However, this explanation stretches credulity. A more likely mechanism is that the truncation is due to pre-Ozaukee isostatic rebound, differential uplift and erosion to the north. As a result, younger units were eroded and older deposits exposed.

CORRELATION OF THE SHOREWOOD TILL

The Shorewood was defined beneath Lake Michigan solely from color and clay mineralogy of three core samples (Lineback and others, 1974). The reported color (pinkish gray, 5 YR) and average clay mineral content (15, 60 and 25 percent expandable clay, illite and kaolinite + chlorite, respectively) raise speculation that the Shorewood unit could be the offshore equivalent of the Oak Creek 1 till. This seems plausible because no other onshore till (Mickel-son and others, 1984) has a composition approaching the Shorewood unit. Unfortunately previous workers were not aware of the existence of Oak Creek 1, and correlation attempts have been controversial.

Because of the pinkish hue, Lineback and others (1974) assumed that the Shorewood must be the equivalent of the oldest red till unit known, the Ozaukee. Because the Ozaukee was not formally defined at that time they gave it the name Shorewood for the prominent exposures at the bluff top along the Village of Shorewood, Wisconsin. They then averaged the clay mineral values from the offshore samples with an onshore sample of their presumed equivalent till exposed in the bluff (apparently an oxidized - and thus altered - sample of the Ozaukee), disregarding marked differences in both clay mineralogy and color. We believe there was insufficient evidence for correlation; the onshore sample was inappropriately averaged with the offshore material causing a false average clay mineral composition for the Shorewood. Hence, in later reports the incorrect averages in table 2 of Lineback and others were adopted. We use the correct averages in their table 1.

Mickelson and others (1977) also correlated the Shorewood to the oldest red till unit, 3A (Ozaukee). Acomb and others (1982) apparently recognized the discrepancies in color and clay mineralogy and provisionally correlated the Shorewood to till unit 2c (Oak Creek 4 till), which they believed was the youngest Oak Creek till. But, the Oak Creek 4 till color and clay mineralogy are even more distinct from the Shorewood than is the Ozaukee. Recognizing the problems in correlation, Mickelson and others (1984) correlated the Shorewood Till to a loosely defined interval spanning the upper Oak Creek and lower Kewaunee Formations.

All past correlation attempts assumed that the Shorewood Till, as defined beneath Lake Michigan, is stratigraphically above the Wadsworth/Oak Creek till. This assumption originated with Lineback and others (1974) from several offshore seismic profiles from which they concluded that the southern extent of the Shorewood Till was a terminal moraine north of points where Wadsworth Till was recovered. However, on none of the lines is the reflector beneath the Shorewood, and presumably marking the top of the Wadsworth Till traceable to a point where Wadsworth/Oak Creek till was recovered. Even if their interpretation is correct, and the Shorewood Till overlies some part of the Wadsworth/Oak Creek units, it does not follow that the entire Wadsworth/Oak Creek Formation lies beneath the Shorewood unit. In the bluffs diamicton 1 with dark gray, high illite Wadsworth/Oak Creek composition is present below the younger Oak Creek 1 till. Therefore, the correlation of the Oak Creek 1 till to the Shorewood Till is compatible with the interpretation of the Shorewood till partly overlying the Wadsworth/Oak Creek Formation beneath Lake Michigan, but does not preclude the possibility that additional Wadsworth/Oak Creek till may overlie the Shorewood Till.

The interpretation that the Shorewood Till must be entirely younger than the Wadsworth/Oak Creek till was based on the implicit assumption that the normal or shingled pattern of tills continues northward in the Lake Michigan Basin. On this premise, a till with distinctly different composition found north of the Wadsworth/Oak Creek subcrop must be stratigraphically higher. At least along the current shoreline this premise is false. The same pattern can be present beneath Lake Michigan as well if differential uplift and erosion are responsible for the exposure of successively older tills northward along the current bluffs. The Shorewood till samples were all recovered from the mid-lake high which probably was exposed to subaerial erosion during low stands of Glacial Lakes Milwaukee and Chicago, and were all recovered at the approximate latitude as Milwaukee, the same latitude where the Oak Creek 1 till is finally uncovered from beneath younger Oak Creek tills (fig. 6).

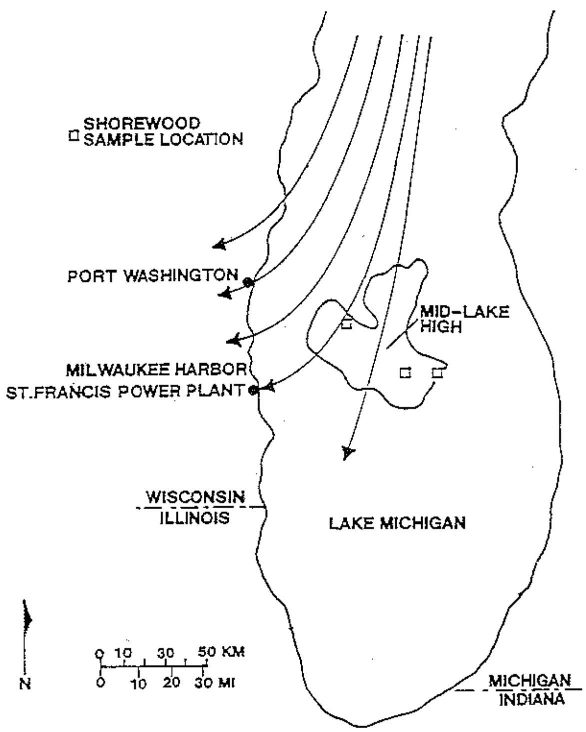


Figure 6. General flow paths (arrows) of the eastern half of a hypothetical Late Woodfordian ice-front.

The difference in composition between the onshore Ozaukee and offshore Shorewood tills might be explained by entrainment of debris and progressive alteration of clay mineral composition downglacier. Therefore, the Shorewood till actually could be the offshore Ozaukee till.

The questionable assumption that a glacier would entrain a significant amount of fresh, previously unincorporated, material near its terminus can be tested. The direction of flow for the Late Woodfordian Lake Michigan lobe is primarily north - south with an east - west component near the glacial terminus (fig. 6), implying a north - south compositional gradient, if compositions were indeed altered. A north - south compositional gradient does not exist within the two till units in question, the Ozaukee and Oak Creek 1 units. Younger tills also do not change in composition over approximately 70 km (Acomb, 1978). The composition of the Ozaukee till is constant from Port Washington, south to its terminus at the St. Francis Power Plant (Borucki and Rovey, 1989; fig. 2 and 3) This 50 kilometer traverse spans the distance over which Shorewood till samples were recovered. The Oak Creek 1 till also has constant composition over 50 km (fig. 2, 3). Therefore an east - west compositional gradient is unlikely, and these till units beneath Lake Michigan should have similar composition to their onshore equivalents.

If the term Shorewood till indeed has any stratigraphic significance, the most likely onshore correlation is to the Oak Creek 1 till. It follows that the Shorewood is not a younger overlying till, but part of the basal Wadsworth/Oak Creek sequence.

SUMMARY

The glacial stratigraphy exposed within the Lake Michigan bluffs is more complex than previously mapped. The Oak Creek Formation includes seven mappable fine-grained units. Five of these are basal till, but the remaining two are crudely stratified diamicton apparently deposited into standing water. The northward succession of older units in the lake bluff result from the southerly dip of the seven units. The most likely explanation for this pattern is an episode of differential uplift and erosion due to isostatic rebound. The oldest definite Oak Creek till is uncovered at the same approximate latitude as offshore samples of the Shorewood Till beneath Lake Michigan, and is the only known onshore till with Shorewood composition. Therefore, the Shorewood Till beneath Lake Michigan is provisionally correlated to the basal portion of the Oak Creek Formation.

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