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SYSTEMATIC VARIATION IN CLAY-MINERAL COMPOSITION OF WISCONSINAN AGE TILL SHEETS IN THE LAKE MICHIGAN BASIN.

By

G. William Monaghan

A DISSERTATION

Submitted to

Michigan State University

in partial fulfillment of the requirements

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DOCTOR OF PHILOSOPHY

Department of Geological Sciences

1989

ABSTRACT

SYSTEMATIC VARIATION IN CLAY-MINERAL COMPOSITION OF WISCONSINAN AGE TILL SHEETS IN THE LAKE MICHIGAN BASIN.

By

G. William Monaghan

X-ray diffraction analyses of till samples collected from multi-till exposures along the Lake Michigan shoreline in Wisconsin and Michigan show a systematic variation in the clay-mineral composition of successive till sheets. A general increase in the relative amount of 10Å clay occurs beginning with early or middle Wisconsinan (Altonian) Glenn Shores till and through late Wisconsinan (mid-Woodfordian) Ganges-New Berlin till and Saugatuck-Oak Creek till. A significant decrease in the relative amount of 10Å clay occurs within post-Mackinaw Interstade (late Woodfordian) Ozaukee-Haven and Two Rivers tills.

Lacustrine sediments sampled from between till sheets maintained a generally constant mineralogy with equal amounts of 7Å and 10Å clays from the mid-Wisconsinan until the Two Creeks Interstade. Post-Two Creekan lacustrine sediments, however, show a significant increase in 10Å clay content. This suggests that incorporation of lacustrine clay within the till in not responsible for the observed systematic variation in till clay mineralogy. A strong, positive relationship, however, exists between the amount of shale/siltstone clasts in the till and the amount of 10Å clay in

the tills. This indicates that the variation in till clay mineralogy results from erosion of differing proportions of lacustrine clay and shale during Wisconsinan advances of the Lake Michigan Lobe.

A progressive unroofing of shale outcrops during successive readvances of the Lake Michigan Lobe is believed responsible for increasing amounts of shale clasts and 10Å clay minerals within successively younger till sheets in the southern half of the Lake Michigan basin. A lack of shale outcroppings as well as compositional similarity between Port Huron and Greatlakean age tills and Lake Chicago sediments, however, suggest that clay minerals in tills of the northern half of the basin were derived primarily from reworking underlying lacustrine clay and silt deposits.

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INTRODUCTION

Research conducted in the Great Lakes region over the past 25 years has both revised and refined the Wisconsinan stratigraphic system (Willman and Frye 1970; Dreimanis and Goldthwait 1973; Evenson 1973; Acomb et al. 1982; Mickelson et al. 1984; Monaghan et al. 1986; Monaghan and Larson 1986; Schneider and Need 1985). Part of this system defined along the east and west margins of Lake Michigan, together with probable correlations of till units from lake basins east of Lake Michigan, is shown in Table 1. For instance, Schneider (1983) and Schneider and Need (1985) have described two mid-Woodfordian age till units along the west shore of Lake Michigan in southeastern Wisconsin (tills of the New Berlin and Oak Creek Formations; Table 1) and concluded that a significant retreat of the Lake Michigan Lobe occurred between the deposition of these tills. Just north of this area, in eastern and northeastern Wisconsin, Acomb et al. (1982) have defined three till units related to the Port Huron advance (Ozaukee, Haven, and Valders till members of the Kewaunee Formation; Table 1) and one till unit related to the Greatlakean advance (Two Rivers Till Member, Kewaunee Formation). They have also noted the occurrence of till units older than the Mackinaw Interstade.

Along the east shore of Lake Michigan in southwestern Michigan, Monaghan et al. (1986) have defined three Wisconsinan till sheets (Glenn Shores, Ganges, and Saugatuck; Table 1) and have suggested that a

significant retreat of the Lake Michigan Lobe occurred between deposition of each of these tills. In addition, they have noted that a systematic variation in clay-mineral composition, apparently related to these retreats, occurs from one till sheet to the next.

Although the above studies have contributed to an understanding of the Wisconsinan, they are based primarily on stratigraphic frameworks developed from empirical analysis of lithologic characteristics of till units. Implicit in this empirical approach to stratigraphy is the assumption not only that the lithology of individual till sheets remains constant over long distances, but also that changes in lithologic composition result from some basic change in ice dynamics. Recently, Eyles et al. (1983) have criticized such "proceedual approaches" to description of glacigenic sediments because they often are not related in any simple fashion to depositional environments and do not generally consider facies variability.

The purpose of this paper is two fold. The first is to show that clay-mineral composition systematically varies between successive till sheets deposited during the Wisconsinan Stage throughout the Lake Michigan basin and that this variation is related to significant fluctuations of the Lake Michigan Lobe. The second is to propose a model which accounts for this variation in a basin-wide erosional/ depositional framework.

LAKE MICHIGAN LOBE					SAGINAW LOBE	ERIE LOBE	TIME kB.P.
NE WI.[1]	SE WI.[2]	N IL.[3]	SW MI.[4]	NW MI.[5]	S MI.[6]	ONT.[7]	
Two Rivers				"Red Valders"			
TWO CREEKS INTERSTADE							11.8
Valders Haven Ozaukee		Manitowoc-Shorewood		"Port Huron"			
MACKINAW INTERSTADE							13.3
"Pre-Port Huron"	Oak Creek	Wadsworth	Saugatuck	"Pre-Port Huron"	Bedford	Port Stanley	
MID-WOODFORDIAN INTERSTADE					ERIE INTERSTADE		15.5
	New Berlin	Haeger Yorkville	Ganges		Fulton	Catfish Creek	
MID-WISCONSINAN INTERSTADE					PT. TALBOT INTERSTADE		>40
			Glenn Shores				

Table 1. Correlation chart of selected till sheets in the Great Lakes Region. [1]Acomb et al. (1982); [2]Schneider (1983), Mickelson et al. (1984), and Schneider and Need (1985); [3]Willman and Frye (1970), and Johnson et al. (1985); [4]Monaghan et al. (1986); [5]Melhorn (1954); [6]Monaghan and Larson (1986); [7]Dreimanis and Goldthwait (1973).

LITHOLOGY AND STRATIGRAPHY OF TILL SHEETS IN THE LAKE MICHIGAN BASIN

Methods

Clay Mineralogy: Most techniques employed to quantify clay-mineral compositions involve peak-height measurements of basal (001) X-ray diffraction reflections from 18Å (smectite), 14Å (chlorite and/or vermiculite), 10Å (illite), and 7Å (kaolinite 001 and/or chlorite 002 reflection) clays (Carroll 1972; Brindley and Brown 1980). These measurements are usually reported either as relative percentages of these reflections (Glass 1981; Acomb et al. 1982; Willman et al. 1963) or as simple ratios between two of the peaks (Rieck et al. 1979; Chung 1973; Monaghan and Larson 1986; Monaghan et al. 1986). The latter method, in this case 7Å/10Å peak-height ratios of the clay-size fraction (<2 microns) of till, has been used in this paper to show the variation in relative amounts of 7Å and 10Å clays. Samples of fresh, generally unleached till and lacustrine sediment were pre-treated with sodium acetate, washed with distilled water, deposited on glass slides as a slurry and air dried. They were then placed in an ethylene-glycol atmosphere for 72 hours and X-rayed. Details of these methods are discussed in Monaghan (1984) and Monaghan et al. (1986).

Matrix and Clast Lithology: Both clast and matrix lithology as well as the distribution of grain-sizes in till matrix (<2 mm) are commonly employed by researchers within the Lake Michigan basin to either differentiate till units (Murray 1953; Willman and Frye 1970; Burgis and Eschman 1981; Acomb et al. 1982; Schneider 1983; Schneider and Need 1985; Mickelson et

al. 1984) or to distinguish provenance (Slawson 1933; Krumbein 1933; Anderson 1957). Generally, lithologies are determined by separating the particle size of interest (usually <2mm for matrix and >3-4 mm for clasts) from a bulk sample and simply counting the number of clasts present from each litholologic class. Matrix grain-size distribution data presented in this study are all reported elsewhere and the techniques used are discussed in the appropriate references.

In this study, the lithology of clasts in the till was examined primarily to quantitatively assess the relative abundance of shale clasts present in till. The lithologic classes counted were chosen both because they represent the dominant lithologies present in till within the region (Anderson 1957) and to enable determination of the amount of shale and siltstone compared to other bedrock types occurring in the tills. Determination of the relative amount of shale is important because (as discussed below), shale may represent the dominate source for clay minerals found in till.

Clast lithologies were determined using a composite of samples analyzed for clay-mineral composition. A composite sample was used because it better represents the bulk composition of the till. Approximately equal amounts of individual samples were placed together in a 16 liter vessel and washed in tap water for several hours to disaggregate the composite. The composite was then wet-sieved and the >3 mm size fraction was saved. At least 75 clasts were then counted from the composite sample.

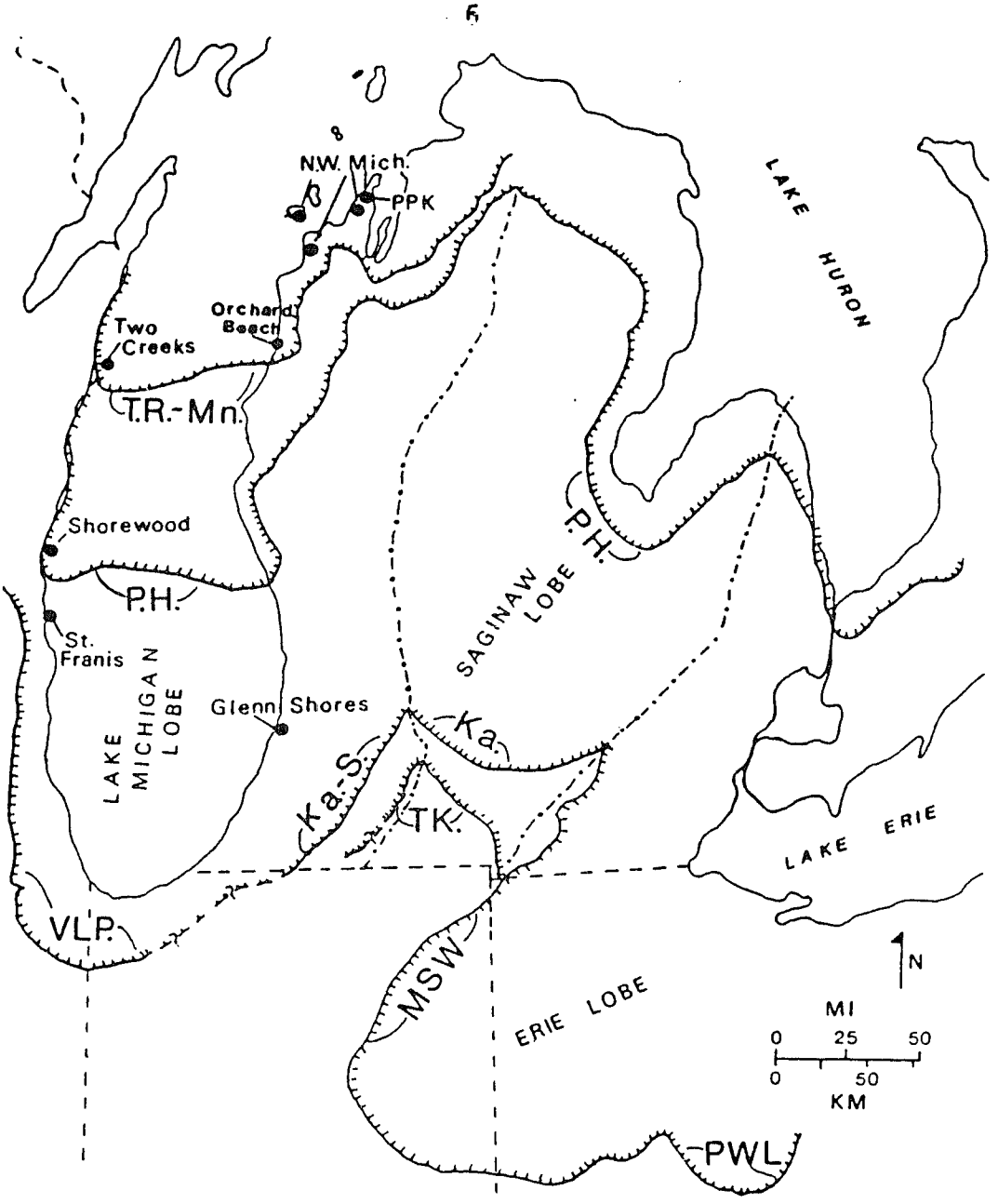


Figure 1 Map of the Great Lakes Region showing the locations of sections studied and moraines of the Erie, Saginaw, and Lake Michigan lobes. Section shown by closed circles. Trend of moraines shown by hatchered line (dashed where approximate); interlobate boundaries shown by dash-dotted line (after Leverett and Taylor 1915).

Ka Kalamazoo Moraine (Saginaw Lobe)
Ka-S Sturgis-Kalamazoo Morainal System
MSW Mississinewa Moraine
PH Port Huron Moraine
PPK Peterson Park Section
PWL Powell Moraine
TK Tekonsha Moraine (Saginaw and Lake Michigan lobes)
TR-Mn Two Rivers (WI) and Manistee (MI) Moraines
VLP Valparaiso Moraine (IN, IL)

Figure 2 Map of axes of major moraines in southwestern Michigan showing the distribution of Saugatuck till (open circles) and Ganges till (closed circles). 7Å/10Å histograms show comparison of the clay-mineral composition of the each of the moraines. Horizontal axis shows 7Å/10Å ratio values; vertical axis shows number of samples with a particular ratio value. Moraine names shown along right side of histograms. Generalized cross section shows the stratigraphy and relationship to sections discussed in the text for the till units along the Lake Michigan shoreline. Moraine positions after Leverett and Taylor (1915); cross section of southwestern Michigan after Larson and Monaghan (1988).

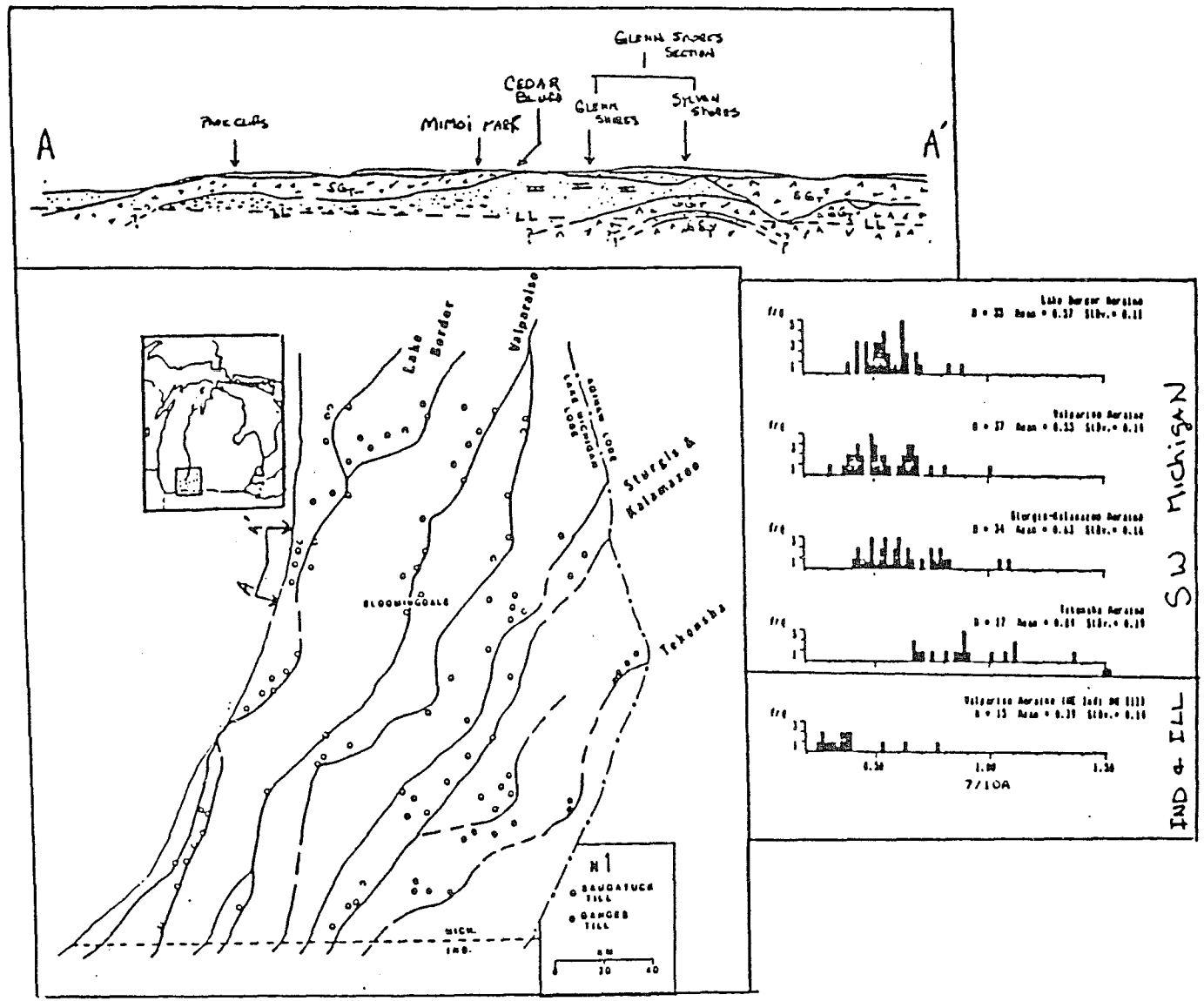

A
A'
Glenn Shores Section
Cedar Bluff
Mimoi Park
Glenn Shores
Sylvan Shores
Lake Border
Valparaiso
Sturgis & Kalamazoo
Tehonsha
A'
Bloomington
N
Sangamon
Danger
Till
km
0
20
40
SW Michigan
IND & ILL
7/10A

Figure 2

Southwestern Michigan

The sequence of till sheets in southwestern Michigan (Table 1) is best exposed at the Glenn Shores section, located along the Lake Michigan shoreline about 16 km north of South Haven, Michigan (Figures 1 and 2). Here three till units (Glenn Shores, Ganges, and Saugatuck tills) are exposed and are separated from each other by lacustrine sand, silt, and clay (Glenn Shores and Ganges) or by lacustrine sand (Ganges and Saugatuck) deposits. Saugatuck till, which represents the surface till throughout most of southwestern Michigan, has been trace eastward along the ground surface from the Lake Michigan shoreline to the Sturgis-Kalamazoo morainal system (Figures 1 and 2) and correlated with the Wadsworth Till Member of the Wedron Formation in Illinois (Monaghan et al. 1986). Ganges till has been traced in the subsurface beneath Saugatuck till from the shoreline eastward to exposures in the Tekonsha Moraine (Figure 2) and correlated with the upper part of Yorkville Till Member (Wedron Formation) of the Joliet Sublobe in Illinois (Monaghan et al. 1986). Gephart et al. (1982) have proposed a middle or early Wisconsinan age for Glenn Shores till (and overlying sand, silt, and clay) based on radiocarbon dates ranging from 37,150 to >48,000 years B.P. on detrital organic material within stratified deposits overlying the till. However, a more recently obtained ^{14}C age date of 64,500 $\pm$ 1000 years B.P. (Larson and Monaghan 1988) from this deposit suggests that Glenn Shores till may be older than middle Wisconsinan.

Based on the regional stratigraphic relationships of the tills and in part on the fact that stratified deposits separate the till units, Monaghan et al. (1986) proposed that a significant retreat of the Lake Michigan Lobe

occurred between deposition of each till sheet. Since Ganges till makes up the Tekonsha Moraine of the Lake Michigan Lobe (Figure 2) while Saugatuck till represents the surface till from the Sturgis Kalamazoo Morainal System (Figure 2) westward to Lake Michigan and overlies Ganges till, Monaghan et al. (1986) were also able to place a minimum distance for the retreat recorded between Ganges and Saugatuck tills. They proposed that following the formation of the Tekonsha Moraine (Figure 2) and deposition of Ganges till, the Lake Michigan Lobe retreated at least 60 km westward into the Lake Michigan basin and that a pro-glacial lake formed in front of the retreating ice margin. The ice margin subsequently readvanced east across southwestern Michigan to the Sturgis-Kalamazoo System (Figure 2). Monaghan and Larson (1986) suggested that this retreat occurred prior to approximately 15,000 years ago and is correlative with the Erie Interstade of the Lake Erie basin.

Average matrix grain-size distribution and clay-mineral analyses reported for the three till units at Glenn Shores are listed in Table 2. Also frequency histograms comparing the clay mineral composition of the tills from Glenn Shores are shown in Figure 3. Application of the T-test to the clay-mineral data show that the three tills exposed at Glenn Shores have different compositions to the 99% confidence level, and indicates that a significant increase in 10Å clay content, relative to 7Å clay, occurs from the lowermost till unit to the uppermost till (Figure 3). Clay-mineral analyses also show that the lacustrine sediments occurring between Glenn Shores and Ganges tills have a clay-mineral composition intermediate between the two tills (Figure 3).

TILL SHEET	CLAY-MINERAL DATA (7A/10A)	MATRIX GRAIN SIZE DATA			% CLAST LITHOLOGY			
		% SAND	% SILT	% CLAY	I/M	CB	SH	OT
Two Rivers[2,1]	0.89 ± 0.31[6]	31	50	19	14[6]	79	1	5
"Valders" (NW Mi.)[3,1]	1.01 ± 0.28[7]	--	--	--	12[7]	86	0	0
Haven[2,1]	0.99 ± 0.34[6]	16	56	28	15[6]	80	0	6
Ozaukee[2,1]	0.87 ± 0.30[8]	13	47	40	15[8]	74	10	1
Oak Creek[4,1]	0.51 ± 0.20[9]	12	44	44	15[9]	49	30	6
Saugatuck[5,6]	0.58 ± 0.12[10]	36	42	22	14[10]	36	45	4
New Berlin[4,1]	0.91 ± 0.30[9]	58	29	13	12[9]	82	3	3
Ganges[5,5]	0.85 ± 0.18[10]	59	22	19	17[10]	52	27	4
Glenn Shores[5,5]	1.22 ± 0.32[10]	46	34	20	15[10]	70	13	2

Table 2. Clay-mineral, matrix grain size, and major clast lithology data from selected till units in the Lake Michigan basin. Grain size boundaries: Sand 2.0 mm; Silt 0.062 mm; clay <0.004 mm. Clast lithology based >3 mm size fraction; I/M Igneous/Metamorphic, CB Limestone-Dolomite, SH Shale, OT Other; dash represents <1%. Superscripts in the "Till Sheet" Column refer to data sources; first number, matrix grain-size data; second number, clay-mineral data. Superscripts in the "Clay Mineral Data" and "Pebble Count Data" columns refer section from which data collected; location of sections found in Figures 1 and 2. [1]This Study; [2]Acomb et al. 1982; [3]Melhorn 1954; [4]Schneider and Need 1985; [5]Monaghan et al. 1986; [6]Two Creeks; [7]Peterson Park; [8]Shorewood; [9]St. Francis; [10]Glenn Shores.

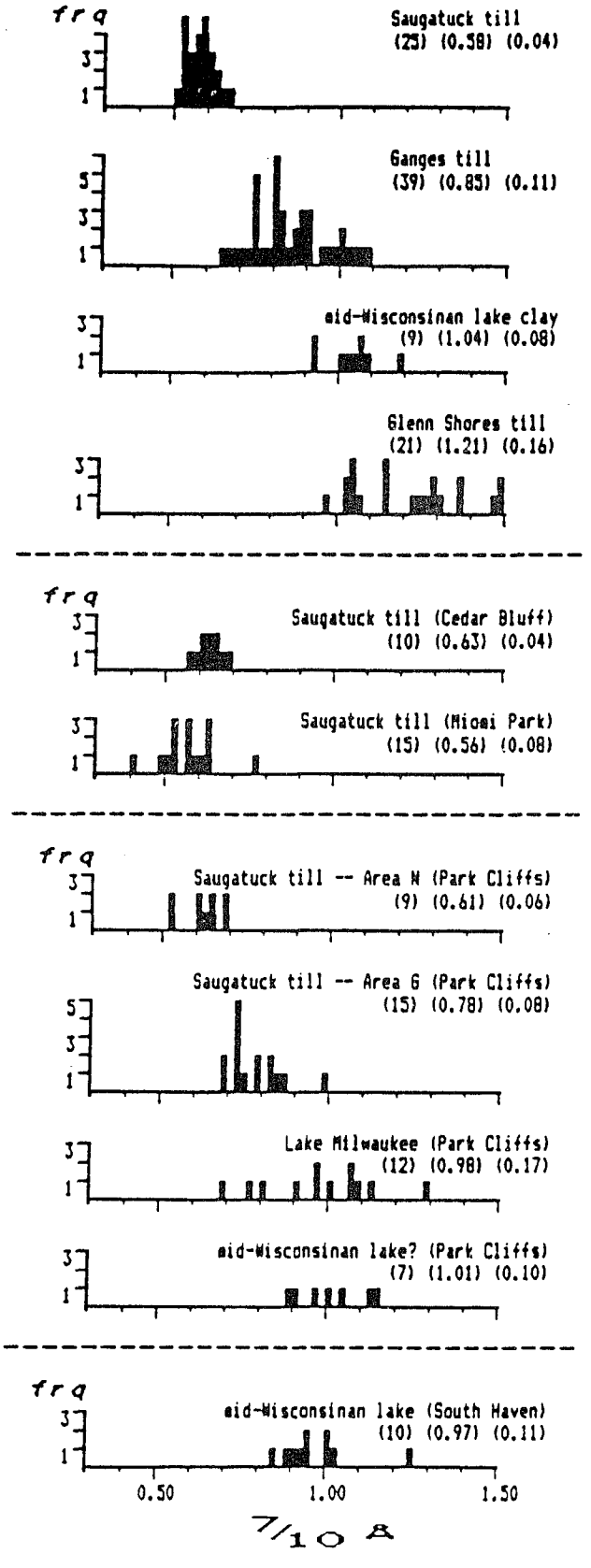


Figure 3 7Å/10Å frequency histograms of till and lacustrine units exposed at sections within southwestern Michigan. Horizontal axis shows 7Å/10Å ratio values; vertical axis shows number of samples with a particular ratio value. Unit names shown along right of histograms; section from which data collected shown along left side of diagram with line separating individual sections. Units from individual section arranged in stratigraphic order. Data from Glenn Shores from Monaghan et al. (1986)

NAME OF TILL SHEET	PERCENT CLAST LITHOLOGIES						NAME OF SAMPLED SECTION
	I/M	CB	SH	SS	CH	OT	
Two Rivers	14	79	1	4	1	-	Two Creeks
"Valders"	15	80	1	4	-	-	Peterson Park
(NW. MI.)	12	86	0	2	-	-	Peterson Park
Filer	14	81	0	3	1	1	Orchard Beach
Haven	15	80	-	4	1	-	Two Creeks
Ozaukee	15	74	10	1	-	-	Shorewood
Orchard Beach	15	80	0	3	2	-	Orchard Beach
Saugatuck	14	36	45	4	1	-	Glenn Shores
	13	45	37	3	2	-	Park Cliffs (A)
	14	40	39	3	1	-	Park Cliffs (N)
	17	28	46	5	2	2	Bloomingdale
Oak Creek	15	49	30	6	-	-	St Francis
	17	56	24	3	-	-	Shorewood
Ganges	17	52	27	2	2	-	Glenn Shores
	14	47	26	9	4	-	Cedar Bluff
	15	51	25	5	4	-	Bloomingdale
New Berlin	12	82	3	0	3	-	St Francis
Glenn Shores	15	70	13	1	1	-	Glenn Shores

Table 3. Pebble count data from composite till samples collected at sections within the Lake Michigan basin. Clast lithology based on percentage of each lithology in the >3 mm size fraction; I/M Igneous-Metamorphic; CB Limestone-Dolomite; SH Shale; SS Sandstone; CH Chert; OT Other. Dash represents <1%.

In order to assess the relative amount of shale compared to other lithologies found in each of the till units at Glenn Shores, the lithologies of pebble clasts (>3 mm) were determined and counted using methods outlined above. The results of these determinations are listed in Table 3 and show that the relative amount of shale increases in progressively younger till units. Importantly, the increase in the relative amount of shale generally corresponds with the increase in the relative amount of 10Å clay in each till unit (Table 3 and Figure 3).

Correlation of Ganges and Saugatuck till with specific end moraines of the Lake Michigan Lobe (Figure 2) is based on similarities in clay-mineral composition between these till units exposed along the lakeshore

and till comprising specific moraines. The clay-mineral data presented in Monaghan et al. (1986), together with additional data collected during the course of this study, shows that the clay-mineral composition of both Saugatuck and Ganges tills remains generally constant throughout southwestern Michigan (Figure 2). In addition, the clay-mineral composition of till comprising the outer ridge of the Valparaiso Moraine around the southern end of Lake Michigan (Wadsworth till in northeastern Indiana and northwestern Illinois) was also determined. These data (Figure 2) show that Wadsworth till in Indiana and Illinois is similar in clay-mineral composition to Saugatuck till.

In order to assess variability in clay-mineral composition of till exposed along the lakeshore in southwestern Michigan, the till units exposed at Glenn Shores were traced southward. A few km south of the Glenn Shores section Ganges and Glenn Shores tills dip under the present beach. Saugatuck till, however, can be followed southward from the Glenn Shores section through several km of relatively continuous exposure (Figure 2). At a few places (Cedar Bluff, Miomi Park, and Park Cliffs; Figure 2), Saugatuck till was sampled and analyzed. The results of these analyses (Figure 3) show that in general the clay-mineral composition of Saugatuck till remains relatively constant. One notable exception, however, is found at the Park Cliffs exposure, the southern most extent of continuous exposure of Saugatuck till, and shows that the clay mineralogy of Saugatuck till can significantly vary over a short distance.

The Park Cliffs exposure occurs in bluffs at the Variety Park trailer park along the Lake Michigan shoreline about 2 km north of South Haven in Allegan County (Figure 2). The generalized stratigraphy of the

exposure begins at lake level (177 m) with about 1-1.5 m of discontinuous deformed, interbedded sand and silt. The interbeds are often tightly folded and the top of the folds commonly truncated. Some rounded clasts of clay also occur within the deposit. Small abraded wood chips occur within this deposits, one of which (300 mg of carbon) was dated and yielded an age of >24,700 years B.P. (WAT-1918; Larson and Monaghan 1988). Based on the age wood within it, the deformed silt may represent evidence for a mid-Wisconsinan (or older) lake in the Lake Michigan basin. At the north and south ends of the exposure the silt dips under the present beach and is not exposed.

The deformed silt is unconformably overlain by 2-4 m of laminated, tabular bedded clay. The tabular beds of clay are 2-8 cm thick and are often separated by thin beds of fine sand and silt. The beds of clay become thinner towards the top of the deposit while the interbedded sand and silt layers become thicker. Thin layers of discontinuous diamicton occur with the clay layers and often exhibit flow structures. The clay grades upwards into a 2-5 m thick deposit of crossbedded and rippled medium to coarse sand. The crossbeds are most common in the lower part the deposit while rippled sand is more common in the upper part. Silt and clay often drape the ripples. This sequence of lacustrine sediment can be traced northward and is probably equivalent to the lacustrine sand which occur between Ganges and Saugatuck till at Glenn Shores. If so, these sediments were deposited in an extensive proglacial lake formed prior to 15,000 years ago when the Lake Michigan Lobe retreated during the Erie Interstade.

The rippled and crossbedded sand is overlain by about 5-6 m of Saugatuck till. The contact between the till and underlying sand is generally sharp; however, discrete layers of clay and diamicton occur in the top several cm of the sand. At the southern end of the exposure, the sand pinches out and the till directly overlies the laminated clay. Saugatuck till is overlain by a few meters of sand and pebble to cobble gravel interpreted to be Glenwood shallow water and/or beach sediment.

Two areas were sampled, one along the shoreline at the north end of the exposure (Area N) and the other about 200 m to the south in a small gully (Area G). Clay-mineral analyses were performed on samples of Saugatuck till as well as mid-Wisconsinan deformed silt and late Wisconsinan laminated clay. These analyses indicate that no significant difference in clay-mineral composition exists between either lacustrine deposit. In fact, the comparison of the composition of these lacustrine deposits with the mid-Wisconsinan lacustrine sediments from Glenn Shores also shows no difference (Figure 3). However, when the clay-mineral composition of tills sampled from Areas N and G at Park Cliffs are compared distinctive differences are observed (Figure 3). While Saugatuck till from Area N is similar to Saugatuck till from the Glenn Shores Section, Saugatuck Till from Area G has a clay-mineral composition more like Ganges till. Till from both Areas N and G, however, each have similar amounts of shale (39% and 37% respectively; Table 3) and are similar to the amount of shale observed for Saugatuck till at Glenn Shores and Miomi Park. These data show that while the clay-mineral composition of till can vary significantly over a relatively short distance, the distribution of pebble lithologies apparently remains relatively constant.

A final site of interest, the South Haven Peat Bed (Zumburge and Potzger 1956), is located along the Lake Michigan shoreline about 3 km south of South Haven in Van Buren County, Michigan. Here, the top meter of a contorted silt bed containing small, abraded wood chips dated to 30,000 ± 800 years B.P. (Eschman 1980) is exposed. The radio-carbon date on this deposit indicates that it may represent sediment deposited in a mid-Wisconsinan lake as has been suggested by Eschman (1980). The silt is unconformably overlain by a discontinuous layer of peat and logs dated at 11,200 ± 600 to 10,860 ± 350 years B.P. which is in turn overlain by 2 to 9 m of medium to coarse sand with stringers and lenses of fine to medium gravel interpreted to represent shallow lacustrine and/or littoral deposit formed during the Calumet transgression. Clay-mineral analyses were performed on samples from the mid-Wisconsinan deformed silt and clay. The results of these analyses show that this deposit has a similar clay-mineral composition to the lacustrine sediments (both mid- and late Wisconsinan) from Glenn Shores and Park Cliffs (Figure 3).

A summary of the clay-mineral variation observed in till exposed along the lake shore in southwestern Michigan, together with intervening lacustrine silts and clays, is presented in Figure 4. It shows that a significant increase in the relative amount of 10Å clay occurs beginning with mid-Wisconsinan Glenn Shores till and continues through deposition of Saugatuck till. The clay-mineral composition of intervening lacustrine deposits, however, shows no such trend. In fact, at least in this small area of southwestern Michigan, the composition of lacustrine sediment deposited in the Lake Michigan basin apparently remains constant from the mid-Wisconsinan through the late Wisconsinan.

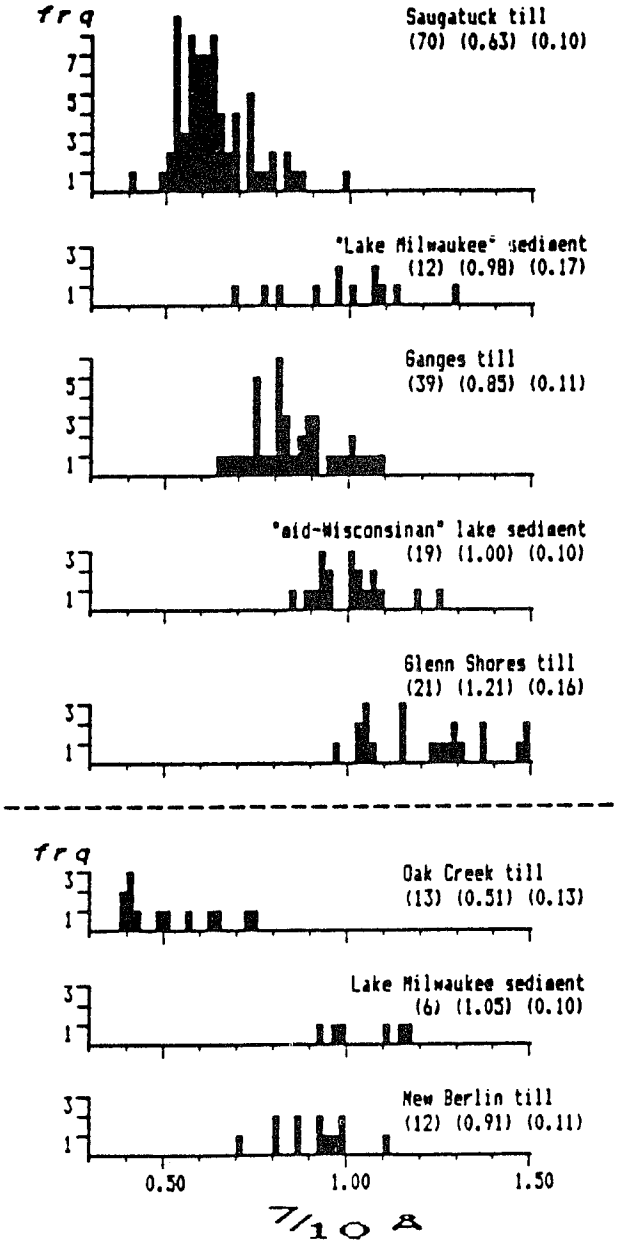


Figure 4 7Å/10Å frequency histo-grams of till and lacustrine samples from southwestern Michigan (upper part of diagram) and St.Francis section (lower part of diagram). Named units shown along right side of each histogram; section or area from which data collected shown along left side of diagram. Units from individual section arranged in stratigraphic order. Horizontal axis shows 7Å/10Å ratio values; vertical axis represents the number of samples with a particular ratio value. Southwestern Michigan data represents a composite of data shown in Figure 3.

Southeastern Wisconsin

The sequence of mid-Woodfordian age till sheets in southeastern Wisconsin (New Berlin and Oak Creek; Table 1) is well exposed at the St. Francis section, located about 8 km south of Milwaukee, Wisconsin (Figure 1). Here, two till units representative of the Oak Creek and New Berlin formations (Mickelson et al. 1984) are separated by a thick sequence of glacial-lacustrine deposits (Christensen and Schneider 1984 and Schneider and Need 1985). The two tills were differentiated by Schneider and Need (1985) based on matrix grain-size (Table 2). The presence of stratified deposits between the two tills at St. Francis as well as several other places in the Milwaukee area led Schneider and Need (1985) to suggest that a retreat of the Lake Michigan Lobe occurred between deposition of New Berlin and Oak Creek tills. They have named a pro-glacial lake which formed during this retreat Lake Milwaukee. In part because of the similarities in matrix grain-size, Schneider (1983), Mickelson et al. (1984), and Schneider and Need (1985) have suggested that New Berlin till correlates with Haeger till of the Harvard Sublobe in Illinois and that Oak Creek till correlates with Wadsworth till in Illinois (Table 1). Monaghan (1985, in press) has further suggested that Oak Creek till correlates with Saugatuck till in southwestern Michigan while New Berlin till probably correlates with Ganges till (Table 1).

The correlation of Saugatuck and Oak Creek till is reasonable since both have been correlated with Wadsworth till in Illinois and all three of these units represent the youngest surface till around much of the southern end of Lake Michigan. Correlation of Ganges with New Berlin till is more problematic, however, since each has been correlated with

different till units in Illinois (Ganges till with Yorkville till and New Berlin till with Haeger till). The correlation of Ganges till with Yorkville till by Monaghan et al. (1986) is based primarily on a summary by Johnson (1976) who suggested that Haeger till correlates in time with Wadsworth till and Yorkville till directly underlies both Haeger and Wadsworth tills. More recently, the relationships between Yorkville, Haeger, and Wadsworth tills has been revised to show that Haeger till (or it's equivalent south of Chicago, Lemont Drift) actually underlies Wadsworth till throughout northeastern Illinois and Yorkville till is older than both Haegar and Wadsworth tills (Johnson et al. 1985). If correct, Ganges till probably correlates with Haeger till (and/or Lemont drift). In fact, Johnson et al. (1985) proposed that a retreat, equivalent in time to that recorded between deposition of New Berlin and Oak Creek tills, occurred in Illinois between deposition of Haeger and Wadsworth tills and have suggested that Lake Milwaukee was formed during this interval. A recently published radiocarbon date of 15,240 $\pm$ 120 years B.P. (ISGS-465; Springer and Flemal 1981) provides a minimum age for Wadsworth till (Johnson et al. 1985) and indicates that the retreat recorded between Ganges-New Berlin and Saugatuck-Oak Creek tills must have occurred before about 15,000 years B.P. If so, it provides further evidence that the retreat is approximately time equivalent to the Erie Interstade of the Lake Erie basin (Table 1) as suggested by Monaghan and Larson (1986) and more recently by Monaghan (1985, in press).

In order to test whether a systematic, stratigraphic variation in clay-mineral composition similar to that observed in southwestern Michigan occurs in eastern Wisconsin, X-ray diffraction analyses were performed on

samples of New Berlin and Oak Creek tills collected at St. Francis. The results of these analyses (Figure 4) indicate that New Berlin and Oak Creek tills not only have significantly different clay-mineral compositions, but also that the two tills exhibit a similar systematic increase in the relative amount of 10Å clay incorporated within the younger till as was observed in southwestern Michigan (Figure 3 and Figure 4). Application of the T-test to the two tills at St. Francis with those from Glenn Shores shows that to the 95% confidence level Oak Creek and Saugatuck till have the same general clay-mineral composition, as do also New Berlin and Ganges tills. Pebble counts of New Berlin and Oak Creek tills (Table 3) indicate that the Oak Creek till contains significantly more shale than does New Berlin. Although differing in absolute amount, both the Glenn Shores and St. Francis sections exhibit a trend toward increasing shale and 10Å clay content in younger till units. Clay-mineral analyses were also performed on samples of Lake Milwaukee clay which occurs between New Berlin and Oak Creek tills. The results of these analysis (Figure 4) show that these sediments have a similar clay-mineral composition to all the lake sediments analyzed from sections in southwestern Michigan.

In part based on their lithologic similarities as well as the regional correlations proposed above, Oak Creek till is correlated with Saugatuck till, while New Berlin till is correlated at least in part with Ganges till. If these correlations are correct then the retreat recognized in southwestern Michigan between deposition of Ganges and Saugatuck tills is probably equivalent to that recorded in Wisconsin between deposition of New Berlin and Oak Creek tills (Table 1).

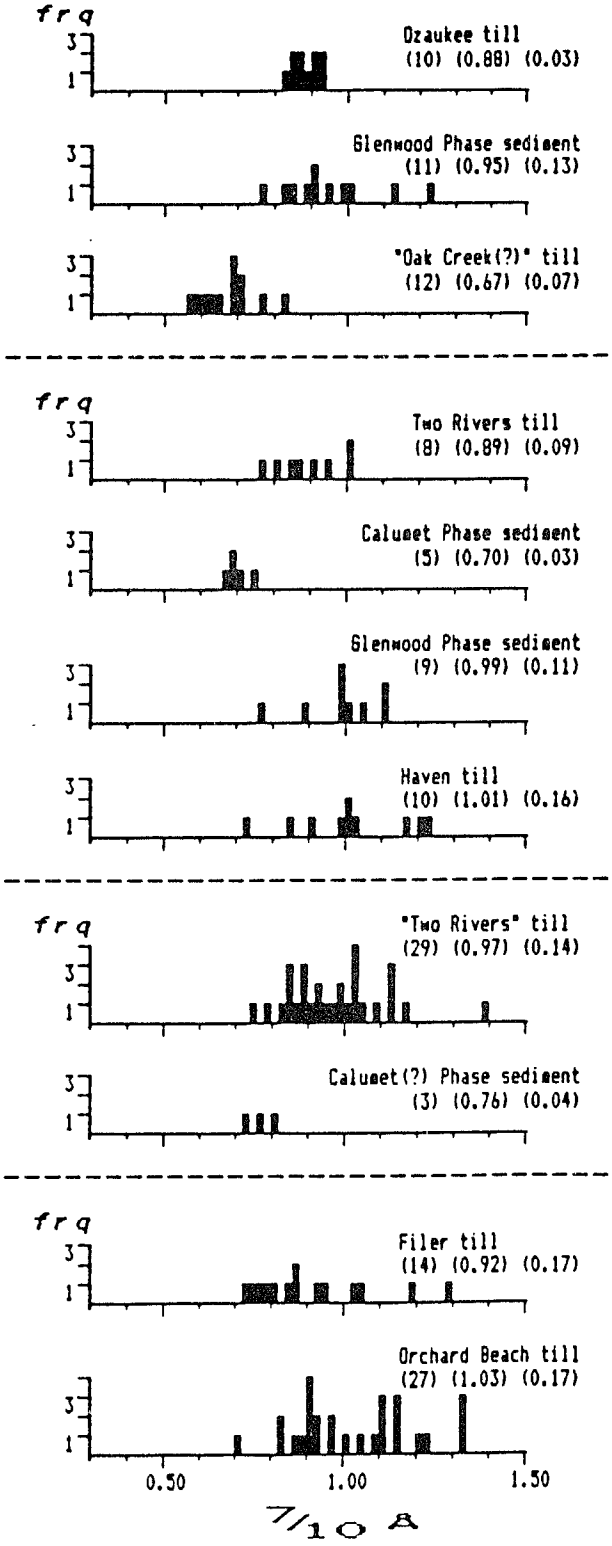


Figure 5 7Å/10Å frequency histo-grams of till and lacustrine samples from the Shorewood section (upper part of diagram), Two Creeks section (middle part of diagram), and NW. Michigan sections (lower part of diagram). Named units shown along right side of each histogram; section or area from which data collected show along left side of diagram. Units from individual section arranged in stratigraphic order. Horizontal axis shows 7Å/10Å ratio values; vertical axis represents number of samples with a particular ratio value. Data from NW Michigan represents a composite from sections discussed in text.

Eastern and Northeastern Wisconsin

A sequence of three Port Huron and one Greatlakean age till units from eastern and northeastern Wisconsin (Table 1) has been described by Acomb et al. (1982). Two of the Port Huron tills, Ozaukee and Haven, occur relatively continuously northward along the Lake Michigan shoreline from the Port Huron Moraine to well north of the Two Rivers Moraine (Figure 1). Greatlakean age Two Rivers till, however, only occurs northward from the Two Rivers Moraine (Figure 1). These till units can be differentiated based on grain-size distribution (Table 2) and the relative amount of expandable clay minerals (Acomb et al. 1982).

To test whether a systematic variation in clay-mineral composition, such as that observed at St. Francis and Glenn Shores, also occurs within younger sequences of till sheets, two sections representative of Port Huron and Greatlakean stratigraphy were studied. The first, informally named the Shorewood section, includes the older sequence of till units, while the second, the Two Creeks Section, includes the younger part of the sequence (Figure 1).

The Shorewood section, located about 16 km north of the St. Francis section and north of the Port Huron Moraine (Figure 1), includes at least two till units separated by a thick sequence of glacial-lacustrine deposits (Acomb et al. 1982). The upper till, Ozaukee Till Member of the Kewaunee Formation, is considered equivalent in time to till comprising the Port Huron Moraine (Mickelson et al. 1983) while the lower till (undifferentiated) is considered to be mid-Woodfordian (pre-Port Huron) in age (Acomb et al. 1982). Thus these two till units are separated by

Glenwood lacustrine sediments deposited during the Mackinaw Interstade (Table 1).

Clay-mineral analyses of Glenwood sediments which separate the pre-Port Huron from Ozaukee till (Figure 5) show that they have a similar composition to Lake Milwaukee and mid-Wisconsinan lacustrine sediments from southeastern Wisconsin and southwestern Michigan (Figure 4). Clay-mineral analyses performed on the two till units, however, show that each has a significantly different clay-mineral composition (Figure 5). Unlike the general increase in the relative amount of 10Å clay observed at Glenn Shores and St. Francis, the sequence of tills exposed at the Shorewood section show a decrease in the relative amount of 10Å clay incorporated within the younger till. Although somewhat lower in 10Å clay content, the composition of the lower till is similar to Oak Creek till from the St. Francis Section (Figure 4) and is probably equivalent to Oak Creek till. Pebble count data compiled for Ozaukee and Oak Creek till from Shorewood (Table 3) also support this relationship since both Oak Creek tills have a similar shale distribution. The shale distribution of Ozaukee and Oak Creek tills from Shorewood also shows a decrease in shale content within the younger till.

The Two Creeks Section occurs approximately 125 km north of the Shorewood section, just north of the Two Rivers Moraine (Figure 1). Here, two till units, separated by lake sediments and the Two Creeks Forest Bed, are exposed. The upper till has been correlated with Two Rivers till and is therefore Greatlakean in age (Evenson 1973). The lower till occurs below the forest bed and is considered Port Huron in age (Evenson 1973; Mickelson et al. 1983) and correlated with Haven till

(Acomb et al. 1982). Based on the ages of the till units, the lake sediments which separate the two tills must be related to Lake Chicago and are separated by the Two Creeks Forest Bed into two different phases. Lake Chicago sediments below the forest bed are pre-Two Creekan and related to the Glenwood phase while sediments overlying the forest bed are post-Two Creekan and related to the Calumet Phase (Hansel et al. 1986).

Pebble count data (Table 3) of samples taken from the two till units exposed at Two Creeks show that both have only trace amounts of shale and contain mostly carbonate clasts. Clay-mineral analyses (Figure 5) of the two tills show that the Two Rivers and Haven tills both exhibit the same general clay-mineral composition and that both are similar in clay-mineral composition to the Port Huron age Ozaukee till from the Shorewood section (Figure 5). Clay-mineral analyses of Lake Chicago sediments, however, show that each phase of the lake has a distinctly different composition (Figure 5). Glenwood Phase sediment is compositionally similar to Glenwood sediment sampled at Shorewood and to mid- and late Wisconsinan lacustrine deposits from the southern end of the basin. Calumet Phase sediment, however, has significantly more 10Å clay than Glenwood Phase sediment (Figure 5). While it is dissimilar to all other lacustrine deposits, it is compositionally similar to Saugatuck-Oak Creek till from the southern end of the basin (Figure 4 and Figure 5).

Northwestern Michigan

In 1954 Melhorn correlated the surface till in Leelanau and Benzie counties in northwestern Michigan with the "Valders" till (as defined by

Thwaites 1943) in Wisconsin. More recently, Melhorn's "Valders" till has been correlated with Two Rivers till in Wisconsin and was therefore deposited following the Two Creeks interval (Evenson 1973). Analyses of the uppermost till units from several sections in northwestern Michigan (Figure 1) show that these tills have a clay-mineral composition similar to Two Rivers, Ozaukee, and Haven tills from Wisconsin (Figure 5). At one section (just south of Peterson Park in Leelanau County, Figure 1), multiple till units, separated by stratified deposits, are exposed. Clay-mineral analyses of the lower and middle till of this section show a similar systematic increase in the relative amount of 10Å clay incorporated in the younger till unit as was observed at Glenn Shores and St. Francis, while the upper till show a decrease in 10Å clay content similar to that observed at the Shorewood section in Wisconsin (Figure 5). Pebble count data (Table 3), however, shows that unlike the high amounts of shale observed in 10Å rich tills in southern Lake Michigan, all tills at Peterson Park have only trace amounts of shale.

At one of the sections analyzed in northwestern Michigan, Pt. Betsie (Figure 1), a thick unit of lacustrine clay, silt, and sand occurs below "Two Rivers" till. Clay-mineral analyses performed on samples of this lacustrine deposits indicates that the clay-mineral composition is similar to the Calumet sediments analyzed at Two Creeks. Since no distinctive stratigraphic break was observed within this section, these sediments are probably related to the Calumet Phase.

Recently, Taylor (1979, 1981) has proposed a more formalized stratigraphic framework for Port Huron and Greatlakean tills occurring in northwestern Michigan. He described two tills, Montague and Orchard

Beach, related to the Port Huron advance and one till, Filer, related to the Greatlakean advance. Orchard Beach till, related by Taylor to the inner Port Huron Moraine and probably correlative with either Ozaukee or Haven till from Wisconsin, is exposed at several places along the shoreline from Ludington northward to Frankfort. Filer till, correlated by Taylor with Two Rivers till, is also exposed along the shoreline but generally restricted to exposures north of Mansitee.

The southernmost exposure described by Taylor (1981) where both Port Huron and Greatlakean age till units are exposed occurs at the Orchard Beach section (Figure 1), located about 3 km north of Mansitee Michigan. Here, Orchard Beach and Filer tills are exposed in a 20-25 m high bluff along the Lake Michigan shoreline at the Orchard Beach State Park. The stratigraphy begins lake level (177 m) with about 6 m of dense, brown sandy till. A discontinuous layer of gravel up to several cm thick in places separates the till into two units. The till is overlain by 3-4 m of cross-bedded sand and pebble gravel. Occasional discontinuous layers of silt and clay also occur within this unit. The sand and pebble gravel is overlain by 2-3 m of red sandy till. The till is overlain by 10-12 m of bedded sand and silt with occasional lenses of crossbedded gravel and diamicton concentrated within the middle of the unit. The exposure is capped by 2-3 m of red sandy till. The uppermost till was related by Taylor (1979, 1981) to Filer till and correlative with Two Rivers till in Wisconsin. Taylor also proposed that the 2 (or 3) till units underlying Filer till each represent some phase Orchard Beach till deposition and suggested that they were deposited as the ice front of the Lake Michigan Lobe oscillated during the Port Huron Stade.

The till units exposed at Orchard Beach can be traced southward for about 2 km and were sampled and analyzed from a few places along this exposure. The results of these analyses (Figure 5) indicate that no significant difference exists in the clay-mineral composition of either Orchard Beach or Filer tills. Comparison of these results with those from Two Rivers equivalent till sampled further north and with Ozaukee, Haven, and Two Rivers tills from Wisconsin indicate that all have the same basic clay-mineral composition (Figure 5). Pebble counts performed on samples of till from Orchard Beach also show that, like other Port Huron and Greatlakean tills from the Lake Michigan basin, Orchard Beach and Filer tills are low in shale-clast content (Table 3).

Summary of Clay-Mineral Variation in the Lake Michigan Basin

A composite summary of the systematic variation of clay-mineral compositions in successive till sheets of the Lake Michigan basin, together with the clay-mineral composition of intervening lacustrine units, is shown in Figure 6. It was constructed by grouping together tills and lacustrine deposits of similar age and shows that two different system must have operated during the Wisconsinan, one controlling the clay-mineral composition of till and another controlling the composition of lacustrine sediment.

In detail, Figure 6 shows a general increase in the relative amount of 10Å clay incorporated in till beginning with early or middle Wisconsinan (Altonian) Glenn Shores till and continuing through late Wisconsinan (mid-Woodfordian) Ganges-New Berlin and Saugatuck-Oak Creek tills. A significant decrease in the relative amount of 10Å clay, however, occurs

for post-Mackinaw Interstade Ozaukee-Haven-Orchard Beach (Port Huron) and Two Rivers-Filer (Greatlakean) tills. Because a retreat of the Lake Michigan Lobe has been proposed between each of these groupings of till, marked changes in clay-mineral composition of till sheets apparently often coincide with significant fluctuations of the Lake Michigan Lobe (i.e. the mid-Wisconsinan Port Talbot Interstade and late Wisconsinan "Erie" and Mackinaw Interstades; Table 1).

Unlike the variation observed in successive till sheets, the clay-mineral composition of lacustrine sediment associated with interstadial intervals occurring between the till sheets appears to remain relatively constant. Beginning with unnamed mid-Wisconsinan lake sediments and continuing through late Wisconsinan age Lake Milwaukee (Erie Interstade) sediments and the Glenwood Phase of Lake Chicago (Mackinaw Interstade) sediments no significant change in clay mineralogy was found. The composition of each of these units is similar to late Wisconsinan Ganges-New Berlin and to Port Huron and Greatlakean age tills. A significant increase in the relative amount of 10Å clay, however, occurs for Calumet Phase of Lake Chicago (Two Creeks Interstade) sediments. The composition of these sediments appears similar to Saugatuck-Oak Creek till.

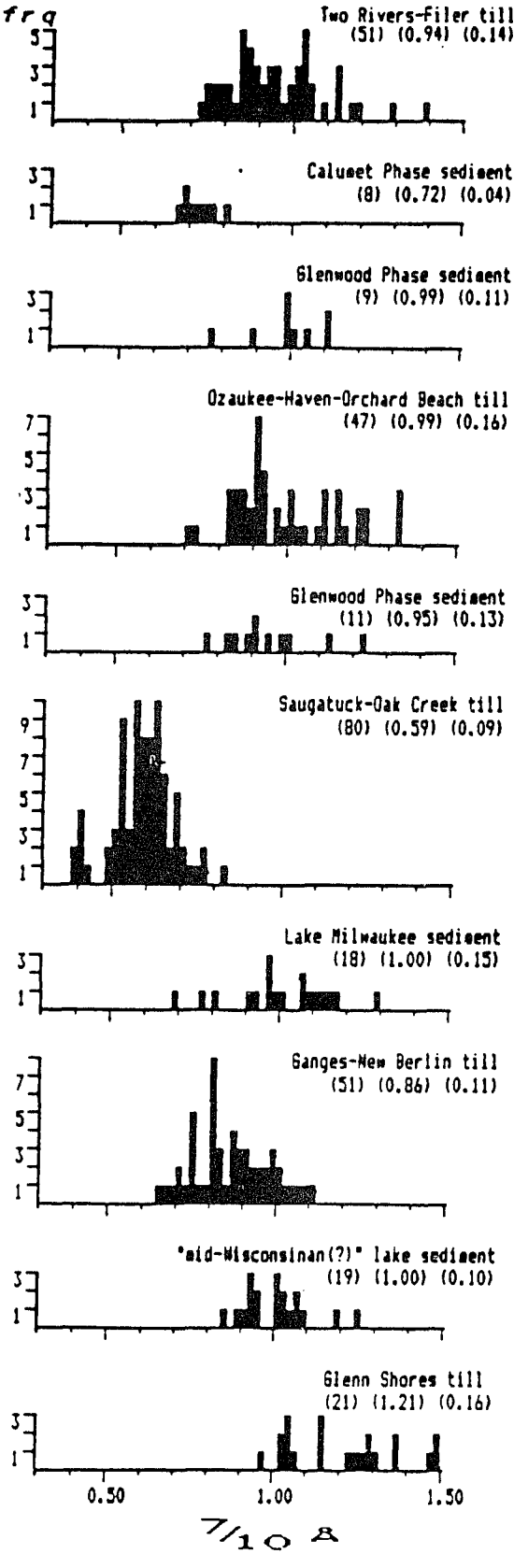


Figure 6 Composite 7Å/10Å frequency histograms for till sheets and intervening lacustrine units in the Lake Michigan basin. Horizontal axis shows 7Å/10Å ratio values; vertical axis represents number of samples with a particular ratio value. Units arranged in strati-graphic order.

THE ORIGIN OF CLAY MINERALS FROM TILLS IN THE LAKE MICHIGAN BASIN

Three basic models can be formulated to explain the systematic variation in clay-mineral composition of tills deposited in the Lake Michigan basin. These model are: 1) a pedogenic model in which clay-mineral variation in till is due solely to formation or alteration of clays after deposition, 2) a lacustrine-mixing model which attributes the variation to incorporation by the ice of previously fractionated lake sediments with different clay-mineral composition, and 3) a bedrock-mixing model which ascribes the variation to erosion by the ice of differing amount of shale during each readvance. Each of these models are discussed below.

Pedogenic Model

The pedogenic model attributes the variation in clay-mineral composition of till to formation or selective alteration of clay minerals after deposition. The model, therefore, ascribes the ultimate clay-mineral composition of sediments to post-depositional transformation processes related to weathering rather than to a basic erosional or depositional mechanism associated with ice dynamics. Two basic transformation processes could account for the observed variation in clay-mineral composition of till; one related to time and the other related to depth. Both processes rely on the fact that, at least in the Great Lakes region, chlorite is generally one of the least stable clay minerals (Droste 1956a, 1956b) while kaolinite one of the most stable. The stability of illite is intermediate between chlorite and kaolinite.

Chlorite can weather to expandable clay minerals such as vermiculite and smectites through hydrolysis of the brucite interlayer. This transformation often proceeds by developing a mixed layer chlorite-vermiculite (or smectite) structures and is most rapid under acidic conditions. Illite can also alter to a mixed-layered structure and ultimately to vermiculite and smectite by similar hydration of the interlayer sites. Under intensive leaching conditions, mono- and di-valent cations are leached from the parent material which promotes acid conditions and desilification and allows the formation of kaolinite. If, on the other hand, leaching rates are low, neoformed vermiculite and smectite may be stable end products. If relatively large amounts of K-ions are present, however, they may be scavenged and allow illite to form. This process of K-fixation is particularly promoted if the parent material undergoes alternating wet-dry cycles.

The transformation processes discussed above are well documented and have been used by numerous researchers throughout the Great Lakes region to explain clay-mineral differences in tills (eg. Droste 1956a, 1956b; Willman et al. 1963; Quigely 1968). If these processes are significant, the variation in clay-mineral composition of tills, at least from the southern part of the Lake Michigan basin, could relate to greater alteration of older till units relative to younger units. For example, if the all the tills were originally illite-rich, then the alteration of illite to kaolinite (or, alternatively, an alteration sequence of chlorite to expandable clay to kaolinite) could produce an apparent progressive increase in the relative amount of 7Å clay within older tills. Such a pattern is similar to that observed at the Glenn Shores and St. Francis sections. Alternatively, if

these tills were all originally low in illite (with a composition, for example, similar to the Glenn Shores till) then an apparent increase in illite within younger (and more shallowly buried) tills may have resulted from an accelerated transformation of chlorite into expandable minerals and/or neoformation of illite by K-fixation processes within near surface deposits.

Although some weathering of the original parent material might have occurred, the pedogenic model is probably not plausible since it can not adequately account for the variation in clay-mineral composition of tills within the Lake Michigan basin. For example, if the increase in 7Å clay content within older tills resulted from neoformation of kaolinite, then the youngest till units should have the lowest amount of 7Å clay. This is clearly not the case since the youngest till units (Ozaukee-Haven and Two Rivers) have nearly the same proportion of 7Å and 10Å clays as the oldest (Glenn Shores till; Figure 6).

The fact that the youngest and oldest tills have similar proportions of 7Å and 10Å clays also shows that the second mechanism for pedogenic formation of clay minerals, neoformation of illite related to near surface weathering, is questionable. Although within the southern end of the basin most high-illite tills occur near the ground surface, within the northern end of the basin near surface tills are relatively rich in 7Å clay while more illitic sediments are found at greater depth (e.g. Shorewood, Two Creeks, and Peterson Park section). A pedogenic origin for clay minerals within tills in southwestern Michigan has also been questioned by Monaghan (1984) and Monaghan et al. (1986). They showed that no

regular trend in clay-mineral composition occurred along closely spaced vertical sampling transects within individual till units.

Lacustrine-Mixing Model

The lacustrine-mixing model requires that extensive lake systems form in the Lake Michigan basin during major ice retreats and that the clay-mineral composition of sediments deposited within these lakes systematically change through time. It, therefore, ascribes the ultimate reason for change in the composition of till to sedimentological processes acting in the lake basin during interstadials. Differential settling of clay minerals in an aqueous system (Gibbs 1977; Praham 1966) may have acted as the fractionation process for these sediments.

During readvances of the Lake Michigan Lobe, these lacustrine sediments were incorporated in the ice by regelation processes and/or larger scale processes such as accretation (Weertman 1961) and block incorporation (Moran 1971, Moran et al. 1980). If frozen, they may also have been plucked as "clasts" from the lake bed. The eroded sediments were then transported by the ice, homogenized, and deposited as till with a clay-mineral composition similar to that of the source lacustrine beds. This mechanism seem plausible particularly since changes in clay content of some tills in the Great Lakes region, as well as changes in the clay mineralogy of till, have been attributed to erosion and incorporation of underlying drift deposits (Schneider 1983; Acomb et al. 1982; Willman et al. 1963). In order to function, however, the model requires that, at least in the southern end of the basin, the amount of 10Å clay must increase in

successively younger lacustrine units. It also implies that this 10Å clay is probably derived from outside of the Lake Michigan basin.

During major interstadial periods in the Great Lakes region, extensive lacustrine systems were formed within the Lake Michigan basin. Such systems also developed within the Lakes Huron and Erie basins and periodically drained westward into Lake Michigan. The thickness of sediment deposited within these lakes was probably controlled by several factors including: the amount of vegetation covering surrounding land areas, the extent and height of bluffs along the shoreline, and the duration and magnitude of the retreat. These later factors (duration and magnitude of the retreat) probably had the greatest control over the thickness of lake sediments since longer time intervals allow more sediment to accumulate.

The magnitude and extent of retreat would not only have affected the thickness of sediment which accumulated in the Lake Michigan basin but could also have affected the mineralogy of sediment deposited. When eastern outlets for the Great Lakes (such as the St. Lawrence Valley) were blocked as was often the case during the middle and late Wisconsinan (Dreimanis 1958; Dreimanis and Goldthwait 1973; Dreimanis and Karrow 1972; Winters et al. 1986, 1988; Gephart et al. 1982), drainage was forced westward through basins of the Great Lakes. During such times the Lake Michigan basin was often the last basin in the drainage system. If differential settling of clay minerals in an aqueous system is a significant fractionation process then during times of westward drainage the eastern basins may have acted as a sink for either kaolinite or chlorite (the principal 7Å clay-minerals) and supplied illite-rich (10Å clay) to the Lake

Michigan basin. This fractionation process is based in part on the fact that illite has a smaller grain size relative to either kaolinite or chlorite (Grim 1968; Gibbs 1977) and would therefore remain in suspension longer. Alternatively, the eastern basins may have simply contained mostly illite-rich sediment which was then washed into the Lake Michigan basin. Weathering of chlorite to vermiculite prior to or during erosion of deposits surrounding the basins, particularly if accompanied by K-fixation during erosion and/or transport, may also have altered the relative amount of 7Å and 10Å clays deposited in the basins.

Although any, and perhaps all, of the above fractionation processes may have operated during the Wisconsinan, apparently none was significant. As illustrated on Figure 6, during most of the Wisconsinan no widespread, significant change in the clay-mineral composition of lacustrine sediment occurred in the Lake Michigan basin; the only exception being Calumet Phase (Lake Chicago) sediments. Compared to older lake deposits, these sediments show a relative increase in 10Å clay content. Rather than fraction due to sedimentalogic processes, however, the increase in 10Å clay may simply reflect increased erosion of tills with high 10Å clay content such as the Saugatuck-Oak Creek till. If these data (Figure 6) are indicative of the basin as a whole then the lake system may have operated as an homogenizing basin for eroded clay material whose composition was influenced by the clay mineralogy of eroded, pre-existing sediment.

Clearly, based on the data presented in Figure 6, the systematic variation in clay-mineral composition of tills is not solely related to the composition of underlying lacustrine sediments. Although not the sole factor for stratigraphic variation, the composition of these underlying

sediments apparently did significantly influence the clay mineralogy of subsequently deposited till. This influence, for instance, is illustrated on a local scale by the dramatic change in composition of Saugatuck till sampled from two areas only a few hundred meters apart at the Park Cliffs section in southwestern Michigan (Figures 2 and 3). Here, the composition of till sampled from Area G shows a relatively greater amount of 7Å clays than Area N and may have resulted from a larger amount of underlying lake sediments being eroded at Area G than at Area N (Figure 3). The fact that this occurred only locally is evidenced both by the persistence of Saugatuck till "mineralogy" elsewhere along the shoreline (such as at Glenn Shores, Cedar Bluffs, and Miomi Park; Figures 2 and 3) and by the uniformity of the composition sampled from moraines throughout southwestern Michigan (Figure 2). A similar process may account for the relatively high amount of 10Å clay observed at the Peterson Park section (Figure 5).

Based on similarities of Ganges-New Berlin till and Port Huron and Greatlakean tills with underlying lake sediments (Figure 6), the incorporation of lake sediments by the ice may also significantly (if not completely) control the clay-mineral composition of some till units on a regional scale. However, the significant increase in 10Å clay content observed in Saugatuck-Oak Creek till clearly can not be accounted for by this process since no similar mineralogy exists for Lake Milwaukee sediments (Figure 6).

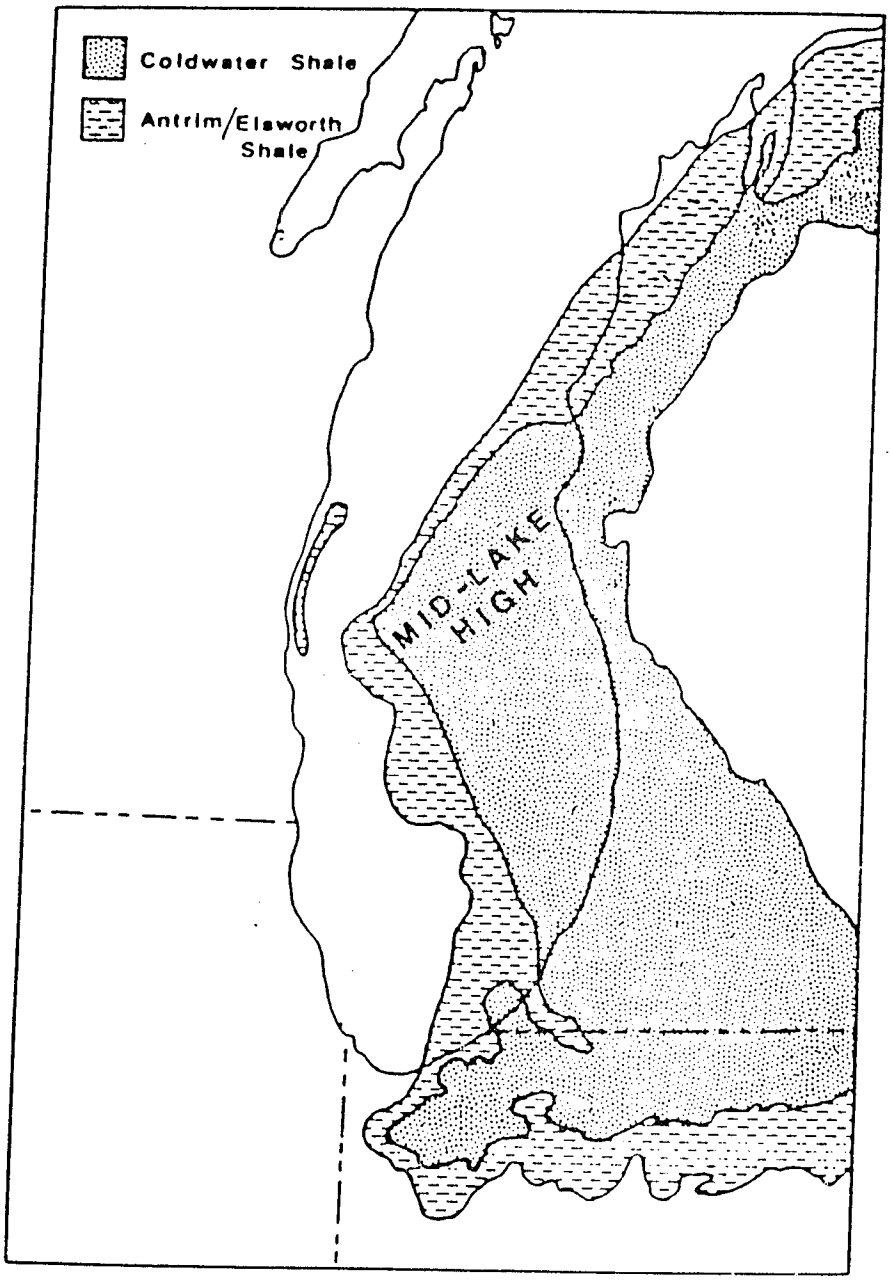


Figure 7 Map showing distribution of Antrim-Ellsworth and Coldwater Formations within the Lake Michigan basin. (After Wold et al. 1981)

Bedrock-Mixing Model

The bedrock-mixing model attributes the variation in clay-mineral composition of till to erosion of differing amount of shale and siltstone bedrock during readvances of the Lake Michigan Lobe. This model is particularly appealing since high amounts of shale have been observed associated with Lake Michigan Lobe tills (Anderson 1957; Krumbein 1933; this study) and have been used to account for the high clay content of the till. Shale is also among the most erodible rocks since it is well jointed, extremely fissile, relatively soft, and often has tensile strength lower than stresses exerted by an over-riding ice sheets (Drewry 1986). When saturated, the tensile strength of shale is even lower (as much as 30% of the unsaturated strength; Mesri and Gibala 1972) allowing it to fail easily under the stresses applied by an overriding ice sheet. During a readvance, shale could be directly incorporated into the ice by plucking (quarrying) and/or larger scale processes such as accretation (Weertman 1961) or block incorporation (Moran 1971, Moran et al. 1980). As the ice flowed across outcrop areas, abrasion at the sole of the glaciers may also have ground the rock into a fine flour or displaced small chips which were then incorporated into the ice by regelation processes. In order to function, the bedrock-mixing model requires that the shale formations must have a relatively high amount of 10Å clay and must, at least in places, outcrop under Lake Michigan. An implicit assumption of the model is that most of the outcrops of these shales must be concentrated in the southern end of the basin.

The principal bedrock clay sources which occur within the Lake Michigan basin are shales of the Devonian-Mississippian Antrim and

Ellsworth Formations and Mississippian Coldwater Formation. The distribution of these deposits is shown in Figure 7 and indicates that most of the southern half of Lake Michigan, particularly the eastern part, is underlain mainly by shale. Except along the eastern shore of Lake Michigan, the northern half of the basin is underlain by middle Devonian dolomites and limestones as well as upper and middle Silurian dolomites and evaporites (Wold et al. 1981).

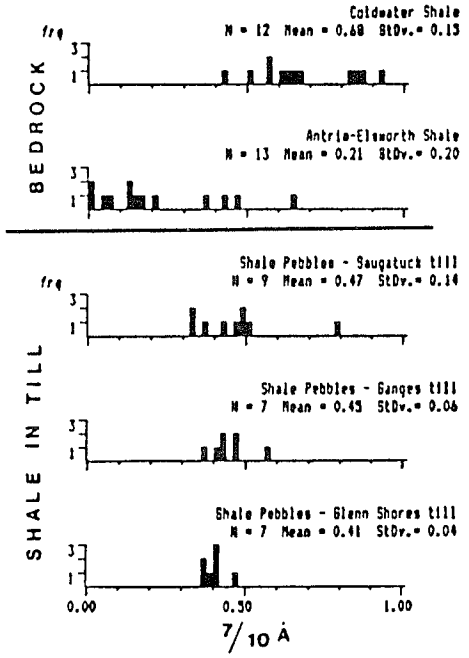


Figure 8 7Å/10Å frequency histograms of Antrim-Ellsworth and Coldwater shales (upper part of the diagram) and shale pebbles collected from the three tills at the Glenn Shores section (lower part of diagram). Horizontal axis shows 7Å/10Å ratio values; vertical axis represents the number of samples with a particular ratio value. Note change in scale of horizontal axis for previous histograms.

The Coldwater Formation consists mainly of grey shale with minor interbeds of dolomite, limestone, and sandstone and is up to 150 m thick. It subcrops under from 30 to 100 m of drift throughout most of

Michigan. Shales of the Coldwater Formation also occur under a few to up to 30 m of sediment in the southern half of the Lake Michigan basin. Clay-mineral analyses for the Coldwater have been reported by Chung (1973) and are based on cuttings sampled from the upper, middle and lower 1/3 of oil wells throughout the lower peninsula of Michigan. The 7/10Å ratio reported for wells underlying Lake Michigan Lobe deposits are shown in Figure 8. These data indicate that a high amount of 10Å (relative to 7Å) clay characterize Coldwater shale. Importantly, Chung (1973) also indicates that the relative amount of 10Å clay increases westward in Michigan. If correct, the amount of 10Å clay in Coldwater shale subcropping under lake Michigan (further west than Chung sampled) might have even more 10Å clay then shown in Figure 8.

The Antrim-Ellsworth Formation, which underlies the Coldwater Formation throughout most of southwestern Michigan (Figure 7), consists of up to 100 m of mostly grey to black (Antrim) and green (Ellsworth) shale. It outcrops extensively along a band extending across the northern part of the lower peninsula from Alpena to Charlevoix and subcrops as an irregular arcuate band under part of the southern end of Lake Michigan (Figure 7). An erosional outlier of Antrim shale also occurs off-shore between Milwaukee and Sheboygan, Wisconsin. The presence of this outlier, as well as the fact that fish fossils and plant fragments found within Antrim shale offshore from Milwaukee that do not indicate proximity to a shoreline, suggest that Antrim-Ellsworth shales once extended much further west than shown in Figure 7 (Wold et al. 1981).

Along most of the east shore of Lake Michigan, Antrim-Ellsworth and Coldwater shales are buried by a thick mantle (up to 200 m) of drift (Wold

et al. 1981). In the southernmost end of the basin, however, they are only buried by a thin layer of sediment (Lineback et al. 1972; Lineback et al. 1974) and may actually outcrop in places along a narrow northeast-southwest escarpment extending from Ludington, Michigan, to Milwaukee, Wisconsin in the central part of Lake Michigan (Wold et al. 1981; Lineback et al. 1974). This escarpment marks the northwestern limit of Antrim-Ellsworth shale under Lake Michigan as well as the northern edge of the "mid-lake high", a 25-50 km wide topographic rise in the lake bottom (and bedrock surface) extending across Lake Michigan (Figure 7). The presence of this escarpment indicates that extensive erosion of the shale, possibly associated with glaciation, must have occurred.

Clay-mineral analyses of Antrim-Ellsworth shale reported by Routsaulla (1980) indicates that, like the Coldwater shale, it has a relatively high amount of 10Å clay. The data was collected by sampling well cores at approximately 3 m (10 ft) intervals from wells distributed throughout the lower peninsula of Michigan. Originally, Routsaulla reported the clay-mineral data as relative percentages of peak-heights of each mineral studied, however, to facilitate comparison with the present study, these data were converted to 7/10Å peak-height ratios. The average of samples reported by Routsaulla for the upper 15 m of wells underlying Lake Michigan Lobe deposits are shown in Figure 8. In order to provide additional checks on the data reported by Routsaulla, two outcrops of Antrim shale were sampled and analyzed; one from the northeastern Michigan near Alpena and one from along the Lake Michigan shoreline in northwestern Michigan near the village of Norwood in Antrim County. The results of these analyses compare well with the range

derived from Routsaulla's data (Figure 8) and indicate that Antrim shale contains relatively high amounts of 10Å clay.

Both the spatial distribution of Antrim-Ellsworth and Coldwater Formations and the fact that both of these formations contain shales with relatively high amounts of 10Å clay fulfill the basic requirements of the bedrock-mixing model. If the bedrock-mixing process actually operated during the Wisconsinan then tills with relatively high amounts of 10Å clay, such as Saugatuck-Oak Creek, should also have a high amount of shale while tills with lower amounts of 10Å clay, such as Ganges-New Berlin and Glenn Shores tills, should have concomitantly lower amounts of shale. Tills deposited well north of the "shale limit" (Figure 7), such as Two Rivers till, should have only trace amounts of shale. In order to test whether such a relationship in fact exists, composite till samples derived from representative sections were wet sieved and the distribution of lithologies in the pebble-size (>4 mm) fraction was determined. The actual techniques employed were described above.

The results of these determinations are listed on Table 3 and indicate that in general tills with the highest amounts of 10Å clay from each section have correspondingly high amount of shale. Port Huron and Greatlakean tills sampled from generally north of the "shale limit" show very low percentages of shale with the highest amount of shale associated with Ozaukee till from the southernmost sampling local (Shorewood section). Data from sections south of the shale limit (St. Francis and Glenn Shores), on the other hand, show a general increase in the amount of both shale and 10Å clay found in progressively younger till units. The

relationship between the amount of shale pebbles and the 7/10Å ratio is illustrated in Figure 9.

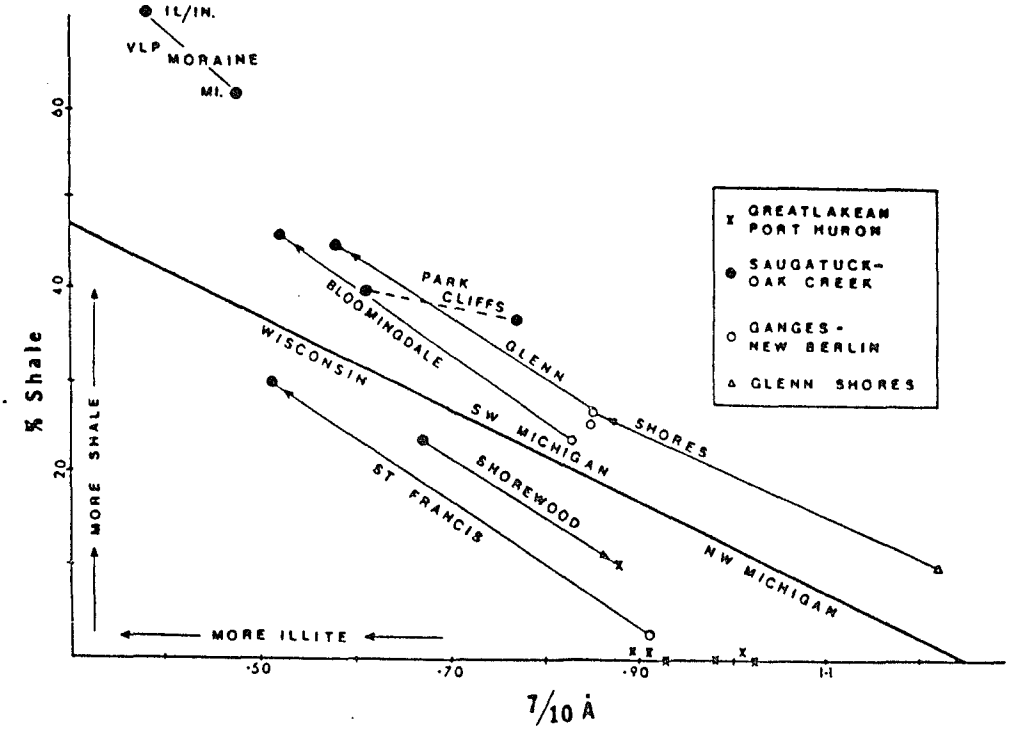


Figure 9 Plot showing relationship between %shale clasts (>3.0 mm) found in till and average 7Å/10Å ratio values for the till unit at the section from which data collected. Trend at selected sections shown by solid line; named sections shown along line. Data from southwestern Michigan separated from rest of the basin by a heavy solid line.

The association of high amounts of shale clasts with relatively high amounts of 10Å clay in till is also supported by pebble count data presented by Krumbein (1933). He sampled till at several-kilometer intervals along the front of the Valparaiso Moraine in Illinois, Indiana, and southwestern Michigan (Figure 1) then separated and counted pebble-size clasts. His results indicate that shale clasts in till from the Valparaiso Moraine in Illinois and Indiana (Wadsworth till) average 72% of all clasts while till samples collected from southwestern Michigan (Saugatuck till) average 62% shale. In order to compare the relative amount of shale to

the clay-mineral composition of till from this area, till samples were collected following a pattern similar to that of Krumbein. Clay-mineral analysis of these samples show that till in Illinois and Indiana which averages 72% shale has a mean 7Å/10Å ratio value of 0.39 (Figure 2). Analysis of till collected from the same area as sampled by Krumbein in southwestern Michigan which averages somewhat less shale (62%) also shows a correspondingly higher mean 7Å/10Å ratio (0.48). These data, as well as the rest included in Figure 9, indicate that an apparent relationship exists between high amounts of shale and 10Å clay content of till.

Although the exact quantitative relationship between amounts of shale and the clay-mineral composition of till varies geographically (particularly between the Michigan and Wisconsin sides of Lake Michigan; Figure 9), a trend towards increased 10Å clay content with increased amounts of shale is prevalent throughout the basin. Such a relationship, together with the similarity in clay mineralogy of shales from the Antrim-Ellsworth and Coldwater Formations (Figure 7) and Saugatuck-Oak Creek till (Figure 6), supports the bedrock mixing model. These data alone, however, do not demonstrate that the model actually operated during the Wisconsinan. In order to have operated, the bedrock source must not only have relatively high amount of 10Å clay, be clay-rich, and be "erodible" but must also be temporally and spatially uniform in clay-mineral composition.

In order to test whether the shale clasts found in till were in fact derived from the Antrim-Ellsworth and/or Coldwater shales (or at least from bedrock with a similar clay-mineral composition), have relatively high amounts of 10Å clay, and have a generally uniform clay mineralogy

through time, several shale clasts from each of the tills at Glenn Shores were analyzed. These clasts were ground into a slurry with distilled water, deposited on glass slides, glycolated, and X-rayed. The results of these analyses are shown on Figure 8 and indicate that 1) based on similarity in composition, they were probably derived from the Antrim-Ellsworth or Coldwater shales and 2) their clay-mineral composition does not vary between tills units. This latter observation shows that the shale source which was eroded by ice apparently did not vary in clay-mineral composition during the Wisconsinan. This is an important observation because it indicates that both major clay-mineral sources (shale and lake clays) which could have been eroded by ice maintained a constant clay-mineral composition throughout the Wisconsinan. Therefore, since neither changed and both have such radically different compositions, neither alone can account for the systematic variation observed in clay-mineral composition show for till units (Figure 6).

Discussion

Based on the above discussion, clay minerals in tills of the Lake Michigan basin were derived largely from erosion by ice of shale bedrock and lacustrine clays. Although similarity in composition can be observed between individual till sheets and one or the other of these sources, the systematic variation in clay-mineral composition shown for successive till sheets (Figure 6) can not be fully accounted for by erosion of either one of these sources alone. Clearly, therefore, variations in clay-mineral composition of Lake Michigan basin tills are probably related to the erosion of differing proportions of shale and lacustrine clay through time.

The reason for erosion of differing proportions of these source beds may relate to one of two processes: 1) changes in ice-flow vectors during the Wisconsinan within the basin or 2) progressive "unroofing" of shale outcrops by erosion of drift mantling bedrock during successive readvances of the Lake Michigan Lobe. These models are briefly outlined below.

Ice Flow Variation Model

Based on the outcrop pattern of shale in the Lake Michigan basin (Figure 7), ice flowing N-S along the axis of Lake Michigan would have been channeled oblique to bedrock strike which would have resulted in a relatively short traverse across the shale. A more NE-SW flow pattern, however, would direct ice along strike of the bedrock and would have erode relatively more shale. Thus, till with low amounts of 10Å clay and shale (Glenn Shores, Ganges-New Berlin, and Ozaukee-Haven) may have been deposited by ice from a north or northwestern source area which was channeled south down the axis (center) of Lake Michigan. Till with high amounts of 10Å clay and shale (Saugatuck-Oak Creek), on the other hand, may have been deposited by ice from a northeastern source area which flowed southwest across northwestern Michigan and into the Lake Michigan basin.

Shifts in ice-flow patterns similar to those suggested above have been proposed by several authors. For example, Denton and Hughes (1980) have proposed a shift in ice-flow direction of the Lake Michigan Lobe from a northern source region to a northeastern source region between 17,000 years ago (deposition of Ganges-New Berlin till) and 14,000 years ago (deposition of Saugatuck-Oak Creek till). They have also suggested that

by approximately 10,000 years ago the source area of the Lake Michigan Lobe had shifted back to the northwest. Likewise, Dworkin et al. (1986) have suggested that the source region for Saugatuck till in southwestern Michigan was north of Lake Huron and have proposed a northeast-southwest flow path for the ice. They also proposed that the source region had shifted westward during deposition of Port Huron tills. A similar westward shift in source region for the Laurentide ice sheet was suggested by Gwyn and Dreimanis (1979). A northwestern source region for Two Rivers till (Greatlakean) has been suggested by Burgis and Eschman (1981). A southeast flow path during the last retreat of ice from northern Michigan has also been suggested by Karrow (1987).

Although, as discussed above, the changes in source area required by the ice-flow variation model have been suggested several authors, the model does not offer a particularly compelling explanation for the clay-mineral variation in till. In order for the model to have actually operated, it requires that ice must flow oblique to the topographic axis of Lake Michigan. Because the Lake Michigan basin forms a long, regional, topographic trough, any ice flow pattern other than directly south down the axis (center) of Lake Michigan seems problematic. This would have been true regardless of the direction from which ice enters the basin. For example, according to the model, ice which deposited Saugatuck-Oak Creek till must first have flowed southwest across the topographic uplands of northwestern Michigan and then entered the trough of Lake Michigan. Moreover, once the Lake Michigan Lobe entered the basin, it must have maintained a general northeast-southwest flow path and must have been completely unaffected by the topography of the lake; a situation which

seems unlikely. The model also implies that shale is generally exposed and available for erosion over large geographic areas throughout the basin. Shale bedrock, however, outcrops extensively in only a few areas which, most notably, are along the mid-lake high in central Lake Michigan (Figure 7) and in extreme northern northwestern Michigan.

The ice-flow model is also questioned based on data presented in Figure 9. These data indicate that no simple relationship exists between the amount of shale clast and clay-mineral composition of till. Although a few mechanisms might explain the absolute differences in amounts of shale clasts in similar age tills with similar clay-mineral compositions between Wisconsin and Michigan (Figure 9), none is satisfactory. For example, differences in amounts of shale clasts and associated clay-mineral composition could be explained by a "threshold" relationship between volume of shale and clay-mineral composition. Such a relationship derives from the fact that the clay-mineral composition of shale clasts found in till is close to that of both Saugatuck and Oak Creek till (Figures 6 and 8) and, therefore, regardless of the volume of shale eroded, no significant change in composition could result. However, if correct then Ganges (in Michigan) and Oak Creek (in Wisconsin) till should exhibit similar clay mineral compositions since they have similar amounts of shale clasts. This is clearly not the case and indicates that a more complex process must have operated.

Unroofing Model

Much recent research concerning the Wisconsinan in the Great Lakes region has concluded that the mid-Wisconsinan (55,000 to 25,000 years ago;

Dreimanis and Goldthwait 1973) generally represents an ice-free interval (Berg et al. 1985; Eschman 1980; Gephart et al. 1982; Rieck and Winters 1982; Winters et al. 1986; Winters et al. 1988). If correct, than as much as 20-30,000 years of lacustrine sediment was deposited within the Lake Michigan basin during this ice-free interval. This probably allowed a thick mantle of lacustrine sediment to mask already sparse bedrock outcrops within the basin. As the initial late Wisconsinan (early Woodfordian) advance filled the basin at about 25,000 years ago, it would have begun to erode this sediment mantle. Thus, tills deposited early in the late Wisconsinan (such as Ganges-New Berlin) should reflect the mineralogy of these lacustrine sediments. Since much of the sediment overlying shale outcrops would have been eroded through time, however, later advances of the Lake Michigan lobe would have eroded relatively more shale and deposited till (Saugatuck-Oak Creek) with a greater influence of bedrock mineralogy. Such a pattern is illustrated in Figures 4 and 7. A dominance of lacustrine-type mineralogy in the youngest (and most northern) tills probably reflects the fact that the shale either did not occur within the northern part of Lake Michigan or subcropped under thick, pre-existing drift.

The quantitative difference in the relative abundance of shale clasts occurring within equivalent age till in Michigan and Wisconsin (Saugatuck and Oak Creek, respectively; Figure 9) may relate to the proximity of shale outcrops to sites of deposition of these tills and to the local basal conditions of the Lake Michigan Lobe. For example, although a simple, positive relationship may exist between the amount of a given rock type eroded by ice and the areal extent of outcrop of that rock type "up-ice"

(Harrison 1960; Peltoniemi 1985), the actual distance clasts are transported and the rate of comminution appear independent of outcrop size. This was suggested by Clark (1987) who further proposed that transport distance of clasts are not controlled by initial concentration but rather by topography of the substrate and basal ice velocity. Topographic obstructions along the bed cause the ice to decrease basal velocity which results in increased frictional drag and tractive forces along the bed, relatively greater debris entrainment, and increased "mixing" of basal debris (Clark 1987). Large tractive forces also result in increased crushing and grinding of sediments (Drewry 1986). Crushing and grinding is probably enhanced under these conditions because low basal velocity increases rates of lodgement, particularly of larger clasts (Boulton 1975), which allow extensive reworking of debris along the base of the ice. Conversely, as ice enters topographic depressions, basal velocity is enhanced. Rapid basal velocity is a consequence of decreased frictional drag between clasts in the ice and the substrate and results in longer transport distances and decreased mixing of debris within the ice (Clark 1987). Lower comminution rates probably also occur under such conditions.

Although the relationship between basal velocity and topographic obstructions is best understood for small-scale features (e.g. less than a few meters in size), it has also been applied on a regional scale to the Great Lakes area (Boulton et al. 1985) and specifically to the Lake Michigan basin (Mickelson et al. 1981). Lake Michigan consists of two deep basins (one restricted to the northern half of the lake and the other to the southern half) which are separated by the mid-lake high (Figure 7). Water depth in the two basins exceeds 150 m but is often <60 m along the

mid-lake high (Wickham et al. 1978). Rapid velocity is predicted as ice flows through the two basins and in places may have even uncoupled from the bed (Mickelson et al. 1981). However, as ice crossed the regional topographic obstruction represented by the mid-lake high, basal velocity would decrease as frictional drag and tractive forces along the bed increased. This, as outlined above, would result in relatively greater entrainment and mixing of basal debris as well as increased crushing and grinding of the entrained sediments.

As the Lake Michigan Lobe flowed across the mid-lake high during the later part of the Woodfordian (about 14-15,000 years ago), it probably eroded a considerable amount of newly exposed shale (as predicted by the unroofing model). Futhermore, if enhanced rates of crushing and grinding actually occurred, the shale would have been rapidly comminuted to fine-grained debris. Continued southwestward flow of the Lake Michigan Lobe toward St. Francis would have caused it to pass from a terrain dominated by shale to one dominated by middle Devonian carbonate (Figure 7; Wold et al. 1981). This would have resulted in dilution of the shale-rich pebble-size debris with carbonate clasts. Because these carbonates are relatively low in clay minerals (Wold et al. 1981), however, no significant change in the clay-mineral composition of the very fine fraction would have resulted.

Flow from the mid-lake high southeastward toward Glenn Shores, on the other hand, would have caused the Lake Michigan Lobe to pass over the southern basin which is not only topographically low but also underlain mainly by shale bedrock (Figure 7). The broad, low, topographic configuration of this area probably resulted in enhanced basal flow velocity and consequently not only allowed ice to carry clasts further, but also

decreased mixing and clast comminution. Because the southern basin is such a broad feature, however, minor bed obstructions probably locally affected the basal flow pattern of the Lake Michigan Lobe and in places increased the rate of erosion and comminution. Importantly, these obstructions would have been composed mainly of either shale or pre-existing drift. Therefore, although ice crossed a significant distance (75-100 km; Figure 7) from the mid-lake high to Glenn Shores and may have crossed and eroded considerable shale outcrop, it also crossed and eroded extensive lake clays. Thus, a dynamic equilibrium between erosion of shale and lake clays may have been achieved and 10Å clay derived from erosion of shale may have been diluted by 7Å clay derived from erosion of lake clays.

As the Lake Michigan Lobe continued to flow south toward Indiana and Illinois it passed out of the southern basin and began to climb out of the lake basin. This area is not only topographically analogous to the mid-lake high but is also underlain by very shallow drift (several meters; Lineback et al. 1972, 1974) and at least in part by shale (Figure 7). This would result in basal ice conditions similar to those suggested along the mid-lake high and allow similarly high rates of erosion and comminution of bedrock.

Regardless of any difference in absolute amounts of shale, however, the data shown in figure 9 and the spatial distribution of shale within the basin demonstrate that shale was apparently rapidly comminuted to clay-size material (within a few to several 10's of km). This suggests that clay-size material in till is not necessarily represent "far-traveled" material and a significant component could be derived locally. This is also implied,

if as suggested, the differences in clay mineralogy between the two areas at Park Cliffs (Area N and G; Figure 3) resulted locally from erosion of lake clays.

Glenn Shores Till?

Although the unroofing model seems most plausible, either of the above models could account for the variation of clay-minerals in late Wisconsinan tills. Neither, however, adequately accounts for the clay mineralogy of Glenn Shores till since it contains higher amounts of 7Å clay than any of the sources discussed above. This compositional dissimilarity with other sediments of the Lake Michigan basin may relate to the relatively great age of the till. For example, if Glenn Shores till was deposited during the Early Wisconsinan (as proposed by Gephart et al. 1982), it may represent one of the earliest post-Sangamon ice advances in the Lake Michigan basin. This ice advance probably traversed an extensively weathered surface which, if weathering had been of sufficient intensity, may have been relatively kaolinite-rich. This weathering surface may, therefore, represent an additional, but now absent, kaolinite-rich, clay-mineral source bed and could account for the anomalously high amount of 7Å clay found in Glenn Shores till.

Although appealing, the above model is none the less speculative since no Sangamon age weathering surface has been reported within the Lake Michigan basin. South of the basin in Illinois, however, Sangamon soils have been studied. For example, Brophy (1959), using heavy minerals as an index of weathering, has suggested relatively intense weathering of Sangamon soils, but indicates that the principal clay-mineral weathering

product is montmorillonite (smectite). Elsewhere in the Great Lakes region, however, kaolinite-rich saprolite has been reported. LaSalle (1984) and LaSalle et al. (1985) have described scattered saprolite deposits developed on shield rocks of southern Quebec that contain abundant authigenic kaolinite. During interglacial periods, these saprolites may have been more wide-spread and may have represented a significant kaolinite source which is now almost completely gone.

In order to test whether Glenn Shores till in fact does contain a significant quantity of kaolinite, the relative contribution of chlorite and kaolinite to 7Å peak intensity must be determined. This is because both kaolinite and chlorite are present in all samples and chlorite and kaolinite both share basal X-ray diffraction reflection at 7.14Å (002 chlorite and 001 kaolinite) and 3.58Å (004 chlorite and 002 kaolinite). Various heat treatments are commonly employed to determine if kaolinite is present in the sample (Carroll 1972; Brindley and Brown 1980). Such treatments, however, usually only allow determination of the presence of kaolinite and are not quantitative. Heat treatments are also not particularly reliable if chlorite is poorly crystalline, as in often the case in "soil" material (Brindley and Brown 1980). A separation of kaolinite and chlorite can also be obtained using warm HCl (Brindley and Brown 1980). This treatment relies on the fact that HCl selectively dissolves chlorite while generally leaving kaolinite untouched and was employed in this study to determine the relative amounts of kaolinite and chlorite in samples.

Previously separated clay-size (<2 um) fraction of samples were split into 2 portions. One portion was placed on a glass slide and X-rayed. The other was placed in a solution of warm, 1N HCl for 4 hours, washed

with distilled water, placed on a glass slide and X-rayed. The acidified X-ray pattern was then compared with the non-acidified. The relative reduction of the 7Å peak of acidified samples represents the amount of chlorite removed by HCl while the peak remaining represents the amount of kaolinite in the sample. The %intensity of the 7Å peak due to kaolinite ($\%K_{7A}$) and chlorite ($\%C_{7A}$) were determine by the following relationships:

$$\%K_{7A} = [(7Å/10Å)_{HCl}]/[(7Å/10Å)_{noHCl}]$$

$$\%C_{7A} = 1-\%K_{7A}$$

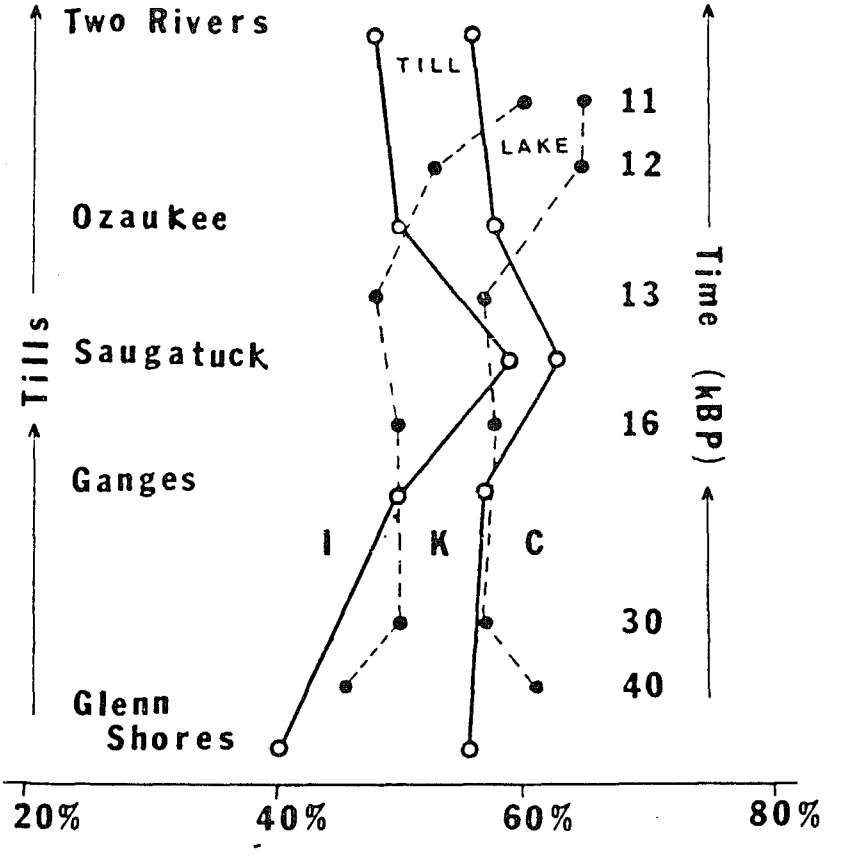


Figure 10 Cumulative percent diagram of relative abundance of illite (I), kaolinite (K), and Chlorite (C) in till and lacustrine units determined by HCL method. Horizontal axis shows cumulative percent; vertical axis shows age. Open circles connected by solid lines shows trend in till units; closed circles connected by dashed line shows trend in lacustrine units (approximate age along right side). One analysis for each unit.

The relative percentages of illite (%I), kaolinite (%K), and chlorite (%C) were determined by calculating the %intensity of each mineral phase to the total intensity (non-acidified diffraction patterns were used) by the following relationships:

$$\%I = 10Å/(7Å+10Å)$$

$$\%K = (7Å*\%K_{7Å})/(7Å+10Å)$$

$$\%C = (7Å*\%C_{7Å})/(7Å+10Å)$$

The above procedure was performed on a sample of each of the major till and lacustrine units found in the basin. The results of these analyses (Figure 10) suggests that compared to younger sediments, kaolinite is most abundant in Glenn Shores till. Although these data do not confirm that the kaolinite in Glenn Shores till were derived from erosion of Sangamon saprolite, they do at least lend support to this explanation.

SUMMARY AND CONCLUSIONS

Data presented in this paper show that the clay-mineral composition of Wisconsinan age till sheets systematically varies throughout the Lake Michigan basin. A general increase in the relative amount of 10Å clay incorporated in till began with the deposition of early or middle Wisconsinan (Altonian) Glenn Shores till and continued through the deposition of late Wisconsinan (mid-Woodfordian) Ganges-New Berlin and Saugatuck-Oak Creek tills. A significant decrease in the relative amount of 10Å clay, however, occurred during deposition of the post-Mackinaw Interstade Ozaukee-Haven-Orchard Beach (Port Huron) and Two Rivers-Filer (Greatlakean) tills.

Unlike the variation observed in successive till sheets, the clay-mineral composition of lacustrine sediment associated with interstadial intervals occurring between the till sheets remains relatively constant. Beginning with deposition in un-named mid-Wisconsinan lakes and continuing through deposition in late Wisconsinan age Lake Milwaukee (Erie Interstade) and the Glenwood Phase of Lake Chicago (Mackinaw and pre-Two Creeks Interstade) no significant change in clay mineralogy was found. The only significant change in clay-mineral composition occurred during deposition of sediment within the final glacial lake phase in the basin (the post-Two Creekan age Calumet Phase of Lake Chicago). These sediments show a significant relative increase in 10Å clay content.

Clay-minerals in tills of the Lake Michigan basin were derived largely from erosion by ice of either shale bedrock and/or lacustrine clays. The composition of Wisconsinan age lacustrine clay sediment is generally similar to that of late Wisconsinan Ganges-New Berlin and to Port Huron and Greatlakean age tills. Lake sediments probably represent the principal clay source for these till sheets. Based on a similarity in clay-mineral composition between Antrim-Ellsworth and Coldwater shale and Saugatuck-Oak Creek till as well as the relatively high amounts of shale clasts in these till units, these bedrocks probably represented the most important clay source for Saugatuck-Oak Creek till. When all the late Wisconsinan age till sheets are considered together, however, the systematic variation observed in their clay-mineral composition can only be accounted for by erosion of differing proportions of lacustrine clay and shale through time. The reason for erosion of differing amounts of these two source beds may relate to one of two processes: 1) changes in ice-flow vectors during the

Wisconsinan within the basin or 2) progressive "unroofing" of shale outcrops by erosion of drift mantling bedrock during successive readvances of the Lake Michigan Lobe.

Although either model could have operated, the progressive unroofing of shale outcrops (model 2 above) seems the most plausible. It relies on basic subglacial processes which, when applied to specific conditions in the Lake Michigan basin account for the patterns in till lithology observed throughout the basin. The model accounts not only for the general homogeneity in clay-mineral composition of till sheets of similar age but also why different age till sheet exhibit systematic compositional variation. Furthermore, the model also explains why important geographic differences should exist in the relative amount of shale clasts present in till sheets. Even though the ice-flow variation model could account for the systematic variations in clay mineral composition, it can not adequately explain geographic differences in the lithology, particularly in the amount of shale, of similar age till sheets. In fact, the topographic configuration of the Lake Michigan basin alone makes a model relying on variation in ice flow questionable.

Regardless of which model is correct, however, neither can adequately explain the clay-mineral composition of early to middle Wisconsinan age Glenn Shores till because this unit contains significantly more 7Å clay (specifically kaolinite) than found in either the lacustrine clay or shale source beds. Although speculative, based on the age of Glenn Shores till, the 7Å clay may have been kaolinite formed during the Sangamon and derived from erosion of this weathering surface during some initial Wisconsinan ice advance.

Based on data presented above, the following additional points are concluded from this study:

1) The clay mineralogy of successive till sheets systematically varies throughout the basin while that of lacustrine generally remains relatively constant.
2) Regional changes in clay-mineral composition of till in the basin occur following significant fluctuations of the Lake Michigan Lobe.
3) In general, the clay mineralogy of an individual till sheet is uniform over relatively large geographic areas, but can exhibit some significant variation within a local area.
4) Clay minerals occurring within till were derived from erosion of underlying drift and/or bedrock while those occurring in lake clays were apparently eroded from pre-existing drift and then homogenized and deposited within the lake basin.
5) Shale bedrock can apparently be rapidly comminuted to clay-size material and, thus, a significant component of the fine-grained fraction of till may represent locally derived material.

Although each of the above conclusions is important, particularly the fact that the clay mineral composition of till sheets systematically vary through space and time, the most important contribution made by this research is the isolation of processes with could account for significant changes in till lithology. An understanding of these processes is especially important because, to date, till stratigraphy in the Lake Michigan basin, and consequently our understanding of the dynamics of the Laurentide ice sheet, is based largely on simple, empirical descriptions of till lithology. In it's construction, it assumes lithologic uniformity of till sheets over

large geographic areas generally without reference to the erosional and depositional processes which are ultimately responsible for the lithology of till. Although, as shown in this study, the lithologies of these till sheets do in fact maintain a generally uniform composition, they can also exhibit significant variation over a relatively short distance (Figure 3) as well as show important geographic differences in some parameters (Figure 8). The fact that till sheet do vary has led some authors to reject the entire stratigraphic system. Considerations of these lithologic parameters as a consequence of subglacial processes that dominated in the erosional and depositional environments specific to the Lake Michigan basin, however, not only lends support to the stratigraphic system by explaining anomalous data but also increases understanding of the dynamics of the Lake Michigan Lobe. In fact, more such studies from other areas may "provide a relatively simple measure of the large-scale behavior of former ice sheets" (Clark 1988, p. 539)

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APPENDIX A: TABLES OF CLAY MINERAL DATA BY GEOLOGICAL UNIT AND SECTION

Saugatuck Till (Glenn Shores Section)

Sample #	7A/10A	Sample #	7A/10A
UT 100	0.55	UT 113	0.65
UT 101	0.58	UT 114	0.53
UT 102	0.53	UT 115	0.53
UT 103	0.59	UT 116	0.61
UT 104	0.60	UT 117	0.63
UT 105	0.57	UT 118	0.57
UT 106	0.59	UT 119	0.54
UT 107	0.63	UT 120	0.57
UT 108	0.51	UT 121	0.55
UT 109	0.58	UT 122	0.67
UT 110	0.52	UT 123	0.53
UT 111	0.57	UT 124	0.61
UT 112	0.58		

Shale Clasts (Saugatuck till; Glenn Shores Section)

Sample #	7A/10A	Sample #	7A/10A
GLSH SGSH-3-86	0.49	GLSH SGSH-7-86	0.47
GLSH SGSH-4-86	0.32	GLSH SGSH-8-86	0.36
GLSH SGSH-5-86	0.52	GLSH SGSH-9-86	0.43
GLSH SGSH-6-86	0.33	GLSH SGSH-10-86	0.78

Ganges Till (Glenn Shores Section)

Sample #	7A/10A	Sample #	7A/10A
MT 1	0.82	MT 21	0.87
MT 2	0.80	MT 22	0.90
MT 3	0.81	MT 23	0.76
MT 4	0.75	MT 24	0.80
MT 5	0.81	MT 25	0.73
MT 6	0.81	MT 26	0.64
MT 7	0.91	MT 27	0.66
MT 8	1.05	MT 28	0.82
MT 9	0.85	MT 29	0.74
MT 10	0.95	MT 30	0.71
MT 11	0.75	MT 500	1.01
MT 12	1.03	MT 501	0.88
MT 13	0.96	MT 502	0.69
MT 14	1.09	MT 503	0.91
MT 15	0.80	MT 504	1.06
MT 16	0.86	MT 505	0.75
MT 17	0.75	MT 506	0.98
MT 18	0.88	MT 507	0.89
MT 19	0.82	MT 508	0.79
MT 20	1.01		

Shale Clasts (Ganges Till; Glenn Shores Section)

Sample #	7A/10A	Sample #	7A/10A
GLSH GGSH-1-86	0.38	GLSH GGSH-5-86	0.41
GLSH GGSH-2-86	0.56	GLSH GGSH-6-86	0.48
GLSH GGSH-3-86	0.47	GLSH GGSH-7-86	0.43
GLSH GGSH-4-86	0.43		

Middle Wisconsinan Lacustrine (Glenn Shores Section)

Sample #	7A/10A	Sample #	7A/10A
GLSH-LC-1-N84	1.19	GLSH-LC1-1-SA84	1.00
GLSH-LC-2-N84	1.03	GLSH-LC1-1-SB84	0.93
GLSH-LC-3-N84	1.04	GLSH-LC1-2-SB84	1.09
GLSH-LC-4-N84	1.06	GLSH-LC1-3-SB84	0.93
GLSH-LC-5-N84	1.07		

Glenn Shores Till (Glenn Shores Section)

Sample #	7A/10A	Sample #	7A/10A
LT 300	1.37	LT 203	1.23
LT 301	1.29	LT 204	1.26
LT 302	1.02	LT 205	1.14
LT 303	1.14	LT 206	1.29
LT 304	1.06	LT 207	1.04
LT 305	1.05	LT 250	1.48
LT 306	1.24	LT 251	1.48
LT 307	1.04	LT 252	1.30
LT 200	1.46	LT 253	1.37
LT 201	1.03	LT 254	0.96
LT 202	1.15		

Shale Clasts (Glenn Shores Till; Glenn Shores Section)

Sample #	7A/10A	Sample #	7A/10A
GLSH GSSH-1-86	0.41	GLSH GSSH-5-86	0.42
GLSH GSSH-2-86	0.36	GLSH GSSH-6-86	0.38
GLSH GSSH-3-86	0.48	GLSH GSSH-7-86	0.42
GLSH GSSH-4-86	0.39		

Saugatuck till (Cedar Bluff Section)

Sample #	7A/10A	Sample #	7A/10A
CDBF SGTI-620-82	0.63	CDBF SGTI-625-82	0.69
CDBF SGTI-621-82	0.60	CDBF SGTI-626-82	0.67
CDBF SGTI-622-82	0.58	CDBF SGTI-627-82	0.65
CDBF SGTI-623-82	0.60	CDBF SGTI-628-82	0.57
CDBF SGTI-624-82	0.62	CDBF SGTI-629-82	0.65

Saugatuck till (Mimoi Park Section)

Sample #	7A/10A	Sample #	7A/10A
MMPK TA-1-A85	0.41	MMPK TA-12-A86	0.58
MMPK TA-2-A85	0.50	MMPK TA-14-A86	0.52
MMPK TA-3-A85	0.63	MMPK TA-16-A86	0.57
MMPK TA-4-A85	0.77	MMPK TA-5-A86	0.62
MMPK TA-5-A85	0.52	MMPK TA-7-A86	0.62
MMPK TA-6-A85	0.60	MMPK TA-8-A86	0.52
MMPK TA-7-A85	0.56	MMPK TA-9-A86	0.57
MMPK TA-10-A86	0.48		

Saugatuck till (Park Cliffs Section; Area G)

Sample #	7A/10A	Sample #	7A/10A
PKCF TA-1-A84	0.99	PKCF TA-3-A84	0.79
PKCF TA-10-A84	0.72	PKCF TA-4-A84	0.79
PKCF TA-11-A84	0.72	PKCF TA-5-A84	0.83
PKCF TA-12-A84	0.75	PKCF TA-6-A84	0.85
PKCF TA-13-A84	0.72	PKCF TA-7-A84	0.82
PKCF TA-14-A84	0.68	PKCF TA-8-A84	0.73
PKCF TA-15-A84	0.72	PKCF TA-9-A84	0.68
PKCF TA-2-A84	0.87		

Saugatuck till (Park Cliffs Section; Area N)

Sample #	7A/10A	Sample #	7A/10A
PKCF TA-1-N85	0.52	PKCF TA-4-N85	0.62
PKCF TA-2-N85	0.61	PKCF TA-5-N85	0.68
PKCF TA-3-N85	0.64		

Lake Milwaukee(?) Sediments (Park Cliffs Section)

Sample #	7A/10A	Sample #	7A/10A
PKCF LA-1-A82	1.00	PKCF LA-5-A82	1.06
PKCF LA-10-A82	0.77	PKCF LA-6-A82	1.07
PKCF LA-11-A82	0.80	PKCF LA-7A-A82	0.91
PKCF LA-2-A82	1.29	PKCF LA-7B-A82	0.97
PKCF LA-3-A82	1.13	PKCF LA-8-A82	0.96
PKCF LA-4-A82	1.09	PKCF LA-9-A82	0.69

Middle(?) Wisconsinan Lacustrine (Park Cliffs Section)

Sample #	7A/10A	Sample #	7A/10A
PKCF LC-1-N86	1.00	PKCF LC-5-86	1.13
PKCF LC-2-N86	0.97	PKCF LC-6-86	1.15
PKCF LC-3-N86	0.90	PKCF LC-7-86	1.05
PKCF LC-4-N86	0.89		

Middle Wisconsinan Lacustrine (South Haven Section)

Sample #	7A/10A	Sample #	7A/10A
SHZB LF-1-82	1.03	SHZB LF-5-82	1.01
SHZB LF-10-82	0.90	SHZB LF-6-82	0.94
SHZB LF-2-82	1.25	SHZB LF-7-82	0.92
SHZB LF-3-82	1.00	SHZB LF-8-82	0.85
SHZB LF-4-82	0.94	SHZB LF-9-82	0.88

Lake Border Moraine (Southwestern Michigan)

Sample #	7A/10A
2S17W 27-1-84	0.65
2S17W 27-2-84	0.51
2S17W 33-1-84	0.56
3S 17W 6-1-84	0.53
3S 18W 14-1-84	0.51
3S18W 12-1-84	0.56
5S 19W 24-1-84	0.44
5S19W 25-1-84	0.48
6S 19W 10-1-84	0.53
6S19W 21-1-84	0.83
7S 19W 18-1-84	0.44
7S20W 24-1-84	0.53
7S20W 36-1-84	0.49
8S20W 19-1-84	0.57
LBM-1	0.57
LBM-2	0.69
LBM-3	0.59
LBM-4	0.56
LBM-5	0.65
LBM-6	0.63
LBM-7	0.62
LBM-8	0.44
LBM-9	0.63
LBM-10	0.47
LBM-11	0.40
LBM-12	0.47
LBM-13	0.89
LBM-14	0.61
LBM-15	0.70
LBM-16	0.62
LBM-17	0.63
LBM-18	0.68
LBM-19	0.55
LBM-20	0.51
LBM-21	0.50

Valparaiso Moraine (Southwestern Michigan)

Sample #	7A/10A
1N15W 24-1-85	0.45
1S14W 11-1-85	0.68
2S15W 30-1-85	0.32
2S15W 34-1-85	0.45
1S14W29-1	0.56
1S14W29-10	0.51
1S14W29-8	0.38
1S14W29-9	0.75
1S14W29-9-T	0.54
1S14W29-25	0.43
1S14W29-27	0.50
1S14W29-29	0.41
1S14W29-30	0.50
1S14W29-31	0.64
BRDV TA-1-85	0.39
BRDV TA-2-85	0.39
BRDV TB-1-A85	0.60
IVM-1	0.57
IVM-2	0.66
IVM-3	0.67
IVM-4	0.51
IVM-5	0.63
IVM-6	1.00
IVM-7	0.81
IVM-8	0.69
IVM-9	0.67
OVM-1	0.64
OVM-2	0.50
OVM-3	0.65
OVM-4	0.53
OVM-5	0.56
2S16W 8-1-85	0.63
3S15W 22-1-85	0.51
3S16W 19-1-85	0.49
3S16W 36-1-85	0.43
3S16W 36-2-85	0.41
5S17W 13-1-85	0.44

Valparaiso Moraine (Indiana and Illinois)

Sample #	7A/10A
VALP 6-9-86	0.25
VALP 5-9-86	0.37
VALP 19-9-86	0.53
VALP 18-9-86	0.77
VALP 17-9-86	0.26
VALP 16-9-86	0.39
VALP 15-9-86	0.40
VALP 14-9-86	0.35
VALP 13-9-86	0.27
VALP 12-9-86	0.35
VALP 11-9-86	0.38
VALP 10-9-86	0.62
VALP 9-9-86	0.33
VALP 8-9-86	0.28
VALP 7-9-86	0.31

Sturgis-Kalamazoo System (Southwest Michigan)

Sample #	7A/10A
5S12W 21-1	0.47
5S12W 28-1	0.53
STM-1	0.57
STM-2	0.74
STM-3	0.43
PAPA TB-1-A84	0.74
PAPA TB-2-A84	0.54
PAPA TB-3-A84	0.66
PAPA TB-4-A84	0.56
3S13W 35-1	0.59
4S13W 26-1	0.65
5S14W 17-1	0.64
5S14W 23-1	1.04
5S14W 26-1	0.80
6S14W 3-1	0.77
6S14W 7-1	0.70
7S15W 19-1-85	0.79
7S15W 31-1-85	0.79
7S15W 31-2-85	0.59
8S16W 2-1-85	0.41
8S16W 2-2-85	0.49
8S16W 2-3-85	0.55
8S16W 2-4-85	0.44
KZM-8	0.55
KZM-1	0.63
KZM-10	0.83
KZM-11	1.08
KZM-2	0.60
KZM-3	0.45
KZM-4	0.49
KZM-5	0.51
KZM-6	0.50
KZM-7	0.60
KZM-9	0.60

Tekonsha Moraine (Southwest Michigan)

Sample #	7A/10A
6S12W 15-1	1.00
6S12W 23-1	0.91
6S13W 13-1	0.75
6S13W 15-1	1.11
7S13W 26-1	1.37
7S14W 26-1	0.70
7S14W 30-1	0.89
8S14W 28-1	0.67
THRS TB-1-84	0.81
THRS TB-2-84	0.84
THRS TB-3-84	1.06
TKM-1	0.67
TKM-2	0.69
TKM-3	0.88
TKM-4	0.87
TKM-5	1.11
TKM-6	0.88

Oak Creek till (St. Francis Section)

Sample #	7A/10A	Sample #	7A/10A
MLKS TA-1-B84	0.74	MLKS TA-4-B84	0.56
MLKS TA-10-B84	0.41	MLKS TA-5-B84	0.40
MLKS TA-12-B84	0.38	MLKS TA-6-B84	0.64
MLKS TA-13-B84	0.40	MLKS TA-7-B84	0.49
MLKS TA-14-B84	0.38	MLKS TA-8-B84	0.42
MLKS TA-2-B84	0.62	MLKS TA-9-B84	0.51
MLKS TA-3-B84	0.72		

Lake Milwaukee Sediments (St. Francis Section)

Sample #	7A/10A	Sample #	7A/10A
MLKS TC-1-B84	1.14	MLKS TC-4-B84	1.10
MLKS TC-2-B84	0.99	MLKS TC-5-B84	0.92
MLKS TC-3-B84	1.17	MLKS TC-6-B84	0.97

New Berlin till (St. Francis Section)

Sample #	7A/10A	Sample #	7A/10A
MLKS TF-1-C84	0.93	MLKS TF-2-C84	0.70
MLKS TF-11-C84	0.86	MLKS TF-3-C84	0.81
MLKS TF-13-C84	0.81	MLKS TF-4-C84	0.95
MLKS TF-14-C84	0.98	MLKS TF-5-C84	0.99
MLKS TF-15-C84	0.86	MLKS TF-6-C84	0.93
MLKS TF-16-C84	1.11	MLKS TF-7-C84	0.96

Ozaukee till (Shorewood Section)

Sample #	7A/10A	Sample #	7A/10A
SHWD TA-1-S84	0.86	SHWD TA-5-S84	0.84
SHWD TA-10-S84	0.88	SHWD TA-6-S84	0.90
SHWD TA-11-S84	0.86	SHWD TA-8-S84	0.93
SHWD TA-2-S84	0.83	SHWD TA-9-S84	0.85
SHWD TA-3-S84	0.90	SHWD TA-4-S84	0.92

Glenwood Sediments (Shorewood Section)

Sample #	7A/10A	Sample #	7A/10A
SHWD TB-10-S84	0.89	SHWD TB-8-S84	0.95
SHWD TB-11-S84	1.00	SHWD TB-9-S84	0.98
SHWD TB-12-S84	0.76	SHWD TB-2-S84	1.12
SHWD TB-13-S84	0.90	SHWD TB-4-S84	0.90
SHWD TB-14-S84	1.23	SHWD TB-16-S84	0.83
SHWD TB-15-S84	0.85		

"Oak Creek(?)" till (Shorewood Section)

Sample #	7A/10A	Sample #	7A/10A
SHWD TF-1-N84	0.77	SHWD TF-1-NA84	0.65
SHWD TF-2-N84	0.63	SHWD TF-2-NA84	0.82
SHWD TF-3-N84	0.68	SHWD TF-3-NA84	0.69
SHWD TF-4-N84	0.70	SHWD TF-4-NA84	0.70
SHWD TF-6-N84	0.60	SHWD TF-5-NA84	0.69
SHWD TF-7-N84	0.58	SHWD TF-8-N84	0.57

Two Rivers till (Two Creeks Section)

Sample #	7A/10A	Sample #	7A/10A
TOCK TA-1-2-B84	0.87	TOCK TA-1-1-B84	0.90
TOCK TA-1-6-C184	1.00	TOCK TA-1-3-B84	1.00
TOCK TA-1-7-C184	0.77	TOCK TA-1-4-B84	0.81
TOCK TA-1-8-C184	0.84	TOCK TA-1-0-B84	0.95

Calumet Sediments (Two Creeks Section)

Sample #	7A/10A	Sample #	7A/10A
TOCK LBU-1-B84	0.69	TOCK LBU-4-B84	0.67
TOCK LBU-2-B84	0.69	TOCK LBU-5-B84	0.74
TOCK LBU-3-B84	0.71		

Glenwood Sediments (Two Creeks Section)

Sample #	7A/10A	Sample #	7A/10A
TOCK LBL-1-B84	1.05	TOCK LBL-7-B84	0.89
TOCK LBL-3-B84	0.98	TOCK LBL-8-B84	1.10
TOCK LBL-4-B84	0.98	TOCK LBL-9-B84	1.00
TOCK LBL-5-B84	1.11	TOCK LBL-10-B84	0.99
TOCK LBL-6-B84	0.77		

Haven till (Two Creeks Section)

Sample #	7A/10A	Sample #	7A/10A
TOCK TC-1-1-C184	0.73	TOCK TC-2-C84	1.21
TOCK TC-1-2-C184	1.17	TOCK TC-3-C84	0.98
TOCK TC-1-3-C184	0.85	TOCK TC-4-C84	1.00
TOCK TC-1-4-C184	1.22	TOCK TC-1-0-C184	1.03
TOCK TC-1-C84	0.91	TOCK TC-1-5-C184	1.00

Two Rivers(?) till (Peterson Park Section)

Sample #	7A/10A	Sample #	7A/10A
PPKS TA-1-A	1.03	PPKS TB-2-A	0.92
PPKS TA-2-A	0.85	PPKS TB-3-A	1.12
PPKS TB-1-A	0.98	PPKS TB-4-A	1.12
PPKS TD-1-A	0.73	PPKS TF-1-1	0.88
PPKS TD-2-A	0.71	PPKS TF-2-A	1.05
PPKS TD-3-A	0.65	PPKS TF-3-A	0.82
PPKS TD-4-A	0.71	PPKS TF-4-A	0.78

Two Rivers(?) Till (Indian Cemetery Section)

Sample #	7A/10A	Sample #	7A/10A
IDCM TB-1-A84	0.84	IDCM TA-2-A84	0.87
IDCM TB-8-A84	0.88	IDCM TA-3-A84	0.94
IDCM TA-1-A84	1.01	IDCM TA-4-A84	0.90

Two Rivers(?) till (South Manitou Island Section)

Sample #	7A/10A	Sample #	7A/10A
SMNT TA-1-A	1.09	SMNT TA-4-A	1.12
SMNT TA-2-A	0.96	SMNT TA-5-A	0.99
SMNT TA-3-A	1.02		

Two Rivers(?) till (Pt. Betsie Section)

Sample #	7A/10A	Sample #	7A/10A
PTBT TA-1-83	0.88	PTBT TA-5-83	1.39
PTBT TA-2-83	0.93	PTBT TB-1-83	1.02
PTBT TA-3-83	1.17	PTBT TB-2-83	1.02
PTBT TA-4-83	0.75	PTBT TB-3-83	0.85

Calumet(?) Sediments (Pt. Betsie Section)

Sample #	7A/10A	Sample #	7A/10A
PTBT LA-2-A83	0.76	PTBT LA-4-A83	0.72
PTBT LA-3-A83	0.80		

Filer till (Orchard Beach Section)

Sample #	7A/10A	Sample #	7A/10A
ORBH TJ-1-A83	0.87	ORBS TA-4	1.02
ORBS TJ-2-A83	0.75	ORBS TA-1-A	0.93
ORBH TJ-3-A83	0.85	ORBS TA-2-A	0.80
ORBH TJ-4-A83	0.79	ORBS TA-3-A	0.77
ORBS TA-1	1.29	ORBS TA-10	0.73
ORBS TA-2	1.04	ORBS TB-1-A	1.32
ORBS TA-7	0.87	ORBS TB-2-A	1.32
ORBS TA-8	0.95	ORBS TB-3-A	1.00
ORBS TA-9	1.19	ORBS TB-4-A	1.20

Orchard Beach till (Orchard Beach Section)

Sample #	7A/10A	Sample #	7A/10A
ORBH TK-1-A83	0.91	ORBH TM-1-A83	1.10
ORBH TK-2-A83	1.15	ORBH TM-2-A83	0.97
ORBH TK-3-A83	0.89	ORBH TM-3-A83	1.09
ORBH TK-4-A83	0.97	ORBH TM-4-A83	1.14
ORBH TK-5-A83	0.93	ORBS TJ-1-B	0.90
ORBH TK-6-A83	0.90	ORBS TJ-2-B	0.83
ORBH TL-1-A83	1.32	ORBS TJ-3-B	0.82
ORBH TL-2-A83	1.22	ORBS TJ-4	0.93
ORBH TL-3-A83	0.90	ORBS TM-1-B	1.10
ORBH TL-4-A83	1.14	ORBS TM-2-B	0.70
ORBH TL-5-A83	1.05	ORBS TM-3-B	0.86
ORBH TL-6-A83	1.10		