Overconsolidated Glacial Tills in Eastern Wisconsin

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A geological and geotechnical analysis of overconsolidated till units in eastern Wisconsin forms the basis of this paper. The glacial stratigraphy and geotechnical properties (grain size, clay mineralogy, Atterberg limits, hydraulic conductivity, strength, and compressibility) of the till units are presented based on a large number of tests on samples from a wide geographical area. The clay tills exhibit varying degrees of overconsolidation depending on their vertical location, but there is no discernible difference between the overconsolidation ratio of different till units and the same effective overburden stress. The preconsolidation stresses are much lower than the total ice pressure, indicating limited drainage during ice loading, possibly because of permafrost conditions that prevailed during the deposition of these tills. The higher overconsolidation ratios and preponderance of jointing encountered in the upper 10 m of these tills could be attributed to groundwater lowering resulting from a drier climate that prevailed subsequent to their deposition. The theories of transport and deposition of glacial till are reviewed and interpreted for the tills of eastern Wisconsin.

Although glaciers entered eastern Wisconsin numerous times in the past, only deposits of the last (late Wisconsin) glaciation are present. They overlie dolomite throughout the area. The path of glacier ice was controlled by the regional topography, and lobes of ice went south into Illinois in the Lake Michigan basin (Lake Michigan Lobe) and south to Madison in the Green Bay–Lake Winnebago lowland (Green Bay Lobe). The lobes advanced into Wisconsin about 23,000 B.P. (before present) and fluctuated numerous times until about 11,000 B.P, when ice finally left the area. The glacier fluctuations left till sheets of different composition, and texture is controlled mostly by the absence or presence and extent of ice-marginal lakes that formed in front of the ice margin. Some readvances of ice incorporated lake sediment, producing a fine-grained till, and other readvances incorporated sand and gravel, producing sandy till.

Significant differences in engineering characteristics may also result from the nature of glacial transport and deposition of the till. It has been suggested that most till in areas away from Lake Michigan was deposited by meltout from debris-rich ice after retreat of ice that was frozen to its bed (*1*). Others (*2*) have suggested that transport of sediment takes place beneath the ice (subglacial deforming bed) as a wet, unfrozen sediment. Subsequent deposition would take place by a decrease in glacier driving stress and dewatering. These two modes of deposition may have produced differences in the internal structure of the till and its strength properties.

In this paper, the glacial stratigraphy of eastern Wisconsin and a compilation of till properties are presented, and possible effects of genesis on overconsolidation of these till units are discussed.

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STRATIGRAPHY OF GLACIAL DEPOSITS

The glacial deposits in eastern Wisconsin have been classified into formations and members (3), and their distribution is shown in Figure 1. Each unit contains till and associated sand and gravel. Generally, major distinctions among units are based on till properties. Sand and gravel are then classified in one formation or another based on correlation with a till unit. The lowermost unit in the Lake Michigan basin, the Tiskilwa Member of the Zenda Formation (Figure 1), contains light reddish-brown silty till. In many areas it rests on bedrock, although in shore bluffs in southern Wisconsin it overlies deformed sand and gravel. Because it is generally thin or absent, few engineering properties have been developed for those materials.

Much of southeastern Wisconsin is covered by sandy, stony till of the New Berlin Formation (Figure 1). The till of this formation generally contains about 65 percent sand in the less than 2-mm fraction and is very rich in dolomite (Table 1). It was evidently deposited when glacier ice was excavating bedrock and sand and gravel and therefore depositing coarse till. In many places it rests on dolomite. Along the Lake Michigan shoreline where it outcrops above beach level, it forms a resistant layer and also an accumulation of boulders on the beach, which slows the rate of erosion of the shoreline. Extensive sand and gravel at the surface and in the subsurface are also considered part of the New Berlin Formation.

By 14,000 B.P. ice retreat had extended far enough north to allow a large lake basin to form in what is now southern Lake Michigan (*4*). Subsequent advances then incorporated lake sediment, therefore depositing a clayey till. Within 10 km of the Lake Michigan shoreline and in the Lake Winnebago–Green Bay lowland, till sheets are commonly separated by lake sediment units that are silty clay or interbedded fine sand and silt. The Oak Creek Formation (Wadsworth Formation of Illinois) contains an extensive gray, clayey till that extends from north of Milwaukee around the south end of the lake basin and northward along the shore of the lake in the state of Michigan. The till is thick (greater than 30 m) in moraines but thin (often less than 3 m) between moraines. Very little sand and gravel is associated with this formation, presumably because little coarse material was available to the streams of meltwater that flowed from the ice. The till is fractured to depths of at least 10 m, and this provides for passage of water and contaminants through the upper part of the unit. Below the 10-m depth, where fractures often appear to be closed or nonexistent, hydraulic conductivity is very low. Presence of the fractures in surface material allows rapid recharge of the groundwater system in locations where Oak Creek till is less than about 10 m thick over sand or sand and gravel. Although moraines in the Oak Creek Formation indicate several readvances, there is no significant difference in engineering properties of Oak Creek till from one moraine to another. In its outer regions (behind what is known as the Valparaiso Moraine) Oak Creek till is thin and sometimes absent.

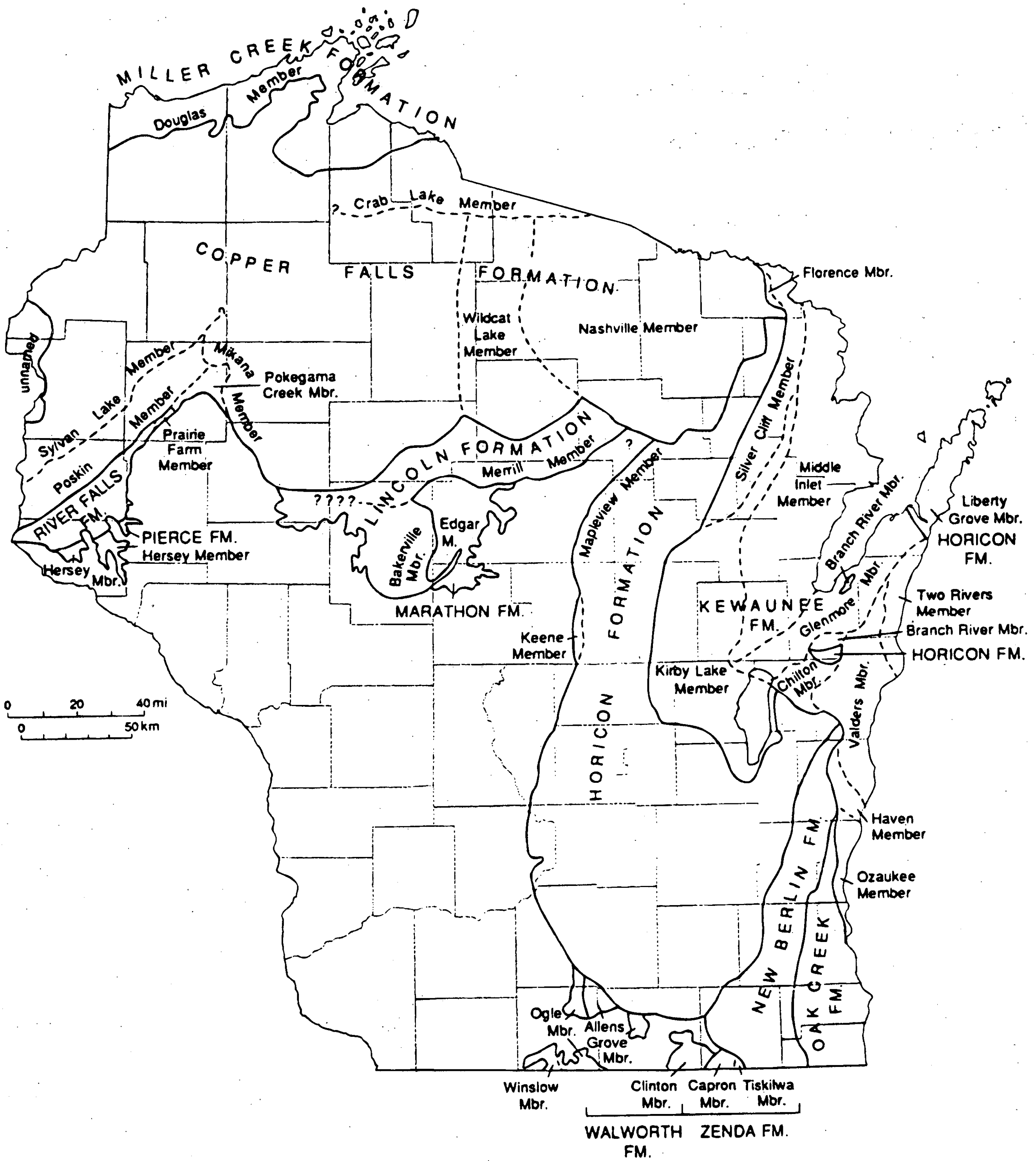

FIGURE 1 Extent of till units in Wisconsin.

At about 13,000 B.P. a series of ice advances began in both the Green Bay and the Lake Michigan lobes that deposited so-called "red till." Just previous to 13,000 B.P. drainage from Lake Superior carried red clay from that basin into the Green Bay and Lake Michigan basins. Subsequent glacial advances deposited reddish-brown silty clay till throughout eastern and northeastern Wisconsin. All of these units are included in the Kewaunee Formation, and numerous members have been described and defined (Figure 1), (*5,6*).

Clayey red-brown till extends southward to Milwaukee in the Lake Michigan Lobe and just south of Lake Winnebago in the Green Bay Lobe. There is little documentation of the engineering properties of these units in the Green Bay Lobe, but those along the Lake Michigan shoreline were analyzed in a 1977 shoreline erosion study (*7*). Grain size and other characteristics of the units are given in Tables 1 and 2. Most of the members cannot be distinguished in the field unless the stratigraphic position is known. A combination

TABLE 1 Mean Grain Size and Atterberg Limits of Tills in Eastern Wisconsin

Till Unit	Percent* Sand	Percent* Silt	Percent* Clay	Number of Samples	Liquid Limit (%)	Plasticity Index	Number of Samples	Activity
Two Rivers M.&	31	50	19	11	26	12	3	0.63
Valders M.&	30	52	18	33	29	15	54	0.83
Haven M.&	16	56	28	27	28	15	14	0.53
Ozaukee M.&	13	47	40	19	28	14	25	0.35
Oak Creek Fm.	12	53	35	566	31	15	627	0.42
New Berlin Fm.	58	29	13	15	17	4	14	0.31
Tiskilwa M.	42	35	23	8	22	9	4	0.39

* Percent of < 2mm fraction. Upper size boundaries used are 2, 0.0625, and 0.002 mm for sand, silt and clay, respectively. Standard deviations were 4 to 8 for grain size and 2 to 6 for Atterberg limits.
& Members of the Kewaunee Formation. Tiskilwa is a member of the Zenda Formation.

of clay mineral composition, texture, and magnetic susceptibility can be used to distinguish the units in the laboratory, and these are described in more detail by Acomb (*8*). Throughout the extent of the Kewaunee Formation, lake sediments are interbedded with the till units. Many of the lake sediments along the Lake Michigan shoreline are interbedded fine sand and silt. In the central part of the Green Bay–Lake Winnebago basin, laminated silt and clay and, in places, massive lake sediment can be mistaken for till.

GEOTECHNICAL PROPERTIES

The soils of eastern Wisconsin vary considerably and, as discussed, can be broadly grouped as glacial till, lacustrine silt and clay, and sandy outwash based on their genesis and geotechnical behavior. The first two are generally cohesive, and the last is cohesionless. The properties and behavior of only the tills are considered here. The geotechnical properties of each unit and variation of these properties between units are presented.

Index Properties

The mean index properties of the till units are summarized in Table 1. Size of the sample population varies from one till unit to another, from as few as 3 to as many as 627 samples. The liquid limits and plasticity indices for all tills, except New Berlin and Tiskilwa tills, vary in a relatively narrow range. Practically all of the means for liquid limit vary between 22 and 31, with corresponding means for plasticity index between 9 and 15 percent. These tills can be classified broadly as low-plasticity silts and clays (CL or CL-ML according to the Unified Soil Classification System). New Berlin till has distinctly different composition and index properties compared with the other tills. However, differences in these properties for the remaining till units are not significant.

The mean textural composition given in Table 1 and the mean clay mineral percentages given in Table 2 indicate marked differences in clay content and amount of expandable minerals among these till units that are not reflected in the Atterberg limits. For example, Ozaukee till has a clay content 12 to 22 percent higher than Haven and Valders tills, respectively (Table 1), yet its liquid limit falls within the same range as those of the Haven and Valders tills. Mean activity numbers, obtained by dividing the mean plasticity index by the mean percent clay fraction, vary somewhat from one till unit to another, often balancing the influence of texture on Atterberg limits, resulting in materials hard to differentiate on the basis of Atterberg limits alone. These groups are usually fairly easily distinguishable by color, and the so-called red tills (Two Rivers, Valders, Haven, and Ozaukee) have long been recognized as distinct from the "gray tills" (Oak Creek) (*9*).

TABLE 2 Mean Relative Clay Mineral Percentages of Tills in Eastern Wisconsin

Till Unit	Percent Expandable Clays*	Percent Illite*	Percent Kaolinite and Chlorite*	Number of Samples Tested
Two Rivers Member&	35	52	13	42
Valders Member&	46	42	12	53
Haven Member&	25	56	19	58
Ozaukee Member&	20	60	20	20
Oak Creek Formation	14	70	16	81
New Berlin Formation	17	66	17	26
Tiskilwa Member	18	67	15	24

*Percentages are relative amounts of clay minerals analyzed (total always adds to 100%). Expandables include smectites and vermiculite. Standard deviations are typically less than 5.
&Members of the Kewaunee Formation. Tiskilwa is a member of the Zenda Formation.

TABLE 3 Mean Hydraulic Conductivity of Tills in Eastern Wisconsin

Till Unit	Laboratory Hydraulic Conductivity (cm/s)	Field Hydraulic Conductivity (cm/s)
Two Rivers Member*	4.0×10^{-8} (11)	- - -
Valders Member*	4.0×10^{-7} (19)	3.2×10^{-5} (12)
Haven Member*	5.0×10^{-8} (27)	5.0×10^{-6} (9)
Ozaukee Member*	- - -	1.6×10^{-7} (1)
Oak Creek Formation	1.8×10^{-8} (102)	1.4×10^{-8} (153)
New Berlin Formation	- - -	2.0×10^{-5} (20)

Note: Number of tests is given in parentheses.

* Members of the Kewaunee Formation.

Hydraulic Conductivity

Hydraulic conductivity data from solid waste, hazardous waste, and sewer pipeline investigations submitted to the Wisconsin Department of Natural Resources by engineering firms were grouped according to till stratigraphic units (*10*) and were supplemented by data from new field sites (*11*). Differences in hydraulic conductivities of the till units are controlled by the grain size distribution of the till. Table 3 presents the mean hydraulic conductivities of various till units as measured in the field as well as on laboratory samples. The influence of the coarser texture of New Berlin till (Table 1) is reflected in its higher hydraulic conductivity. Field-measured hydraulic conductivity of the fine-grained units (all but New Berlin) is higher than laboratory-measured values. This difference is probably due to significant fracture porosity observed in the upper several meters of the fine-grained tills. Fractures and sedimentary heterogeneity in the upper 10 m cause hydraulic conductivity to be much higher than below the 10-m depth (*12*).

Shear Strength

The mean natural water content and density values of the tills are given along with the effective strength parameters in Table 4. The lack of differentiation observed in the Atterberg limits of the Kewaunee and Oak Creek formations is also apparent for the natural water content. Mean unit dry weights also vary in a relatively small range (17.7 to 19.9 kN/m^3), and all of these tills are very dense. The standard penetration number of the tills varies with water content, from a high of about 50 down to 20 blows /0.3 m. The logarithm of unconfined strength of the tills follows a typical linear relationship with water content. There is an observable differentiation in this relationship between the Kewaunee and Oak Creek formations. The unconfined compressive strength of these till units varies between 200 and 500 kPa (*13*).

The effective strength parameters, ϕ' and c' (Table 4), are parameters normalized with respect to the influence of consolidation pressure and corresponding equilibrium void ratio. Thus, they are fundamental parameters and basically are functions of the composition, texture, fabric, and stress history of soils. They are determined from consolidated, undrained, triaxial compression tests with measured pore pressures. The sample population is much smaller for these tests, varying from one to five samples per till unit; however, often the samples of the same unit were obtained over great distances from each other. Based on the *SD* of the effective friction angle and cohesion, it becomes apparent that the shear strength parameters vary within very narrow limits for a given till unit despite the geographic distances involved. The effective angle of internal friction,

TABLE 4 Mean Natural Density, Water Content and Effective Strength Parameters of Tills in Eastern Wisconsin

Till Unit	Dry Unit Weight (kN/m^3)	Water Content (%)	Friction Angle* (degrees)	Cohesion* (kPa)
Two Rivers Member&	19.0	16	30	11
Valders Member&	17.7	17	29	28
Haven Member&	18.6	17	31	24
Ozaukee Member&	17.9	18	30	7
Oak Creek Formation	17.7	18	31	6
New Berlin Formation	19.9	8	35	0
Tiskilwa Member	19.3	14	27	17

* Number of samples tested varied from 1 to 11. Standard deviations were 0.5 to 3 degrees for friction angle and 5 to 13 kPa for cohesion.

& Members of the Kewaunee Formation. Tiskilwa is a member of the Zenda Formation.

ϕ′, had an *SD* of less than 0.5 to 3 degrees in each till unit. Most units exhibited no or low effective cohesion intercept, whereas Haven and Valders tills had effective cohesion intercepts varying between 20 and 30 kPa. A generalization cannot be drawn relating the Atterberg limits of a particular sample and its effective strength parameters. Presence of higher cohesion intercept in the Haven and Valders Members indicates higher overconsolidation of these tills in the range of test consolidation pressures (100 to 600 kPa). This overconsolidation can possibly be traced back to the processes that took place during deposition, postdepositionally, or both, and this is discussed in the next section.

Compressibility and Preconsolidation

The conventional consolidation tests performed on selected samples from the Kewaunee Formation tills provide information regarding the compressibility and stress history (Table 5). The preconsolidation stress (the maximum vertical stress under which the soil is consolidated) can be estimated from a laboratory compression curve by observing the stress at which a change in the slope of the compression curve occurs from recompression to virgin compression. This transition is gradual, so it may not be very easy to identify the preconsolidation stress. Four methods of determining the preconsolidation stress, including the most widely used procedure suggested by Casagrande (*14*), were used (*15*). The most probable values of the preconsolidation stress based on these methods are summarized in Table 5 along with the other compression parameters.

These tills, in general, are relatively stiff, with compression indices between 0.10 and 0.20 with a mean value of 0.16. The compression index values obtained from the consolidation tests compare well with the values predicted by the empirical equation based on liquid limit (*16*). The overconsolidation ratio (OCR) varies in general with depth of the sample or, more specifically, with the effective overburden stress (σ_0) as shown in Figure 2. For $\sigma_0 < 100$ kPa, OCR is quite high (9 to 31); for $\sigma_0 = 100$ to 200 kPa, OCR = 4, and for larger σ_0, OCR decreases to 2 (at 330 kPa). Presence of fractures in the upper 6 to 9 m in these tills supports the high overconsolidation values observed in the laboratory for $\sigma_0 < 100$ kPa.

OVERCONSOLIDATION OF TILLS

The characteristics of tills deposited by various glacial advances are relatively consistent over extended distances (Figure 1), roughly along the direction of transport. Natural water content, liquid limit, and plasticity index (Tables 1 and 3) show minor differences among the various tills, with the exception of New Berlin till, even though they exhibit discernible compositional differences. The effective friction angle also varies over a relatively narrow range within each till unit as well as between till units, except New Berlin till. Effective cohesion intercept, although varying relatively little within each till unit over large geographic distances, is markedly higher for Valders and Haven tills than the others. The consolidation stress history, in addition to the compositional factors, is the most important factor in defining the mechanical properties of soils. Therefore, a careful consideration of stress history is warranted for a clearer understanding of the mechanical behavior of the tills.

Consolidation Stress History

Traditionally, the transport of sediment by glaciers has been observed and interpreted to be either supraglacial (on top of the ice), englacial (within the ice), or basal (as a debris-rich ice layer at the base of the glacier). Release of sediment from the base of the ice to produce till takes place by lodgment (plastering on) from beneath an active glacier sole or by melt-out of the debris-rich layer after it has stopped being transported by the glacier. Sediment is also released at the ice surface because of melting or sublimation. This sediment is slowly let down onto the ground surface as the ice below it melts. Both of these processes have been observed on modern glaciers in Alaska (*17–19*). Till deposited from basal debris-rich ice is called basal till and is characterized by having fairly uniform properties over broad areas, a wide range in grain size, poor sorting, and little stratification, and it is being compact and sometimes overconsolidated. Supraglacial sediment is typically loose and normally consolidated, more variable in texture over small distances both vertically and horizontally, and typically more rich in boulders.

In an earlier investigation of the preconsolidation characteristics of eastern Wisconsin tills by the authors, it was believed that there

TABLE 5 Compressibility and Preconsolidation of Kewaunee Formation Tills in Eastern Wisconsin

Till Unit	Depth of Sample (m)	Initial Void Ratio	Compression Index	Effective Overburden Stress (kPa)	Preconsolidation Stress (kPa)	Over-consolidation Ratio, OCR
Two Rivers	1.5	0.50	0.20	30	931	31
Member	4.8	0.49	0.15	109	518	5
Valders	2.4	0.38	0.10	58	518	9
Member	6.9	0.54	0.20	156	614	4
Haven	6.5	0.48	0.17	87	835	10
Member	6.6	0.44	0.12	132	518	4
	8.4	0.49	0.14	182	672	4
	9.2	0.48	0.11	118	413	4
Ozaukee	6.0	0.54	0.20	130	422	4
Member	12.3	0.54	0.13	156	413	3
	15.3	0.51	0.20	330	634	2
	15.3	0.48	0.17	330	672	2

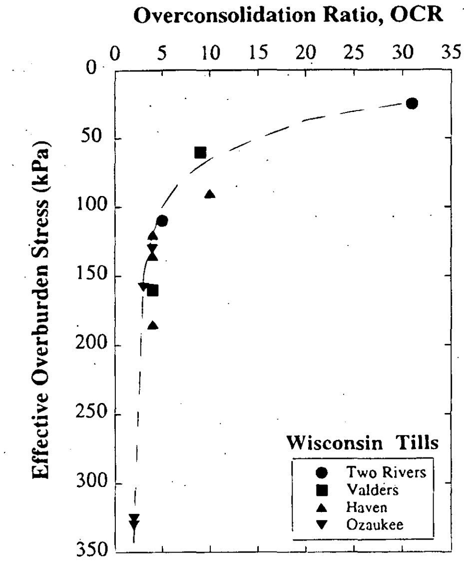

FIGURE 2 Over consolidation ratio versus effective overburden stress for Kewaunee Formation.

was a difference in the overconsolidation of these tills and thus in their mode of deposition (*20*). Several workers, especially Boulton (*21*), have also tried to explain the presence or absence of overconsolidation in tills. Harrison (*22*) suggested that the weight of glacial ice was responsible for creating the preconsolidation often found in tills. Others have suggested that desiccation, fluctuation of the water table, erosion of overlying materials, and ability of pore water to drain under loading are also ways of explaining preconsolidation (*23*). Boulton (*21*) concluded that the state of consolidation "depends almost entirely on depositional and postdepositional changes." He also concluded that lodgment tills are generally overconsolidated, that flow tills often have low preconsolidation pressures, and that melt-out (ablation) tills seem likely to be normally consolidated. In the cases investigated here it seems likely that all of the tills are basal in origin. Washed or flow tills have been noted in local areas but were not included in the samples reported here. In some localities, the lower parts of the till units are probably waterlaid, but these were also avoided for the geotechnical sampling. Thus, the apparent difference in the overconsolidation between the two younger units (Valders and Haven) and the two older units (Ozaukee and Oak Creek) as evidenced by the difference in effective cohesion and preconsolidation stress had to be explained (*20*).

All of these units occur at different heights above Lake Michigan in different places along the bluff, and these samples of the tills were taken at various depths below the bluff top. It seems unlikely that the mode of deposition or general source of materials was different. All of the units are fine-grained compared with the older New Berlin till. All seem to have been derived from fine-grained lake sediments deposited in the Lake Michigan basin. The lake level during the time of deposition of the tills was probably the same (Glenwood, or about 18 m above present level) during the deposition of all of these tills. There is no consistent relationship between the presence or lack of overconsolidation and the presence of permeable sandy units above or below the till. There is no stratigraphic reason why Haven and Valders tills should have drained more easily than the others.

The consolidation tests (Table 5) indicate that, in all cases, the preconsolidation stress is less than the total effective stress that the glacier ice would be expected to exert (as much as 3000 kPa) if tills were deposited under fairly thick ice or during ice advance and if pore pressures were fully dissipated. Another possible factor causing different overconsolidation is a difference in load due to ice thickness. This explanation would require thicker ice during or after the deposition of Haven and Valders tills than the older tills. There seems to be no evidence of this (*5*). In addition, there are situations in which overconsolidated till lies stratigraphically above, in the same section, as a till showing less overconsolidation. Clearly, factors other than ice thickness are more important in determining the values measured today.

The degree of overconsolidation exhibited by a soil is related not only to ice thickness but also to the duration of loading and the ability to drain. As discussed here, the duration of loading (hundreds of years) is sufficient for 100 percent consolidation if adequate drainage is provided, and therefore the ability to drain appears to be the remaining factor controlling the amount of overconsolidation. It is expected that near the margin of a stagnant (not advancing) glacier, complete drainage could occur through the underlying layers; however, farther under the ice mass, where flow paths are longer, incomplete drainage would be the rule rather than the exception even though downward groundwater gradients might be quite significant. Field investigations (*24*) have indicated that the pore-water pressure at the bed of modern temperate glaciers can have a head on the order of two-thirds of the ice thickness. In this situation, the soil would be consolidating under an effective stress equal to only a portion of the weight of the ice mass. This may partially explain the relatively low overconsolidation values of these tills but not the differences among their OCRs.

In the late 1970s it was thought that a likely reason for differences in OCRs was the temperature regime and resulting distribution of frozen or melted bed and subbed (*20*). Attig et al. (*25*) have shown that in southern Wisconsin, tundra conditions were present until about 14,000 B.P., when the ice melted and a spruce-dominated woodland developed. They suggest that permafrost lasted until at least 13,000 B.P. in northeast Wisconsin.

The best minimum date available on the advance of the Ozaukee till is about 13,500 B.P. in the northern part of the lower peninsula of Michigan (*26*). Minor retreat after deposition of this till was followed by advance and deposition of the Haven and Valders tills about 13,000 B.P. All but Two Rivers till, deposited about 11,800 B.P., were deposited under permafrost conditions. Therefore, it was concluded (*20*) that the difference in preconsolidation of the tills might be due to the presence or absence of ice in pore spaces of the till while it was under an ice load. Additional consolidation data obtained since then, as presented in Table 5 and Figure 2, now indicate that the differences in overconsolidation are more a function of sample depth than till unit, with all tills having approximately the same OCR at the same range of effective overburden stress, i.e., OCR of 4 for σ_0 of a range of 100 to 200 kPa.

Recent Theories of Transport and Deposition of Tills

During the last 10 years a new hypothesis of subglacial transport and deposition has developed. Evidence of deformation, such as folding and faulting, has commonly been observed in and beneath till sheets. Most interpretations before 1980 stated that the till was carried as debris-rich ice and that the deformation of stratified sediments below took place in either a frozen or unfrozen state because of shear stress applied from above. In most deformed units below till, strain is relatively small relative to the movement of the glacier above. Now a number of researchers argue that in some situations, much of the flux of glacier ice is the result of transport on a deforming bed beneath. It is suggested that this unfrozen deforming layer can be several meters thick and can result in till evidently similar in most respects to that derived from basal melting. It is further suggested that this type of deformation takes place beneath the Antarctic ice sheet (*27,28*) as well as the Pleistocene ice sheets (*2,29*). Theoretical considerations are given by Boulton and Hindmarsh (*2*) and Boulton (*30*). Although there is no field evidence for extensive subglacial deformation in the unfrozen state in eastern Wisconsin, it may be that within the Lake Michigan basin subglacial deformation was a significant contributor to southward transport of sediment and ice.

Whether or not sediment is mobilized and transported beneath the ice is controlled by the relationship between shear strength, as determined by the Coulomb relationship, and the driving stress or basal shear stress. The driving stress is controlled by the following relationship:

$$\tau = \rho g h \sin \alpha$$

where

τ = shear stress,
ρ = density of ice above,
g = acceleration of gravity,
h = thickness, and
α = surface slope of the ice.

Sin α and h are self-adjusting to produce the flow of ice required by continuity arguments. It is argued that where bed strength is low because of low effective pressure (high pore pressure) or where the sediment has low friction angles, ice surface slope is low, and thickness is not as great for any given distance back of the margin. In areas where bed materials are stronger, the ice surface slope is greater, and the ice is thicker at any given distance behind the ice margin.

It is argued that there are several degrees of deformation possible in deformable beds. The thickness of the continuously deforming layer is a function of the balance between strength and driving stress. Hart et al. (*31*) predict that this reaches a maximum perhaps 50 km behind the ice margin, and the base of deformation decreases under thicker ice as well as toward the ice margin. Under the right conditions up to 10 m of sediment could be continuously deforming and producing the layers that are now interpreted as till.

Alley and others (*27,28*) have argued that this continuously deforming layer is responsible for the rapid flow velocities of ice streams in the Antarctic. Although this has not been observed first hand, geophysical evidence suggests a wet, very weak layer just beneath the base of the glacier. Because of the shape of the Lake Michigan basin it is possible that the ice sheet here behaved in a similar way. Water would have been confined because of the shape of the basin and the fine-grained nature of rocks and lake sediment beneath. This would lead to low effective stress and relatively low resistance to deformation. Ronnert (*32*) examined sediment at three localities along the Lake Michigan shoreline and concluded that sediments were deposited from debris-rich ice and were not continuously deforming unfrozen sediment. Others, however (*33*), have argued that there was likely a deforming bed in the Lake Michigan basin at the time the tills under discussion were deposited.

It is not clear how the process of deposition affected the OCR, except that if the zone of deforming bed thinned as ice thinned, this hypothesis would predict larger OCRs with depth. The overconsolidation profile evident in Figure 2 shows the highest OCRs near the ground surface, the opposite of the above hypothesis. On the other hand, a drier climate prevailed in this region between 9,000 and 5,000 B.P., which would be expected to have lowered the groundwater table to levels below the current levels. Soderman and Kim (*34*) suggested that a period of lower water table was responsible for overconsolidation of near-surface samples of St. Claire till in Ontario. This argument is further supported by the evidence of oxidation of the tills sampled below the current groundwater table. The authors noted in field investigations that such samples had a reddish-gray matrix with a thin reduction zone adjacent to the joints in the till. This long-term lower groundwater episode is likely to explain the overconsolidation of the tills and the preponderance of jointing observed in the upper 6 to 9 m, which coincides with the most heavily overconsolidated till samples.

CONCLUSIONS

The glacial stratigraphy and geotechnical properties (grain size, clay mineralogy, Atterberg limits, hydraulic conductivity, strength, and compressibility) of eastern Wisconsin tills are presented based on a large number of tests conducted on these materials under the authors' supervision over many years. These till units show discernible differences in their grain size distribution and mineralogical composition. However, these differences are not reflected in their index properties (Atterberg limits) and are not traceable in their strength and compression parameters. In other words, index properties do not lead to identifying different till units. The clay tills exhibit varying degrees of overconsolidation depending on their depth, but there is no discernible difference between the OCR of different till units with the same effective overburden stress. The preconsolidation stresses are much lower than the total ice pressure, indicating limited drainage during ice loading possibly due to permafrost conditions that prevailed during the deposition of these tills. Decreasing OCRs with depth are not consistent with the view of a thinning deforming layer during deglaciation. The higher OCRs and the preponderance of jointing encountered in the upper 10 m of these tills could be attributed to groundwater lowering resulting from the drier climate that prevailed subsequent to the formation of these tills.

The ability to identify different till units is important because it leads to better correlation among the properties of samples retrieved from a given unit. The ranges of values reported for engineering properties allow better prediction of the distribution of measured properties based on a smaller number of samples. Furthermore, a clear knowledge of the cause of overconsolidation is important in assisting us to know where to expect it because it is an important factor in differentiating the engineering properties of the tills.

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REFERENCES

1. Clayton, L., D. M. Mickelson, and J. W. Attig. Evidence Against Pervasively Deformed Bed Material Beneath Rapid Moving Lobes of the Southern Laurentide Ice Sheet. *Sedimentary Geology*, Vol. 62, 1989, pp. 203–208.
2. Boulton, G. S., and R. C. A. Hindmarsh. Sediment Deformation Beneath Glaciers: Rheology and Geological Consequences. *Journal of Geophysical Research*, Vol. 92, 1987, pp. 9059–9082.
3. Mickelson, D. M., L. Clayton, R. W. Baker, W. M. Mode, and A. F. Schneider. *Pleistocene Stratigraphic Units of Wisconsin*. Miscellaneous Paper 84-1. Wisconsin Geological and Natural History Survey, 1984.
4. Hansel, A. K., and W. H. Johnson. Fluctuations of the Lake Michigan Lobe During the Late Wisconsin Subepisode. *Sveriges Geologigska Undersokning*, Series Ca 81, 1992, pp. 133–144.
5. Acomb, L. J., D. M. Mickelson, and E. B. Evenson. Till Stratigraphy and Late Glacial Events in the Lake Michigan Lobe of Eastern Wisconsin. *Geological Society of America Bulletin*, Vol. 93, 1982, pp. 289–296.
6. McCartney, M. C., and D. M. Mickelson. Late Woodfordian and Greatlakean History of the Green Bay Lobe, Wisconsin. *Geological Society of America Bulletin*, Vol. 93, 1982, pp. 297–302.
7. Mickelson, D. M., L. J. Acomb, N. Brouwer, T. B. Edil, C. Fricke, B. J. Haas, D. Hadley, C. Hess, R. Klauk, N. Lasca, and A. F. Schneider. *Shoreline Erosion and Bluff Stability Along Lake Michigan and Lake Superior Shorelines of Wisconsin*. Shore Erosion Technical Study Technical Report, Coastal Management Program, State Planning Office, 1977.
8. Acomb, L. J. *Stratigraphic Relations an Extent of Wisconsin's Lake Michigan Lobe Red Tills*. M. S. thesis. Department of Geology and Geophysics, University of Wisconsin-Madison, 1978.
9. Alden, W. C. *The Quaternary Geology of Southeastern Wisconsin*. Professional Paper 106. U.S. Geological Survey, 1918.
10. Rodenbeck, S. A. *Merging Pleistocene Lithostratigraphy with Geotechnical and Hydrologic Data—Examples from Eastern Wisconsin*. M. S. thesis. University of Wisconsin-Madison, 1988.
11. Simpkins, W. W. *Genesis and Spatial Distribution of Variability in the Lithostratigraphic, Geotechnical, Hydrogeological, and Geochemical Properties of the Oak Creek Formation in Southeastern Wisconsin*. Ph.D. thesis. University of Wisconsin-Madison, 1989.
12. Simpkins, W. W., S. A. Rodenbeck, and D. M. Mickelson. Geotechnical and Hydrological Properties of Till Stratigraphic Units in Wisconsin. *Proc., Symposium on Methods and Problems of Till Stratigraphy*, LUNDQUA Report, Vol. 32, 1990, pp. 11–15.
13. Edil, T. B., and B. J. Haas. Proposed Criteria for Interpreting Stability of Lakeshore Bluffs. *Engineering Geology*, No. 16, 1980, pp. 97–110.
14. Casagrande, A. The Determination of the Pre-Consolidation Load and Its Practical Significance. Discussion D-34, *Proc. 1st International Conference on Soil Mechanics and Foundation Engineering*, Cambridge, England, Vol. III, 1936, pp. 60–64.
15. Pulley, S. R. *Determination of Preconsolidation Pressures of Wisconsin Glacial Tills by Various Methods*. M.S. thesis. University of Wisconsin-Madison, 1980.
16. Terzaghi, K., and R. B. Peck. *Soil Mechanics in Engineering Practice*, 2nd ed. John Wiley & Sons, Inc., New York, 1967.
17. Mickelson, D. M. Nature and Rate of Basal Till Deposition in a Stagnating Ice Mass. *Arctic and Alpine Research*, Vol. 5, 1973, pp. 17–27.
18. Lawson, D. E. *Sedimentological Analysis of the Western Terminus Region of the Matanuska Glacier, Alaska*. Report 79-9. U.S. Army Engineer Cold Regions Research and Engineering Laboratory, 1979.
19. Boulton, G. S. On the Deposition of Subglacial and Meltout Tills at the Margin of Certain Svalbard Glaciers. *Journal of Glaciology*, Vol. 9, 1970, pp. 231–245.
20. Mickelson, D. M., L. J. Acomb, and T. B. Edil. The Origin of Preconsolidated and Normally Consolidated Tills in Eastern Wisconsin, U.S.A. In *Moraines and Varves: Origin, Classification and Genesis* (C. Schluchter, ed.), Balkema, Rotterdam, 1979, p. 179–188.
21. Boulton, G. S. The Genesis of Glacial Tills—A Framework for Geotechnical Interpretation. *Proc., Symposium on The Engineering Behavior of Glacial Materials*, Midland Soil Mechanics and Foundation Engineering Society, 1975, pp. 53–59.
22. Harrison, W. Marginal Zones of Vanished Glaciers Reconstructed from the Preconsolidation-pressure Values of Over-ridden Silts. *Journal of Geology*, Vol. 66, 1958, pp. 72–95.
23. Dreimanis, A. Tills: Their Origin and Properties. In *Glacial Till* (Legget, ed.), Royal Society of Canada Special Publications, Vol. 12, 1976, pp. 11–49.
24. Hodge, S. M. Direct Measurement of Basal Water Pressures: A Pilot Study. *Glaciol*, Vol. 16, 1976, pp. 205–218.
25. Attig, V. W., D. M. Mickelson, and L. Clayton. Late Wisconsin Landform Distribution and Glacier Bed Conditions in Wisconsin. *Sedimentary Geology*, Vol. 62, 1989, pp. 399–405.
26. Farrand, W. R., R. Zahner, and W. S. Benninghof. *Cary—Port Huron Interstate: Evidence from a Buried Bryophyte Bed, Cheboygan County, Michigan*. Geological Society of America Special Paper 123, 1969, pp. 249–262.
27. Alley, R. B., D. D. Blankenship, C. B. Bentley, and S. R. Rooney. Deformation of Till Beneath Ice Stream B, West Antarctica. *Nature*, Vol. 322, 1986, pp. 57–59.
28. Alley, R. B., D. D. Blankenship, C. B. Bentley, and S. R. Rooney. Till Beneath Ice Stream B.3. Till Deformation: Evidence and Implications. *Journal of Geophysical Research*, Vol. 92, 1987, pp. 8921–8929.
29. Boulton, G. S., and A. S. Jones. Stability of Temperate Ice-caps and Ice-sheets Resting upon Beds of Deformable Sediment. *Journal of Glaciology*, Vol. 24, 1978, pp. 29–44.
30. Boulton, G. S., and K. E. Dobbie. Consolidation of Sediments by Glaciers: Relations Between Sediment Geotechnics, Soft-Bed Glacier Dynamics and Subglacial Ground-Water Flow. *Journal of Glaciology*, Vol. 39, No. 131, 1993, pp. 26–44.
31. Hart, J. K., R. C. A. Hindmarsh, and G. S. Boulton. Styles of Subglacial Glaciotectonic Deformation within the Context of the Anglian Ice Sheet. *Earth Surface Processes and Landforms*, 1990, Vol. 15, pp. 227–241.
32. Ronnert, L. Genesis of Diamicton in the Oak Creek Formation of South-East Wisconsin, U.S.A. *Sedimentology*, Vol. 39, 1992, pp. 177–192.
33. Clark, P. U., and G. A. Rudloff. Sedimentology and Stratigraphy of Late Wisconsin Deposits, Lake Michigan Bluffs, Northern Illinois. In *Late Quaternary History of the Lake Michigan Basin* (A. F. Schneider and G. S. Fraser, eds.), Geological Society of America Special Paper 251, 1990, pp. 29–41.
34. Soderman, L. G., and Y. D. Kim. Effect of Groundwater Levels on Stress History of the St. Claire Clay Till Deposit. *Canadian Geotechnical Journal*, Vol. 7, No. 173, 1970, pp. 173–193.