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CLAY MINERAL ANALYSIS OF THE LATE
PLEISTOCENE/HOLOCENE SEDIMENTS OF LAKE MICHIGAN:
EVIDENCE FOR DIFFERENT SOURCES THROUGH TIME

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TRINA KIM JOHNSON

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CLAY MINERAL ANALYSIS OF THE LATE PLEISTOCENE / HOLOCENE SEDIMENTS OF LAKE MICHIGAN: EVIDENCE FOR DIFFERENT SOURCES THROUGH TIME

By

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ABSTRACT

CLAY MINERAL ANALYSIS
OF THE LATE PLEISTOCENE / HOLOCENE SEDIMENTS OF LAKE MICHIGAN:
EVIDENCE FOR DIFFERENT SOURCES THROUGH TIME

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Three important questions that relate to the source of sediment to the Lake Michigan basin are: 1) Does the mineralogy of modern lake sediments reflect that of the till within the basin? 2) Does the mineralogy of the late Pleistocene / Holocene lake sediments vary, reflecting changes in source over time? 3) Does the mineralogy of these sediments record catastrophic discharges of water into the Great Lakes basin? Samples of till, lacustrine sediments from Lake Michigan and Lake Superior, and shale bedrock were analyzed to determine the clay mineralogy, specifically the 7/10Å peak height ratio. The results indicate the lacustrine sediments of Lake Michigan reflect the till within the basin, and that the 7/10Å ratios vary and record pulses of sediment from the ice margin itself. The 7/10Å ratio does not record a significant variation that corresponds to the Wilmette Bed. However, discharge may have still occurred without the 7/10Å ratio being affected.

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Table of Contents

LIST OF FIGURES

Introduction

Since the early part of the century, the stratigraphy of the glacial sequence of the Lake Michigan lobe has been studied in detail (Leverett and Taylor, 1915; Thwaites, 1957; Hansel et.al., 1985; 1992) and has provided a framework for interpretation of glacial events in the Lake Michigan basin. However, the stratigraphy of the late Pleistocene/Holocene lacustrine sequence at the bottom of Lake Michigan has not been studied as long (Hough, 1958; Moore, 1961; Lineback et.al., 1979; Hansel et.al., 1985; Colman et.al., 1990; 1994)) and many questions remain as to the source of the lake sediments, which ultimately affects how the lacustrine history of the Lake Michigan basin is interpreted. Three of the most important of these questions are:

1) Does the mineralogy of modern lake sediments reflect that of the till within the basin?

2) Does the mineralogy of the late Pleistocene/Holocene lake sediments vary, reflecting changes in source over time?

3) Does the mineralogy of late Pleistocene/Holocene lake sediments record catastrophic discharges of water into the Great Lakes basin as has been proposed by Farrand and Drexler (1985), Teller (1985), and Colman and others (1990;1994)?

The first question will be addressed by comparing the clay mineralogy, or more specifically the 7/10 Å peak height ratios of samples of recent lacustrine sediments in Lake Michigan with that of till collected from beneath the lake and bluffs along the lake shore. The second and third question will be answered by examining a lake core to see if relative differences in 7/10Å peak height ratios exist throughout the core that would indicate a change in source for the lake sediments.

Geologic History of Lake Michigan

Lake Michigan is one of the five Great Lakes located in the central part of North America formed during the late Pleistocene when the Laurentide ice sheet extended over most of Canada as well as the northern portion of the United States. The direction of flow along the margin of the ice sheet was influenced by pre-existing topography and, in places, the glacier itself eroded areas of soft rock, creating depressions that later filled with water to form the modern Great Lakes (Hough, 1958).

Lake Michigan, the third largest of the Great Lakes, is located on the western edge of the Michigan basin, a structural basin composed of various sedimentary rocks of the Paleozoic. Prior to the Pleistocene, weaker rock formations such as the Antrim Shale and the Salina Group probably formed a broad stream valley in what is now the Lake Michigan basin (Moore, 1961). This valley of weaker rocks exerted control over the direction of the Lake Michigan lobe which moved preferentially parallel to the trough axis in a north-south direction, eroding the softer material to form an elongated basin (Hough, 1958).

Glacial Lakes

According to Hansel and Johnson (1992), the late Wisconsin subepisode in the Lake Michigan basin includes eight glacial phases indicated by glaciogenic sequences in the sediment record of the Lake Michigan lobe. The eight phases of the Lake Michigan lobe (Marengo, Shelby, Putnam, Livingston, Woodstock, Crown Point, Port Huron, and Denmark) are based on till units and morainal systems. The first four are generally not applicable to the lacustrine history of the Lake Michigan basin because the ice margin associated with them never retreated into the basin (Hansel and Johnson, 1992), and therefore they will not be discussed in this paper.

During the last four phases the ice margin did oscillate back and forth over the Lake Michigan basin, advancing less farther south each time and allowing proglacial lakes to form. Schneider and Need (1985) have proposed that Lake Milwaukee existed between the Woodstock and subsequent Crown Point phase and have suggested that the lake lasted from 14,500 to 15,500 ybp. Presumably, Lake Milwaukee drained southward throughout much of its history. The Glenwood I phase of Lake Chicago, which extended between the ice margin and the end moraines encircling the southern part of the lake basin, formed during the retreat of the Crown Point phase around 13,600-13,300 ybp (Hansel and Johnson, 1992) and discharged by way of a southern outlet located southwest of Chicago (Hansel et.al., 1985). It was followed by the Glenwood II phase of Lake Chicago, which formed during the ice advance of the Port Huron phase (13,000 ybp) and drained to the south at the Chicago outlet (Hansel et.al., 1985). During the latter half of the Port Huron phase around 12,000 ybp, however, either the Straits of Mackinac or the Indian River lowlands in northern lower Michigan opened resulting in a drop in lake level (Hansel et.al., 1985). Lake Calumet subsequently formed around 11,800-11,200 ybp during the ice advance of the Denmark phase. It drained southward through the Chicago outlet and is believed to have been relatively short-lived (Hansel et.al., 1985).

With the opening of the Straits of Mackinac sometime prior to 11,000 ybp the waters of Lake Michigan, Lake Superior, and Lake Huron became confluent in what is known as the Kirkfield phase of Lake Algonquin (Hansel et.al., 1985).

It lasted roughly from 11,000 to 10,000 ybp and drained through the Fenelon Falls outlet at the southeastern side of the Georgian Bay in Ontario (Hansel et.al., 1985). Subsequent deglaciation of the North Bay outlet at the eastern side of Georgian Bay in Ontario caused the lake level to drop, creating the Chippewa low phase in Lake Michigan around 10,000 ybp which drained through the Straits of Mackinac (Hansel et.al., 1985). Subsequent uplift of the North Bay region, however, caused the lake levels of the Michigan and Huron basins to rise and stabilize at 4,500 ybp in what is known as Lake Nipissing, which temporarily drained through three outlets: Port Huron, Chicago, and North Bay (Larsen, 1985). The North Bay outlet however was later abandoned as uplift continued (Hansel et.al., 1985), leading to the formation of Nipissing II around 4,700-3,700 ybp (Cowan, 1978). Following Nipissing II, the Port Huron outlet was further eroded, the Chicago outlet was abandoned, and the lake level dropped to the Algoma level, and then to the modern level with continued erosion of the Port Huron outlet (Hansel et.al., 1985).

Marquette Phase

The Marquette phase, which is a glacial phase of the Superior lobe, occurred about or shortly after 10,000 ybp (Farrand and Drexler, 1985). At the height of this phase glacial ice filled almost all of the Lake Superior basin and extended to the Michigan shores of the present Lake Superior (Farrand and Drexler, 1985). Evidence for the Marquette phase includes radio-carbon-dated wood specimens from a buried forest near Marquette, Michigan (Futyma, 1981) and the Grand Marais I moraine that extends from Marquette to Whitefish Point (Farrand and Drexler, 1985). Two more moraines lakeward also represent minor adjustments of the ice front (Farrand and Drexler, 1985). During these adjustments, waters from the western part of the Superior basin flowed southeastward through the Au Train-Whitefish channel into the Lake Michigan basin (Farrand and Drexler, 1985).

Lake Agassiz

Lake Agassiz, one of the largest glacial lakes in North America, came into existence about 11,700 ybp when the ice of the Red River-Des Moines Lobe retreated north of the Hudson Bay-Mississippi River divide and water was impounded in the Red River Valley (Teller, 1985). According to Teller (1985), the lake had different outlets throughout its existence. For example, the early phases of the lake (Cass and Lockhart) discharged to the south via the Minnesota River into the Mississippi River basin. However, between 11,000 and 10,000 ybp (Moorhead phase) lower outlets into the Superior basin were uncovered by the retreating ice of the Superior lobe and the discharge was diverted eastward into the Great Lakes basin and ultimately into the Atlantic Ocean via the St. Lawrence Valley (Teller, 1985).

Several workers have linked the onset of the Younger Dryas in Europe to the drainage of Lake Agassiz eastward into the Atlantic Ocean and have suggested that the diversion of glacial meltwater from the Mississippi to the St. Lawrence caused temporary termination of deep water formation in the North Atlantic, resulting in the Younger Dryas, a brief but intense cooling period which temporarily halted the retreat of major ice caps (Broecker et.al., 1988). According to Broecker et.al. (1988), the Younger Dryas occurred at 10,500-9,900 ybp and ended abruptly with the readvance of ice during the Marquette phase which cut off Lake Agassiz flow to the east and channelled it once again south into the Mississippi River Valley.

Sediments of Lake Michigan

Tills and lacustrine units associated with the Lake Michigan basin , as well as the event in which they were deposited are presented in a generalized stratigraphic column in Figure 1. It includes the Haeger till, which was deposited during the Woodstock phase and is found around the southern shoreline of Lake Michigan (Hansel and Johnson, 1992). Above the Haeger till are fine grained sediments associated with glacial Lake Milwaukee. These have been observed along the lake shore in both Wisconsin and Michigan (Schneider and Need, 1985; Larson and Monaghan, 1988). The Wadsworth till that overlies Lake Milwaukee sediments was deposited during the Crown Point phase (Hansel and Johnson, 1992) and is present under Lake Michigan (Foster and Colman, 1991). The overlying Shorewood and Manitowoc tills were deposited in rapid succession (Acomb et.al., 1982) during the Port Huron phase (Hansel and Johnson, 1992) and also occur beneath the lake (Foster and Colman, 1991). The last unit of till found beneath Lake Michigan is the Two Rivers till deposited during the Denmark phase (Hansel and Johnson, 1992).

During the retreat of the ice margin at the end of the Woodstock, Crown Point, Port Huron, and Denmark phases, ice-distal sublacustrine outwash of the Equality Formation, which consists of sublacustrine outwash in the deep basin that laterally grades into till on the basin slopes, was deposited over parts of the basin (Foster and Colman, 1991). According to Foster and Colman (1991), the outwash also grades both upward and southward (laterally) into the lower Lake Michigan Formation.

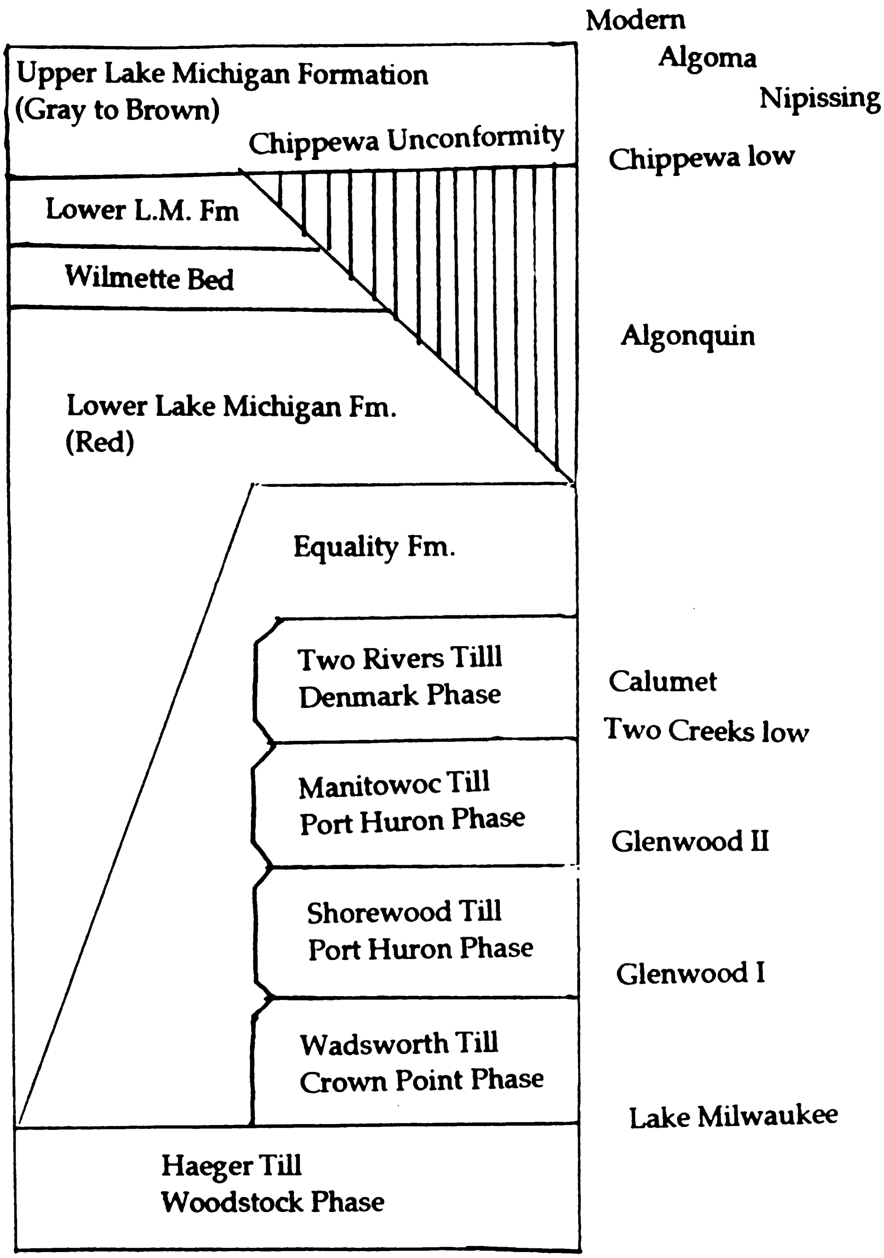

Figure 1: Quaternary stratigraphy and associated glacial ice and lake phases of Lake Michigan. Vertical ruling indicates parts of the section missing due to erosion (after Colman and Foster, 1990).

The lower Lake Michigan Formation, an extremely fine-grained reddish lacustrine clay with occasional beds of clay and lithified clasts and also silt rhythmites, was deposited in the Lake Michigan basin during the Kirkfield phase of Lake Algonquin (Foster and Colman, 1991). The Wilmette Bed occurs within the upper portion of the lower Lake Michigan Formation and is a distinctive marker bed (Foster and Colman, 1991). Its source is debated and will be discussed later. The Chippewa unconformity separates the lower Lake Michigan Formation from the upper Lake Michigan Formation and is marked in shallower areas of the lake basin by a sand and shell layer and in deeper areas of the lake basin by a gradual conformable transition to brown clay (Foster & Colman, 1991). The postglacial deposits of the upper Michigan Formation are gray-brown and extend throughout the Lake Michigan basin, although the deposits vary in both distribution and thickness, suggesting a variable rate of sedimentation influenced by river input and coastal erosion (Foster and Colman, 1991). The pattern of deposition has essentially remained the same for the last 10,000 years (Foster and Colman, 1991).

Wilmette Bed

Colman and others (1994) have looked most recently at the origin of the Wilmette Bed, which is a gray silty clay that occurs throughout the Lake Michigan basin and has long been used as a marker bed. They have set an age for the Wilmette Bed at between 11,200 and 10,300 ybp based on dates of the retreat of the Two Rivers ice (11,200 ybp) and the start of the Chippewa low phase (10,300 ybp). Lower magnetic susceptibility, the lack of ostracodes, a higher amount of black streaks of iron monosulfides, the gray color, and the distinct, massive nature of the Wilmette Bed compared to the surrounding sediments are the basis for claiming the Wilmette Bed as unique compared to the rest of the Lake Michigan Formation (Colman et.al., 1994).

Based on the physical differences in the Wilmette Bed, Colman et.al., (1994), as well as Teller (1985), have argued that the Wilmette Bed represents an infilling of water from Lake Agassiz during the beginning of the Moorhead Phase, at 11,000-10,000 ybp. At this time, Lake Michigan was a far corner of a Lake Algonquin through which the discharge passed (Colman et.al., 1994). Due to the magnitude of the effects on southern Lake Michigan sediments, the episode may have involved large, probably catastrophic discharges (Colman et.al., 1994).

Sampling

A total of 94 samples were analyzed for this study. Samples were taken at shallow sediment depths (less than 2 cm) throughout Lake Michigan using box cores, vibracores, and gravity cores by the U.S. Geological Survey in 1989 as part of a program to determine the Geologic framework of Lake Michigan. One sample from the southern part of the basin and three more from the northern part of the basin were collected at shallow sediment depths by using box cores as part of the NOAA sponsored National Undersea Research Program, the U.S. EPA, and the Great Lakes Protection Fund. In addition, one long, continuous core was collected using a piston core of lacustrine clay down to 1100 cm in depth in the southern part of the basin by the same U.S. Geological Survey study. The locations of the Lake Michigan samples are given in Figure 2. Lacustrine

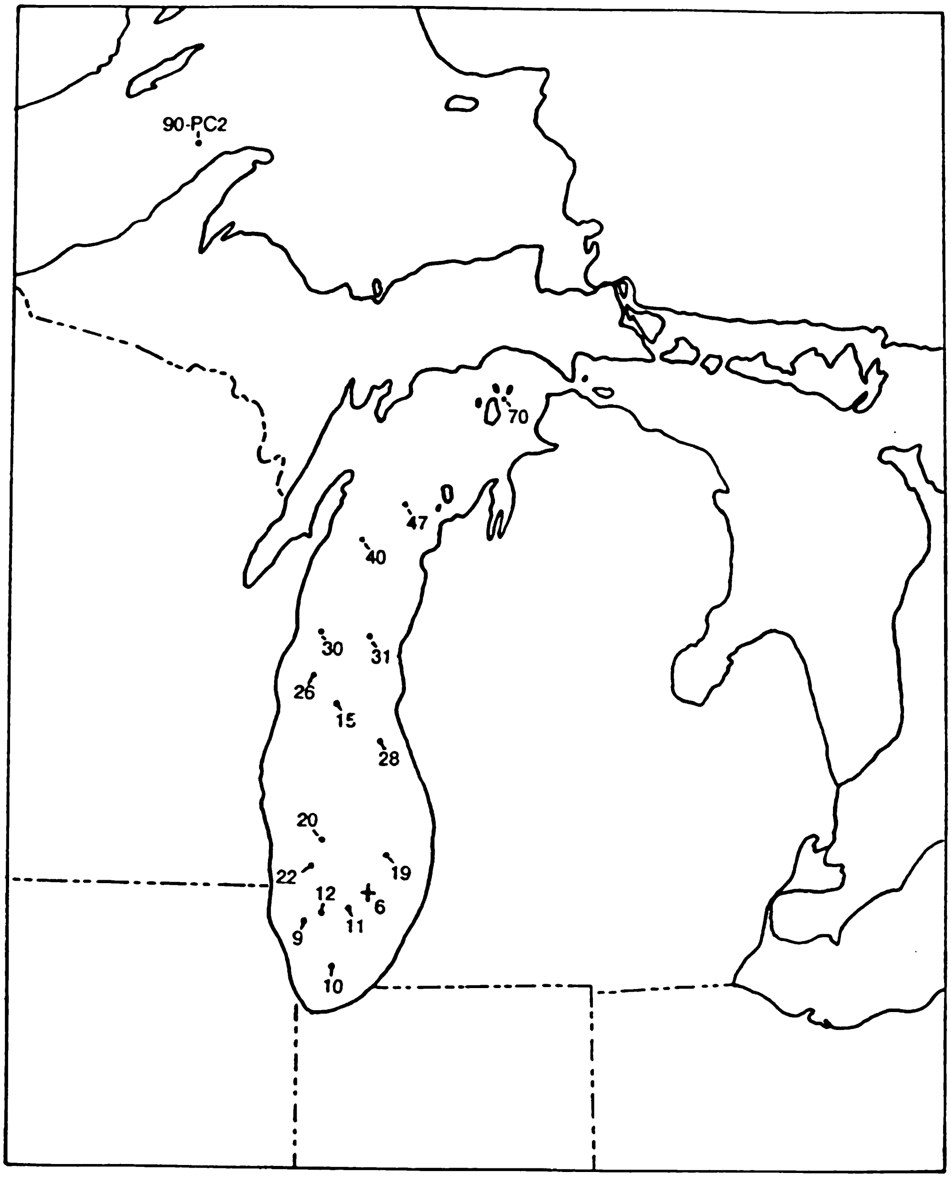

Figure 2: Schematic map of the locations of samples. Samples 9 and 15 are tills; sample 6 is the lake core.

samples were also collected from southeastern Lake Superior by NOAA as part of the National Undersea Research Program.

Samples from the Wadsworth and Manitowoc till from beneath Lake Michigan were collected by vibracore and gravity core as part of the same study in 1989 by the U.S. Geological Survey. Also, samples of Antrim shale bedrock as well as shale clasts in till from Porter County in Indiana were collected from borings provided by the Indiana Geological Survey. Additional shale clasts in till were collected from Racine County in Wisconsin by Dr. Grahame Larson.

Clay Mineral Analysis

All samples were sieved to remove the > 2mm particles and the carbonates and soluble salts were removed following the methods of Jackson (1975). Organic matter and MnO_2 were oxidized according to Jackson (1975). The samples were placed in a cylinder following Jackson's (1975) cylinder sedimentation method to extract the clay fraction. The clay was then saturated with magnesium or potassium, according to methods of Whittig and Allardice (1987), spread on glass slides, and allowed to dry. The magnesium-saturated slides were placed in an ethylene glycol atmosphere. Three potassium-saturated slides were prepared: one at 25 degrees Celsius, one heated to 300 degrees Celsius in a muffle furnace for two hours, and one heated to 550 degrees Celsius in the same manner. The slides were then scanned from 2-32 degrees of two-theta on an X-ray diffractometer, except for the magnesium-ethylene glycol treated slides, which were scanned from 2-15 degrees of two theta.

The potassium-saturated slides were used to indicate whether a clay mineral is present, not the specific amount of the clay mineral that is in the sample. The magnesium-ethylene glycol diffractograms were used to quantify 7A/10Å peak height ratios, where the 7Å peak is due to the presence of chlorite, kaolinite, and/or vermiculite, and the 10Å peak is produced by illite. The 7Å and 10Å peak was measured to the nearest millimeter from an established base line.

Results

The results of analysis of the clay mineralogy of Lake Michigan and Lake Superior sediment, as well as till samples and shale clasts are presented in Figure 3 and listed in the Appendix. Smectite was determined in some of the samples by the presence of an 18Å peak in magnesium-ethylene glycol treated clays. Chlorite was indicated in varying degrees in most of the samples by the presence of a 14Å peak in all treatments. Also, the chlorite (004) peak at 3.53Å was present in many of the samples, although that peak decreased upon heating. Illite was indicated by the 10Å peak present in all treatments. Kaolinite was found to be in some samples due to a (002) peak at 3.57Å. Vermiculite was also present in some of the samples and was indicated when the ratio of 10Å to 14Å peaks was higher in the potassium-saturated samples than in the magnesium-saturated samples. The determination of hydroxy interlayered vermiculite was made by noting whether there was a progressive collapse of the 14Å peak to a 10Å peak upon heating to 300 and then 550 degrees.

The results of the 7/10Å peak height ratios for all the samples are given in Figure 4 and show that the lacustrine samples taken at shallow depths for Lakes Michigan and Superior (5-A) are two separate populations with no overlap and

	Tills	Lake Core	Shallow-MI
Illite	Present	Present	Present
Chlorite	Present	Present	Present
Biotite	Present	Mostly	Mostly
Smectite	Occasionally	Occasionally	Mostly
Kaolinite	Present	Occasionally	Rarely
Vermiculite	Mostly	Mostly	Mostly
HIV	Never	Occasionally	Occasionally

Figure 3: Clay mineralogy averaged from the samples of the tills from Lake Michigan, the shallow sediment depths, and the lake core. Present means the mineral was found in all the samples; Mostly means the mineral was found in 60-100% of the samples; Occasionally means the mineral was found in 30-60% of the samples; Rarely means the mineral was found in <30% of the samples, and Never means the mineral was not found in any of the samples.

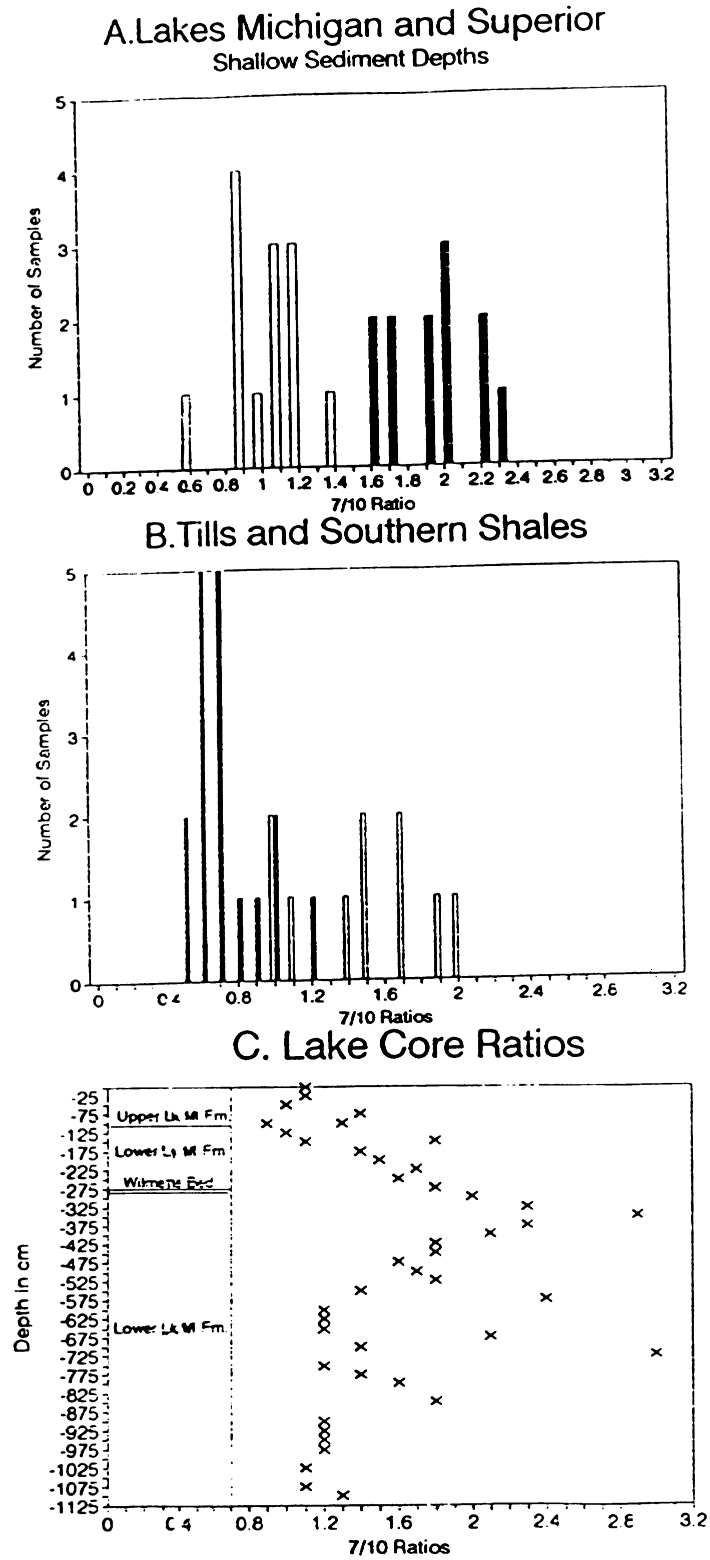

Figure 4: Chart of the 7/10Å ratio of the samples. A) Clear are Lake Michigan samples and black are Lake Superior, B) Clear are the tills and black are southern shales.

that the average peak height ratio is 1.03 for Lake Michigan and 1.93 for Lake Superior sediments. In addition, the data show that the tills from beneath Lake Michigan and the shale clasts also form distinct populations (5-B), with that of the till averaging at 1.69 and 1.16 and the shale clasts average at 0.70.

The lake core from Lake Michigan was analyzed in 25 cm intervals from 0-1100 cm in depth and the resulting peak height ratios (5-C) show distinct differences from the base to the top of the core. The peak height ratios between the interval 450-1100 cm average at about 1.5 with occasional random samples that have a much higher ratio. Between the interval 75-450 cm the ratios gradually increase to a value of 2.1 followed by a similar gradual decrease to a value of 1.2. From 75 cm to the top of the lake core, the peak height ratios again average at 1.0.

North/ South Endmember

When viewed together with the 7/10Å ratio data for the Lake Michigan core the two populations for the Lake Michigan and Lake Superior basins appear to represent endmembers. The lower endmember indicates less chlorite relative to more illite and may represent lacustrine sediment that was sourced by the tills and shales that compose the southern end of Lake Michigan. The upper endmember contains more chlorite relative to illite and represents lacustrine sediment that had chlorite-rich rocks of the Canadian Shield that compose most of the shoreline of Lake Superior as its source.

Tills and shallow depth samples

It is apparent that the 7/10Å peak height ratios of the tills from beneath Lake Michigan fall between that of the shale samples and clay from Lake Superior (Figure 5-A and 5-B). Therefore, the tills appear to consist of a mixture of the more illite-rich source (shale) representative of the Lake Michigan basin and chlorite-rich material representative of the Lake Superior basin. Monaghan et.al. (1986;1990) have studied the relationship of different till units and have found that the till of the Lake Michigan lobe appears to be sourced in part by the shale bedrock and in part by the rocks of the Canadian shield. The 7/10Å peak height ratio results of this paper appear to substantiate that claim.

The 7A/10Å peak height ratios from the lacustrine samples taken from Lake Michigan indicate that the clay minerals reflect shoreline erosion and deposition of till and shale bedrock surrounding Lake Michigan since the ratios for the lacustrine sediments fall between the shales and the tills (Fig.5-A and 5-B). The ratios also indicate that the lake may undergo mixing processes, giving the lake a uniform ratio for a very shallow depth. Several researchers dealing with the transport of phosphorous (Johnson and Nicholls, 1989), organic matter (Meyers and Eadie, 1993), and lipids and alkanes (Parrish et.al., 1992) have concluded that Lake Michigan sediment undergoes a period of suspension before it is deposited. Also, during spring and fall overturn the surface (<5 cm) sediments can become resuspended (Robbins and Eadie, 1991) and while in suspension the material can be transported elsewhere by lake currents. Rivers can also carry in additional loads of sediment that will mix in the lake (Johnson, 1991). Finally, lake focusing, or the accumulation of sediment toward the center of basins with losses of sediment from the margins (Robbins and Eadie, 1991), can mix clay particles originally derived from till or from shale bedrock.

Samples taken at depth

The clay mineralogy of the late Pleistocene/Holocene lake sediments varies, reflecting changes in source over time. The lowest portion of the core, from 1100 cm to 425 cm, shows an average peak height ratio that corresponds to the southern endmember, indicating that the clays were sourced by the till and the shale of the region surrounding the Lake Michigan basin. This would fit with Colman et.al.'s (1990) interpretation that the lacustrine units of the lower part of the lake core was deposited in conjunction with the Equality Formation and the Shorewood, Manitowoc, and Two Rivers tills. However, there are several peak height ratios in the lower portion of the lake core that correspond to the northern endmember. Since the ice margin of the glacier formed the northern shore in all of the glacial lakes, the ice margin itself may have contributed pulses of chlorite-rich sediment to the Lake Michigan basin. The ice would have contained a high amount of chlorite in the sediment due to the northern chlorite-rich Canadian Shield rocks that the glacier overrode.

The middle of the core shows a gradual transition to a higher chlorite content that approaches the northern endmember. This portion of the lake core represents the period of time in which the lakes Huron, Michigan, and Superior were confluent in glacial Lake Algonquin (Figure 5). The higher chlorite content for Lake Algonquin indicates a lake mixing process that reflects the addition of chlorite-rich material from the Superior and northern Lake Huron basin shores and from the ice margin which formed the north shore of Lake Algonquin (Figure 5), which gave Lake Algonquin an overall peak height ratio that was

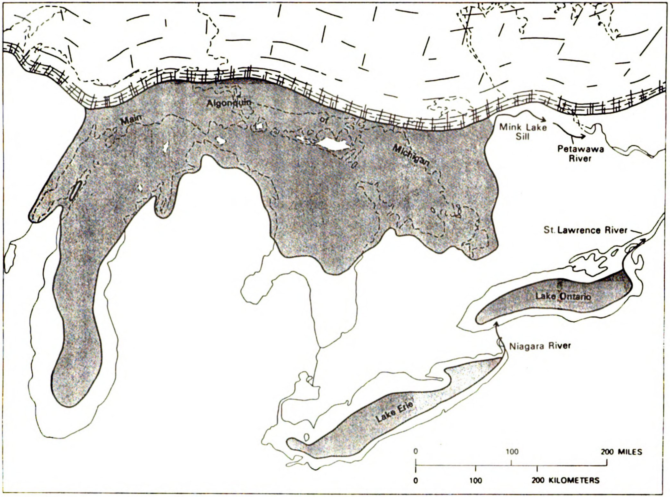

Figure 5: Schematic map of Lake Algonquin around 11,000 ybp (after Larsen, 1987).

much higher than that for the Lake Michigan basin alone. The gradual decrease in the chlorite content in the lake core represents the retreat of the ice, the draining of Lake Algonquin, and the forming of Lakes Chippewa, Nipissing, Algoma, and Michigan. These lakes were isolated from the influence of the other Great Lakes, resulting in a return to the low chlorite/high illite tills and shales of the Lake Michigan basin shoreline as a source for the lacustrine sediment.

The Wilmette Bed

The 7/10Å peak height ratio of the Wilmette Bed does not appear anomalous with the rest of the lake core. The peak height falls in between the southern and northern endmember and also follows the trend of that portion of the lake core of a gradually decreasing chlorite content.

There may be several reasons for the lack of mineralogical differences. One explanation that might account for the above observations is that the source of the Wilmette Bed is not from clays derived from the Superior basin or Red River basin during the Lake Agassiz flood but rather from accelerated erosion of the Lake Michigan basin shores when the level of Lake Algonquin rose in response to the flood. The discharge would have raised water levels significantly, which may not have necessarily been accompanied by an additional sediment load. The increased erosion of the shores of Lake Algonquin would not have contributed any different material than normal erosion alone, and the 7A/10Å peak would not have been affected.

Increased erosion of the shore due to rising water level from Lake Agassiz discharge may explain Colman et.al.'s (1994) observed differences of the

Wilmette Bed. The gray color may be because the sediment layer was not in the water column long enough to oxidize. A large load of sediment may have been deposited rapidly without much mixing, which would also explain the massive nature of the Wilmette Bed. Lack of ostracodes in the Wilmette Bed may also be explained by increased shoreline erosion with rapid deposition. The black streaks of iron monosulfides may be due to the breakdown of organic matter derived from erosion of shoreline vegetation. Finally, the lower magnetic sucseptibility may be due to erosion of till that was not high in magnetite.

Conclusion

The lacustrine clay minerals of Lake Michigan reflect that of the till and shale surrounding the basin. Also, at different stages of the lake basin the peak height ratios correspond to those of the Lake Superior clay minerals, reflecting a chlorite-rich source of lake sediment. The lower portion of the lake core was deposited in conjunction with the Wadsworth, Shorewood, and Manitowoc tills, and the anomalous high chlorite peak height ratios may represent fluctuations in the ice margin that lead to pulses of high chlorite content sediment being deposited. The middle portion of the core was deposited while Lake Algonquin existed which possessed a much larger shoreline that included both the Canadian Shield rocks and the ice margin as a source for the lake clay. The high chlorite peak drops in the upper portion of the core reflecting the demise of Lake Algonquin and the return to only the till and the shales surrounding the Lake Michigan basin as the source for lacustrine material in the lake. The Wilmette Bed may represent a catastrophic discharge by Lake Agassiz that raised water level and increased shoreline erosion.

APPENDIX: CLAY MINERALOGY DATA AND PEAK HEIGHT RATIOS FOR TILLS, SHALLOW SEDIMENT DEPTHS, AND LAKE CORE

Tills and Shallow Sediment Depth Clay Mineralogy Analysis

sample #	smectite	illite	biotite	chlorite
9g-620till	no	yes	yes	yes
9g635till	no	yes	yes	yes
9g665till	yes	yes	yes	yes
9g670till	yes	yes	yes	yes
15-550till	no	yes	yes	yes
15-600till	yes	yes	yes	yes
15-650till	no	yes	yes	yes
150700till	no	yes	yes	yes
15-750till	yes	yes	yes	yes
15-780till	no	yes	yes	yes
19shallowsed	no	yes	no	yes
31shallowsed	yes	yes	yes	yes
30shallowsed	yes	yes	yes	yes
28shallowsed	no	yes	yes	yes
26shallowsed	yes	yes	yes	yes
22shallowsed	no	yes	yes	yes
20shallowsed	no	yes	yes	yes
12shallowsed	yes	yes	yes	yes
11shallowsed	yes	yes	yes	yes
10shallowsed	yes	yes	yes	yes
40shallowsed	yes	yes	yes	yes
47shallowsed	yes	yes	yes	yes
70shallowsed	no	yes	yes	yes

Tills and Shallow Sediment Depth Clay Mineralogy Analysis-Continued

HIV	kaolinite	vermiculite	quartz	unknown
no	yes	yes	yes	no
no	yes	no	yes	no
no	yes	yes	yes	no
no	yes	yes	yes	no
no	yes	yes	no	yes
no	yes	no	yes	yes
no	yes	yes	yes	yes
no	yes	yes	yes	yes
no	yes	yes	yes	yes
no	yes	yes	yes	yes
no	no	no	no	no
no	yes	yes	yes	no
yes	no	yes	yes	no
yes	no	yes	yes	no
yes	no	yes	yes	yes
no	no	yes	yes	yes
no	no	yes	yes	no
yes	no	yes	yes	no
yes	no	yes	yes	no
no	yes	yes	yes	no
yes	no	yes	yes	yes
no	no	yes	yes	no
yes	no	no	no	yes

Lake Core Clay Mineralogy Analysis

Sample&depth	smectite	illite	biotite	chlorite
6p-00	no	yes	yes	yes
6p-25	no	yes	yes	yes
6p-50	yes	yes	yes	yes
6p-75	no	yes	yes	yes
6p-100	no	yes	yes	yes
6p-125	no	yes	yes	yes
6p-150	yes	yes	yes	yes
6p-175	no	yes	yes	yes
6p-200	no	yes	yes	yes
6p-225	no	yes	yes	yes
6p-250	no	yes	yes	yes
6p-275	no	yes	yes	yes
6p-300	no	yes	yes	yes
6p-325	no	yes	yes	yes
6p-350	no	yes	yes	yes
6p-375	no	yes	yes	yes
6p-400	no	yes	yes	yes
6p-425	no	yes	yes	yes
6p-450	no	yes	yes	yes
6p-475	yes	yes	yes	yes
6p-500	no	yes	no	yes
6p-525	no	yes	no	yes
6p-550	no	yes	no	yes
6p-575	no	yes	yes	yes
6p-600	no	yes	yes	yes
6p-625	no	yes	yes	yes
6p-650	yes	yes	no	yes
6p-675	no	yes	yes	yes
6p-700	yes	yes	yes	yes
6p-725	no	yes	yes	yes
6p-750	yes	yes	yes	yes
6p-775	yes	yes	yes	yes
6p-800	no	yes	no	yes
6p-850	no	yes	no	yes
6p-900	yes	yes	yes	yes
6p-925	yes	yes	yes	yes
6p-950	yes	yes	yes	yes
6p-975	yes	yes	yes	yes
6p-1000	yes	yes	yes	yes
6p-1025	yes	yes	no	yes
6p-1050	no	yes	yes	yes
6p-1075	yes	yes	yes	yes
6p-1100	yes	yes	yes	yes

Lake Core Clay Mineralogy Analysis-Continued

HIV	kaolinite	vermiculite	quartz	unknown
yes	no	yes	yes	no
yes	no	no	yes	yes
yes	no	yes	yes	no
yes	no	no	yes	no
no	no	yes	yes	yes
no	no	yes	yes	no
yes	no	yes	no	ues
yes	yes	yes	yes	yes
no	no	yes	no	yes
no	yes	yes	no	yes
no	no	yes	yes	yes
no	no	yes	no	yes
no	no	yes	yes	yes
no	yes	no	yes	yes
yes	yes	no	yes	yes
no	no	yes	yes	yes
no	yes	yes	yes	yes
no	yes	yes	no	yes
no	no	yes	yes	yes
yes	yes	no	yes	yes
no	yes	no	yes	yes
no	no	yes	yes	yes
no	no	yes	yes	yes
no	no	no	no	yes
no	no	yes	yes	yes
yes	no	yes	yes	yes
no	yes	yes	yes	yes
no	yes	yes	yes	yes
no	no	yes	yes	yes
no	no	yes	yes	yes
yes	no	yes	no	yes
yes	no	yes	no	yes
no	yes	yes	no	yes
no	yes	yes	yes	yes
no	yes	yes	no	yes
yes	no	yes	no	yes
no	yes	yes	no	yes
yes	no	no	no	yes
no	no	yes	no	yes
yes	no	yes	no	yes
no	no	no	no	yes
no	no	yes	yes	yes
yes	no	yes	yes	yes

Till and Shallow Sediment Depth 7/10Å Ratios

	Trial 1	Trial 2	Average	
Manitowoc				Average
15V550	1.38	1.54	1.46	1.69
15V600	1.61	1.75	1.68	Standard
15V650	1.54	1.37	1.46	Deviation=.21
15V700	2.45	1.3	1.88	
15V750	1.73	1.56	1.65	
15V 780	1.16	2.8	1.98	
Wadsworth				Average
9G 620	1		1	1.16
9G 935	0	1.36	1.36	Standard
9G 665	1	1.22	1.11	Deviation=.18
Surface Sed.				Average
VC 10	1.17	0.925	1.05	1.03
BC 28	1.19	1.26	1.23	Standard
BC 11	0.828	0.975	0.902	Deviation=.20
BC 12	0.934	0.871	0.903	
BC 19	0.857		0.857	
BC 31	1.07	1.26	1.17	
BC 26	1.04		1.04	
BC 20	1.39		1.39	
BC 22	1.26	1.15	1.21	
BC 30	1.07	0	1.07	
BC 40	1.11	1.04	1.08	
S 47	0.614	0.608	0.611	
M 70	0.932		0.932	

Lake Core 7/10Å Ratios

Sample&depth	TRIAL 1	TRIAL 2	AVERAGE
6P 00	1.28	0.946	1.11
6P 25	0.872	1.33	1.1
6P 50	0.971	0.945	0.958
6P 75	1.48	1.23	1.36
6P 100	0.913		0.913
6P 125	1.08	0.949	1.01
6P 150	1.06	1.16	1.11
6P 175	1.53	1.26	1.4
6P 200	1.5	1.42	1.46
6P 225	1.67	1.75	1.71
6P 250	0	1.62	1.62
6P 275	1.61	2.06	1.84
6P 300	2.09	1.8	1.95
6P 325	2	2.63	2.32
6P 350	2.36	3.46	2.91
6P 375	2.66	2	2.33
6P 400	2.07	0	2.07
6P 425	2	1.64	1.82
6P 450	1.8	1.75	1.78
6P 475	1.51	1.77	1.64
6P 500	1.53	1.87	1.7
6P 525	1.7	1.98	1.84
6P 550	1.48	1.29	1.39
6P 575	2.14	2.73	2.43
6P 600	1.19	0	1.19
6P 625	1.15	1.33	1.24
6P 650	1.14	1.26	1.2
6P 675	2.93	1.19	2.06
6P 700	1.57	1.18	1.38
6P 725	2.57	3.45	3.01
6P 750	1.15	1.26	1.21
6P 775	1.56	1.27	1.42
6P 800	1.55	1.7	1.63
6P 850	2.48	1.17	1.83
6P 900	1.11	1.28	1.2
6P 925	1.01	1.29	1.15
6P 950	1.26	1.18	1.22
6P 975	1.04	1.27	1.16
6P 1000	1.11	1.42	1.27
6P 1025	1.13	0	1.13
6P 1050	1.76	1.76	1.76
6P 1075	1.13	1.14	1.14
6P 1100	1.3		1.3

Lake Superior 7/10Å Ratios

Sample	Sample	Sample	Average
90-PC2-22	90-PC2-23	90-PC2-24	1.93
1.96	2.2	1.87	
2.3	1.68	2.15	Standard
1.95	1.59	1.97	Deviation=.23
	1.89	1.63	
		1.67	

Southern Lake Michigan Shale 7/10Å Ratios

Racine	Antrim	Porter	Average (all)
0.637	0.667	0.732	0.7
0.958	0.811	0.482	
0.514		0.542	Stand. Dev. (al
0.711		0.703	0.18
0.607		0.601	
0.583		1.2	
0.657		0.889	
		0.571	
Average	Average	Average	
0.67	0.74	0.72	

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