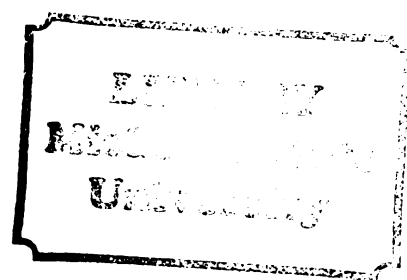


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DIFFERENTIATION AND CORRELATION OF TILL SHEETS
USING 7A/10A X-RAY DIFFRACTION PEAK HEIGHT RATIOS,
ALLEGAN COUNTY, MICHIGAN

presented by

Gregory David Gephart

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DIFFERENTIATION AND CORRELATION OF TILL SHEETS
USING 7Å/10Å X-RAY DIFFRACTION PEAK HEIGHT RATIOS,
ALLEGAN COUNTY, MICHIGAN

By

Gregory David Gephart

A THESIS

Submitted to
Michigan State University
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for the degree of

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1982

ABSTRACT

DIFFERENTIATION AND CORRELATION OF TILL SHEETS USING $7\overset{\circ}{A}/10\overset{\circ}{A}$ X-RAY DIFFRACTION PEAK HEIGHT RATIOS, ALLEGAN COUNTY, MICHIGAN

By

Gregory David Gephart

The objective of this research was to determine whether semi-quantitative clay mineral analyses can be used to differentiate multiple till sheets exposed in stratigraphic section, and to correlate these till sheets to moraines that occur further inland.

Till samples were collected from each of three till units exposed stratigraphically in the Glenn Shores section, located along the Lake Michigan shoreline in southern Allegan County, Michigan. Tills that comprise each of four moraines that occur inland in the county were also sampled. The clay-size fraction of each sample was analyzed using x-ray diffraction, and the $7\overset{\circ}{A}/10\overset{\circ}{A}$ peak height ratios were calculated.

The results of these analyses show that the three tills exposed in the Glenn Shores section have significantly different clay mineral compositions, and tills that comprise each of the moraines in the county each have similar clay mineral compositions to that of the uppermost till unit at Glenn Shores.

6120010

dedicated to my parents

Acknowledgement

I would like to express my sincere appreciation and gratitude to my thesis advisor, Dr. Grahame Larson, for the advice, encouragement, and friendship he has given throughout the completion of this project. I would also like to thank my committee members, Dr. William Cambray and Dr. John Wilband for their help and advice. Special thanks also go to Bill Monaghan, for the countless discussions (and arguments?) we have had that aided in solving many of the problems encountered in the project, and especially to my wife Carol, for her moral support and encouragement throughout my graduate career.

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INTRODUCTION

Since the 1940's, numerous researchers in the Great Lakes region have shown that till sheets can sometimes be traced over extensive distances using one or more lithologic criteria (Dean, 1969; Dreimanis and Morgan, 1975; Gwyn and Dreimanis, 1979; Killey, 1980; Shilts, 1973a; 1973b; 1978; Lineback, et al., 1979). Some of the most successful stratigraphic correlations within drift deposits of a single ice lobe have involved the use of semi-quantitative clay mineral analyses. For example, Killey (1980) has used semi-quantitative clay mineral data to differentiate between two till units of the Yorkville Till Member in a morphologically complex area of northeastern Illinois, and was able to relate each till unit to individual moraines occurring in the area. In addition, Lineback, et al. (1979) has used semi-quantitative clay mineral analyses to differentiate and correlate Late Wisconsinan till units and post-glacial lake sediments in lakes Superior and Michigan. Several researchers are also employing the use of semi-quantitative clay mineral analyses in an attempt to solve the "Valders" problem in Wisconsin and northern Michigan (Glass, 1981; Taylor, 1981). As yet, however, no attempts have been made to differentiate and correlate till units associated with drift of the Lake

Michigan Ice Lobe in southwestern Michigan. It is the object of this research to test whether semi-quantitative clay mineral analyses can be used to differentiate multiple till units exposed in stratigraphic section along the Lake Michigan shoreline in Allegan County, Michigan, and then to correlate these till units to moraines that occur further inland in the county.

In order to attempt correlations between till sheets and moraines, however, a thorough understanding of the surficial geology and glacial history of the study area is essential. For example, before an attempt can be made to correlate the till sheets exposed along the Lake Michigan shoreline with moraines that occur inland, the moraines must first be identified. Recent research involving geochemical prospecting in glaciated areas underscores the need for a prior knowledge of the glacial history of the area under study. Levinson (1974, p.451-452), in discussing mineral exploration in glaciated regions of Canada, states that "numerous studies in recent years have shown that geochemical methods can be used successfully in many glaciated areas of Canada provided that there is a careful selection and adaptation of the well-established sampling and analytical procedures; above all, an understanding of the glacial history of the area is essential".

For this reason, a detailed surficial geologic map, based on field observations of drift materials exposed in road cuts, gravel pits, and eroded stream banks, was

produced for Allegan County (Figure 4). Both 7½ and 15 minute topographic maps were used as base maps, and the contacts were drawn on the basis of lithology and topography. Descriptions of the map units and a discussion of the Pleistocene history of Allegan County are included in part I of the thesis. The differentiation and correlation of the till units exposed along the Lake Michigan shoreline by using semi-quantitative clay mineral analyses are then discussed in part II.

PART I: SURFICIAL GEOLOGY AND PLEISTOCENE HISTORY OF
ALLEGAN COUNTY, MICHIGAN

Allegan County is located in southwestern Michigan between latitude $42^{\circ}25'$ and $42^{\circ}46'$ north and longitude $85^{\circ}40'$ and $86^{\circ}11.3'$ west. It extends 35 miles (56.4 kilometers) east from the shore of Lake Michigan, and 24 miles (38.6 kilometers) north to south (Figure 1). Surficial deposits in Allegan County are comprised mostly of drift associated with the Late Wisconsinan retreat of the Lake Michigan Ice Lobe - a retreat that began 18,000 to 21,500 years BP (before present) from the Late Wisconsinan maximum, with the entire state becoming ice-free about 10,000 years BP (Dreimanis, 1977; Farrand and Eschman, 1974). Allegan County was deglaciated during the approximate time period 14,800 to 13,800 years BP (Farrand and Eschman, 1974).

Two morainic systems, the Lake Border and Valparaiso, extend through the county, trending in a southwest-northeast direction. Separating these moraines are till plains, outwash deposits, and glacio-lacustrine deposits. Post-glacial deposits include dunes, floodplains, and marsh areas.

The county is underlain by rocks that are Mississippian in age (Figure 2). The Coldwater Shale underlies most of the county, and the Napoleon Sandstone underlies the northeastern portion. The Michigan Formation, which is comprised of dark shale, limestone, beds of gypsum and anhydrite, breccias, and red sandstone and shale, underlies a small

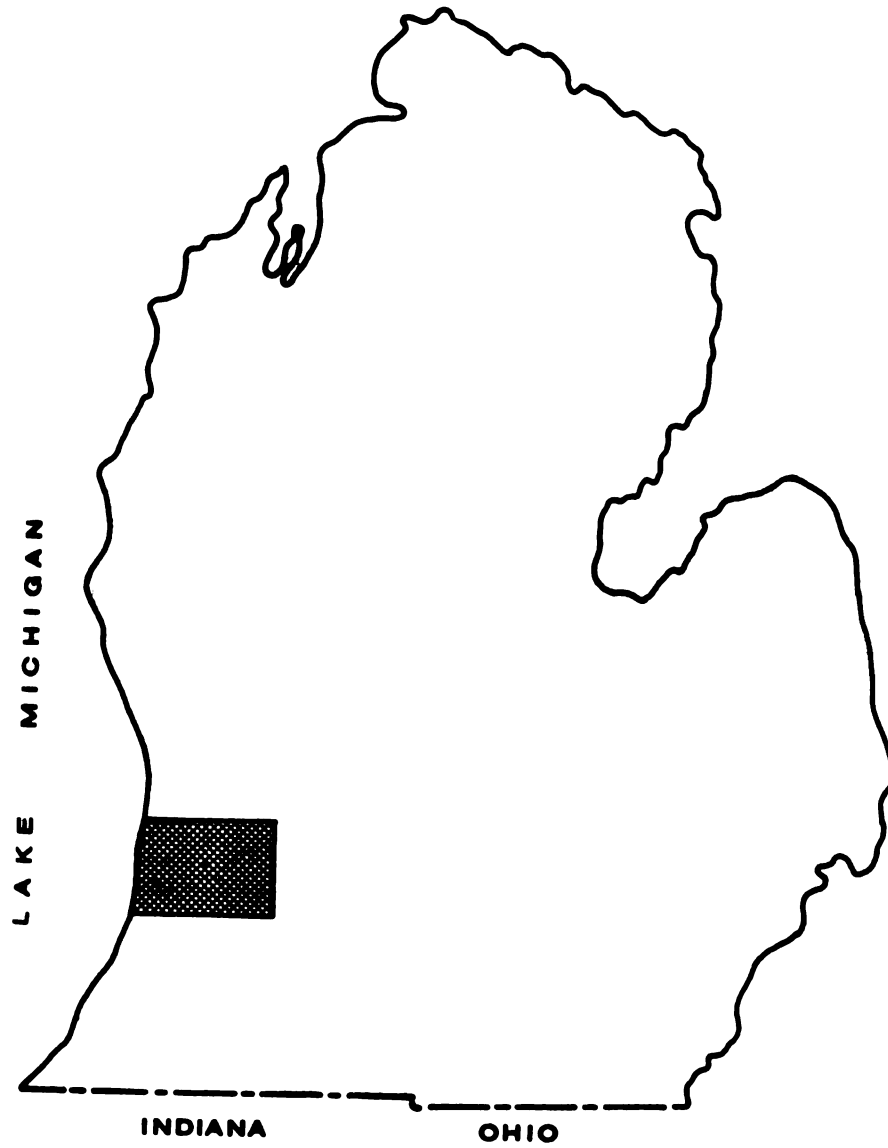


Figure 1: Location of Allegan County, Michigan.

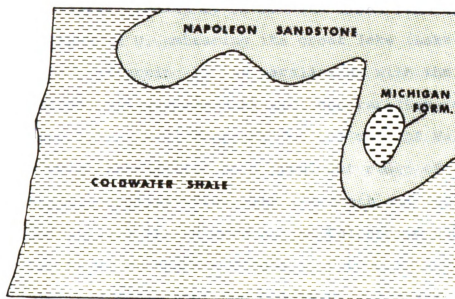


Figure 2: Bedrock lithology of Alleghen County.

area in the east-central portion of the county (Martin, 1936). The thickness of the drift overlying the bedrock in the county varies greatly but is generally between 150 and 300 feet (46 and 91 meters) thick.

PLEISTOCENE GEOLOGY

Valparaiso Morainic System - The Valparaiso Morainic System was first studied by Chamberlin (1883) who described it as an "immense U, embracing the great lake (Lake Michigan) in its arms", referring to its parallelism with the shore of Lake Michigan, and was named by L.C. Wooster (Leverett, 1897, from manuscript by L.C. Wooster) for the city of Valparaiso, Indiana, which is situated on a prominent ridge of the system in northwestern Indiana. Leverett (Leverett and Taylor, 1915) identified it as a system because the Valparaiso System includes two or more separate ridges that tend to merge at short intervals throughout the course of the system, and did not deem it necessary to name the individual ridges. Because it is important to distinguish between the constituent ridges on a detailed surficial geologic map such as this study of Allegan County, the two ridges of Leverett's Valparaiso Morainic System in Allegan County have been given informal names - the eastern-most ridge will be referred to as the "Outer Valparaiso Moraine", and the western-most ridge will be referred to as the "Inner Valparaiso Moraine".

Outer Valparaiso Moraine - The Outer Valparaiso Moraine

occurs as a prominent southwest-northeast trending ridge in the eastern part of the county. It extends from the southern border of the county just west of the city of Otsego, to just west of Green Lake in the northeastern corner of the county. The elevation of the moraine ranges from approximately 710 feet (216 meters) to over 970 feet (295 meters) above sea level, and stands 50 to 200 feet (15 to 61 meters) higher than the till plain to the west. The moraine consists primarily of massive, unsorted heterogenous till that ranges from clay-rich to sandy.

In the area south of, and extending approximately one mile (1.6 kilometers) northeast of the Kalamazoo River, the Outer Valparaiso Moraine attains its greatest elevations, and tends to be more "kamic" in character. The surficial deposits in this area are coarse-textured, ranging from fine sand to boulders. Between the northern edge of this kamic area and a position approximately two miles (3.2 kilometers) east of the city of Moline in northern Allegan County, surficial deposits of the Outer Valparaiso Moraine are comprised mostly of a dense, massive, clayey till overlying sand and gravel. At the locations where this stratigraphy was observed, the overlying till was 5 to 10 feet (1.5 to 3 meters) thick. Between the northern border of the county and a position approximately two miles (3.2 kilometers) south of the border, the moraine is again quite kamic in character. The surficial deposits of this portion of the moraine are comprised primarily of sand, pebbles, and cobbles. Where exposure was

good (ie. SW $\frac{1}{4}$ SE $\frac{1}{4}$ SW $\frac{1}{4}$ sec.9 T4N R11W), these deposits were observed to be well stratified. Also, several sand and gravel excavations in the Outer Valparaiso Moraine immediately north of the county line show exposures of stratified sand, pebbles, cobbles, and boulders.

Inner Valparaiso Moraine - The Inner Valparaiso Moraine forms a series of prominent ridges and knolls that extend from the southern border of the county near the town of Cheshire, to the northern border of the county northeast of the town of Dorr. The moraine ranges in elevation from approximately 700 feet (213 meters) to over 980 feet (297 meters) above sea level. The lowest elevations occur on the proximal side of the moraine where glacio-lacustrine sediments lap up onto the moraine, and the highest elevations occur in the vicinity of the town of Monterey. The surficial materials comprising the moraine consist of a till that ranges from clay-rich to sandy. Boulders and cobbles commonly occur at the surface.

Between the city of Allegan and the southern border of the county, the Inner Valparaiso Moraine consists of two ridges that are comprised of a clay-rich till and are separated by a highly collapsed deposit of fine to medium-grained sand. Between the Kalamazoo River and the town of Dorr, the Inner Valparaiso Moraine forms a belt that is generally 3 to 5 miles (5 to 8 kilometers) wide. This part of the moraine is comprised of till that is highly variable in texture, and the moraine is characterized by extensive

collapsed areas and numerous kamic deposits. The northern portion of the moraine is breached by the Dorr Channel. The portion of the moraine that occurs east and north of the Dorr Channel attains elevations greater than 830 feet (252 meters), and is comprised of clay-rich till.

Lake Border Morainic System - The Lake Border Morainic System consists of a series of till ridges that lie between the Inner Valparaiso Moraine and the Lake Michigan shoreline. Leverett (1899) was the first to study the Lake Border Morainic System in Allegan County, and described the constituent till ridges of the system. The ridge that extends from the southern border of the county, along the Lake Michigan shoreline to the Kalamazoo River, and then northeastward from the town of East Saugatuck to the town of North Dorr he termed "Covert Ridge", named for the town in Van Buren County that is situated on its crest. "Zeeland Ridge", named for the town of Zeeland in Ottawa County, extends from the Kalamazoo River northward along the Lake Michigan shoreline to the Ottawa County border.

The portion of Covert Ridge that occurs south of the Kalamazoo River is generally 1.5 to 2 miles (2.4 to 3.2 kilometers) wide, thinning to about .25 mile (.4 kilometer) near the Kalamazoo River. The elevation of the crest of this ridge is generally slightly greater than 700 feet (213 meters), but reaches elevations greater than 720 feet (219 meters), standing 50 to 70 feet (15 to 21 meters) higher than the lake plain to the east, and 30 to 50 feet (9 to 15

meters) higher than the till plain to the west. North of the Kalamazoo River, Covert Ridge is generally 1 to 2 miles (1.6 to 3.2 kilometers) wide, and in places is as much as four miles (6.4 kilometers) wide. Elevations greater than 770 feet (234 meters) are attained, but the crest is generally 730 to 740 feet (222 to 225 meters) in elevation, standing 70 to 110 feet (21 to 33 meters) higher than the lake plain to the southeast and 30 to 70 feet (9 to 21 meters) higher than the till plain to the northwest. Zeeland Ridge is generally 0.5 to 1 mile (0.8 to 1.6 kilometers) wide and stands 720 to 730 feet (219 to 222 meters) in elevation, locally reaching elevations greater than 770 feet (234 meters). It stands 100 to 120 feet (30 to 37 meters) higher than the lake plain to the west, and 30 to 50 feet (9 to 15 meters) higher than the till plain to the east.

Covert Ridge, both north and south of the Kalamazoo River, is comprised mostly of massive, clay-rich till that contains pebbles and cobbles. Fine to medium-grained sand overlies the till locally, especially between the town of Ganges and the Kalamazoo River. Zeeland Ridge is also comprised of a massive, clay-rich till that contains pebbles and cobbles. The portion of the moraine that lies south of the town of Graafschap is overlain in several areas by fine to medium-grained eolian sand deposits.

Shelbyville - Martin Outwash Plain Deposits - The Shelbyville-Martin outwash deposits form a plain, the surface of which slopes gently east-southeastward from the Outer

Valparaiso Moraine. Materials comprising the outwash plain include fine to coarse sand, pebbles, and cobbles. Boulders commonly occur at the surface. The plain is pitted and contains numerous kettle lakes and marshy areas. Extensive muck fields occur within the northern portion of the outwash plain.

Gun Plain Outwash Deposits - The Gun Plain Outwash Deposits form a valley train system, the surface of which slopes gently from northeast to southwest at an approximate gradient of 2.5 feet per mile (.5 meters per kilometer). The valley train system is comprised of fine to coarse sand, with gravel occurring in some areas. Muck fields are also common throughout.

South Monterey Outwash Deposits - The South Monterey Outwash Deposits form an apron that slopes east-southeastward from the Inner Valparaiso Moraine, and are comprised of fine to coarse sand, and pebbles. Kamic deposits, muck fields, and small areas of till occur at the surface in several areas throughout the outwash apron.

Dorr Channel Outwash Deposits - Leverett (Leverett and Taylor, 1915) described a meltwater drainage channel that he termed the "Ross Channel". It is graded to an outwash apron south of the city of Grand Rapids, and extends southward from the apron past a point approximately one mile (1.6 kilometers) east of the town of Byron Center, to the Rabbit River near the town of Dorr. The Dorr Channel, an apparent continuation of the Ross Channel, extends

southward from the town of Dorr along the eastern margin of the Inner Valparaiso Moraine, past the town of Hopkins, and enters the Kalamazoo Valley approximately four miles (6.4 kilometers) northwest of the city of Otsego. The channel continues westward through the present Kalamazoo Valley, breaches the Inner Valparaiso Moraine where the city of Allegan is located, and terminates at the western margin of the Inner Valparaiso Moraine where it entered a proglacial lake. The materials forming the floor of the Dorr Channel vary in texture, but all are glaciofluvial or glaciolacustrine in origin and are comprised chiefly of fine sand and silt. Large areas of muck and clay deposits occur throughout the channel, and medium to coarse-grained sand and gravel deposits occur locally.

New Salem - Burnips Outwash Deposits - The New Salem - Burnips Outwash Deposits form small aprons that slope south-southeastward from the east ridge (Covert Ridge) of the Lake Border Morainic System north of the Kalamzoo River, terminating in a lake plain that lies to the southeast. These outwash aprons are comprised of fine to coarse sand, and pebbles. Some boulders occur at the surface, and muck fields, kamic deposits, and small areas of till are common.

Fennville Outwash Plain Deposits - The Fennville Outwash Deposits from a pitted plain near the town of Fennville, the surface of which slopes southeastward from the Lake Border Moraine at an approximate gradient of 25 to 50 feet per mile (4.7 to 9.4 meters per kilometer). These deposits are

comprised mostly of fine to coarse sand and pebbles, and include a few cobbles and boulders. Muck fields and small areas of till are common throughout the Fennville Outwash Plain.

Till Plains - Till plains comprised of lodgement till occur in various locations throughout Allegan County. An extensive till plain occurs between the Inner and Outer Valparaiso moraines, and extends from the southern border of the county to the northern border. The till is dense, massive, clay-rich, and contains pebbles and cobbles. South of the Kalamzoo River, numerous kettle lakes and swampy areas occur within the plain. North of the river, stratified fine sand and silt deposits commonly overly the till. The till plain exhibits flat to gently rolling topography, the flattest areas being those that are overlain by the sand and silt deposits.

Another extensive till plain occurs within the Lake Border Morainic System north of the Kalamzoo River, between Zeeland Ridge and Covert Ridge. It is characterized by a gently rolling topography, and is comprised of a clay-rich till that contains pebbles and cobbles. Much of the till plain is overlain by deposits of fine to medium sand, some of which is eolian and forms dunes.

A small till plain occurs immediately west of the Inner Valparaiso Moraine near the southern border of Allegan County. It exhibits a gently rolling topography, and is comprised of a sandy-clay till, with boulders commonly

occurring at the surface. Deposits of fine to medium sand often overlie the till. Several northwest-southeast trending sand and gravel-cored drumlins occur within the till plain near the town of Chicora.

Another small, gently rolling till plain occurs immediately west of Covert Ridge, and extends from the Kalamazoo River southward to the town of Glenn. It is bordered by glaciolacustrine sand deposits on the west, and grades eastward to Covert Ridge. It is comprised of a dense, massive, clay-rich till, and is commonly overlain by fine to medium-grained eolian sand deposits.

Undifferentiated Sand And Gravel Deposits - Several individual kames occur within the lake plain north of the Kalamazoo River between the Lake Border Morainic System and the Inner Valparaiso Moraine. Exposures within these kames show stratified and cross-bedded sand, pebbles, cobbles, and boulders, which indicate a glaciofluvial origin. Also, deformation structures (i.e. folding and faulting) suggest deposition into large ice holes in a disintegrating ice front.

Kame fields also occur adjacent to the Inner Valparaiso Moraine, on both the proximal and distal sides of the moraine in the following areas: southwest of the town of Dorr; near and within the South Monterey Outwash Plain; and within the till plain southwest of the town of Chicora near the southern border of the county. Exposures within these kames show stratified glaciofluvial sediments comprised of sand,

pebbles, cobbles, and boulders. A highly collapsed outwash deposit comprised of fine to medium-grained sand and pebbles also occurs between two ridges of the Inner Valparaiso Moraine south of the Kalamzoo River.

Extensive kamic deposits occur in both the northeastern and southeastern corners of Allegan County, and form the kame and kettle topography that is characteristic of both areas. These deposits are comprised of a variety of stratified sediments ranging from sand to boulders.

Glacial Lake Deposits - Glaciolacustrine sediments occur extensively in the western two-thirds of Allegan County, and form a plain that covers most of the area between the Lake Border Morainic System and the Inner Valparaiso Moraine. These deposits are comprised mostly of fine to coarse sand, and contain small pebbles. Small isolated areas of silt and clay occur throughout the lake plain; muck fields occur in the areas of lowest elevation, mostly in the western part of the lake plain south of Hutchins Lake. These glacial lake deposits occur at elevations up to approximately 700 feet (213 meters) along the Inner Valparaiso Moraine, and up to approximately 650 to 660 feet (198 to 201 meters) along the northeast portion of Covert Ridge in the vicinity of the town of Burnips.

Kettle lakes and swampy areas, indicating ice collapse, are common in the southeast part of the lake plain, east of a line that runs from the town of Pearl southward to the southern border of Allegan County. Sand dunes are common

throughout the area south of the Kalamazoo River.

Glaciolacustrine deposits also occur between the Lake Michigan shoreline and the Lake Border Morainic System at elevations up to 650 to 660 feet (198 to 201 meters). These deposits are also comprised of fine to coarse sand, and pebbles.

POST-GLACIAL GEOLOGY

Eolian Sand Deposits - Eolian sand deposits, generally 3 to 9 feet (1 to 3 meters) thick, cover two extensive areas along the western margin of the Inner Valparaiso Moraine. One of these deposits, approximately 1 to 2 miles (1.6 to 3.2 kilometers) wide, occurs immediately south of the Kalamazoo River and extends for approximately five miles (8 kilometers) along the margin of the moraine. The other deposit occurs about three miles (4.8 kilometers) north of the river and extends northward approximately six more miles (9.7 kilometers) along the moraine. These deposits are comprised of wind-blown sand and small pebbles derived from glaciolacustrine deposits that occur in the lake plain to the west. Numerous dunes and deflation basins occur throughout these eolian sand deposits.

Dune Deposits - Dunes are abundant throughout the western portion of Allegan County. Numerous barchan dunes occur on the glacial lake plain between the Inner Valparaiso Moraine and the Lake Border Morainic System, especially south

of the Kalamazoo River. Barchan dunes also occur on the Lake Border Morainic System, and on the till plains that separate, and are adjacent to, the constituent ridges of the Lake Border System. In addition, numerous barchan dunes occur on the glacial lake deposits that occur immediately west of Zeeland Ridge.

Extensive shoreline dunes extend along the Lake Michigan shoreline southward from the northern border of the county to the town of Douglas, and spread inland as much as 1.5 miles (2.4 kilometers). Many of these dunes reach heights that are more than 250 feet (76 meters) greater than the elevation of the present beach (approximately 580 feet - 176 meters), and most possess a well-developed forest cover.

Both the barchan and shoreline dunes are comprised of wind-deposited sand and granules, generally derived from glaciolacustrine and modern beach sand deposits.

Marsh And Swamp Deposits - Marsh and swamp deposits occur in several kettle holes, and in river and stream valleys throughout the county. These deposits are comprised mostly of decaying freshwater plants, mixed with sand and silt. Several of these deposits contain standing water.

Recent Floodplain Deposits - Modern floodplain deposits occur along several streams throughout Allegan County, with the most extensive deposits occurring along the Kalamazoo and Rabbit rivers. These deposits are comprised mostly of bedded sand and silt.

PLEISTOCENE HISTORY

The surficial drift of Allegan County was deposited during the Late Wisconsin retreat of the Lake Michigan Ice Lobe. Older drift deposits occur in the county, but are not exposed at the surface. For example, till and lacustrine sediments associated with pre-Late Wisconsin glaciation can be observed along the Lake Michigan shoreline about one mile (1.6 kilometers) southwest of the village of Glenn in southern Allegan County (SW $\frac{1}{4}$ SW $\frac{1}{4}$ section 31 T2N R16W). These sediments are exposed in a 66 to 82 feet (20 to 25 meter) high section, and record several fluctuations of the Lake Michigan Lobe (Figure 3). The sequence begins at present lake level (580 feet - 177 meters) with the uppermost meter of a dense silty-clay till of unknown thickness. The till is overlain by a thin (2 to 4 inches - 5 to 10 centimeters) discontinuous beach gravel and 6.6 feet (2 meters) of lacustrine silt and sand containing large pieces of abraded wood, reworked organic mat, and peat balls. Samples of the wood have been dated at 37,150 $\pm$ 540 (BETA 3311), 38,130 $\pm$ 740 (BETA 3310), > 37,000 (GX-8193), and > 48,000 (ISGS-948) radio-carbon years BP, and a sample of organic mat has been dated at > 43,000 years BP (SI 5183). Above the silt and sand is another till 16.4 to 19.7 feet (5 to 6 meters) thick.

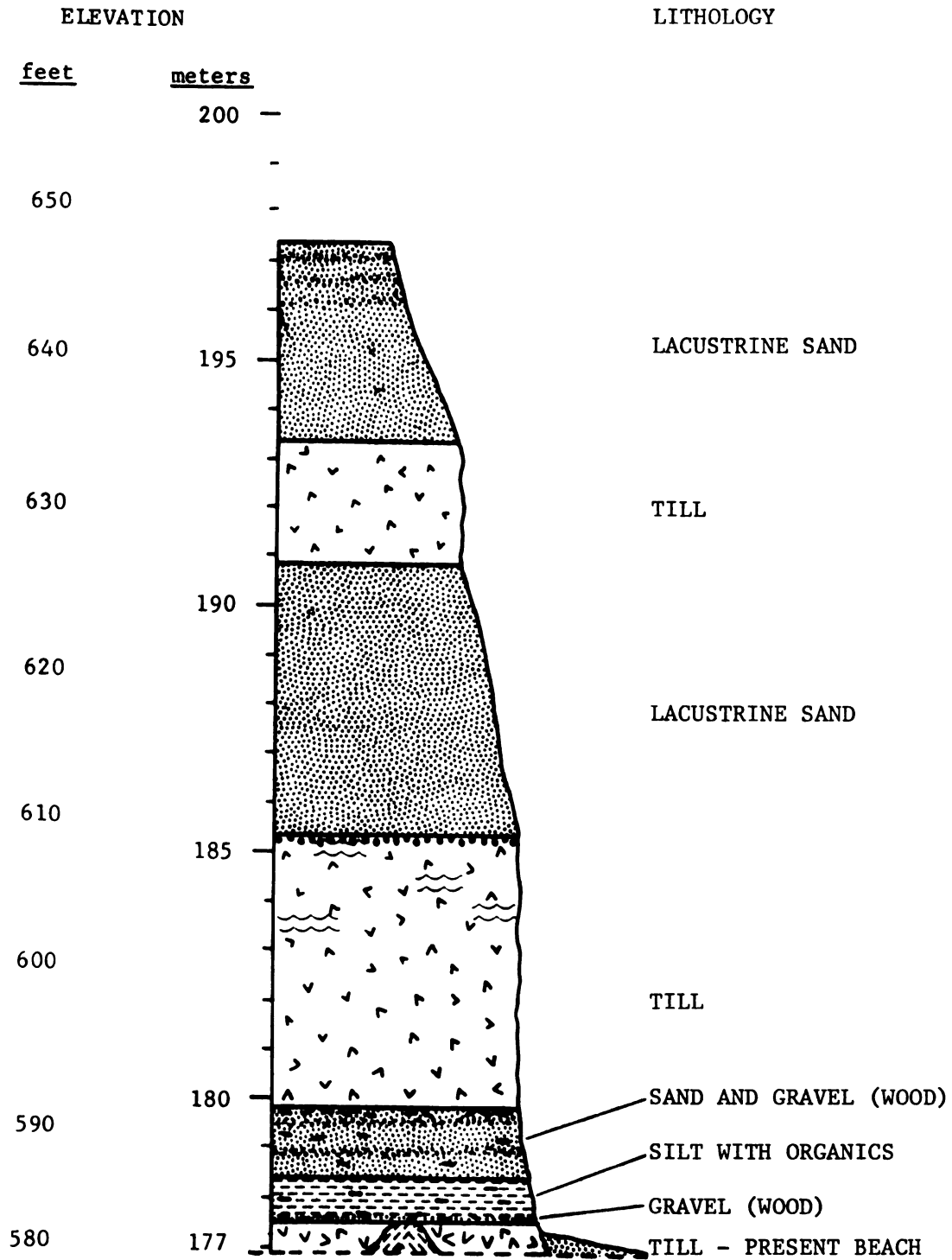


Figure 3: Stratigraphic section at Glenn Shores, Allegan County, Michigan.

The upper part of this till is water-laid in places, and is overlain by a 16.4 to 19.7 feet (5 to 6 meters) thick lacustrine sand. This second lacustrine unit is overlain by a third till that is 8 feet (2.5 meters) thick. The section is capped by 6.6 to 9.9 feet (2 to 3 meters) of Lake Chicago (Glenwood Stage) sediments and a series of dunes that in places overlie wood dated at $5,780 \pm 90$ (BETA-2048) radio-carbon years BP (Gephart, et al., 1982).

The lower part of the section (lowest till unit and overlying lacustrine sediments with incorporated organic debris) records a major retreat of ice out of the Lake Michigan basin and subsequent low lake level probably during the Middle Wisconsinan (Port Talbot), followed by a readvance that blocked drainage north and eastward and raised the lake to a higher-than-present level. The middle till unit represents a later advance of the Lake Michigan Lobe, and is probably Late Wisconsinan (Woodfordian) in age. The thick deposit of lacustrine sand that overlies the middle till unit indicates that another retreat of the ice margin occurred after deposition of the middle till unit. The uppermost till unit, which can be traced southward to Covert Ridge, resulted from a Late Woodfordian readvance of the Lake Michigan Lobe to the Lake Border Morainic position. The Lake Chicago (Glenwood Level) sediments that overlie the upper till unit were deposited during the final retreat of the Lake Michigan Lobe from southwestern Michigan (Gephart, et al., 1982).

The maximum extent of the Late Wisconsinan ice advance

occurred approximately 18,000 to 21,500 radio-carbon years BP. This is based on radio-carbon dates of spruce and other organic debris incorporated in tills near the terminal position of Late Wisconsinan ice that, in the Great Lakes region, extended nearly to the Ohio River in western Ohio and eastern Indiana, and a little south of the middle parts of western Indiana and eastern Illinois (Dreimanis, 1977; Farrand and Eschman, 1974). The glacial margin was characterized by minor oscillations at the terminal zone until about 17,500 years BP when a significant retreat, followed by a readvance, occurred (Dreimanis, 1977). Following this event, all three ice lobes in Michigan (the Huron-Erie, Saginaw, and Lake Michigan lobes) began a general retreat about 16,000 years BP that culminated in the total deglaciation of the state by about 10,000 years BP (Farrand and Eschman, 1974). This general retreat, however, was interrupted by several significant readvances of the ice margin, with each readvance generally falling short of the previous advance (Black, 1978; 1980; Evenson, 1973a; 1973b; Evenson, et al., 1976a; Farrand and Eschman, 1974).

The first part of Michigan to become ice-free was the middle portion of the state just north of the Indiana state line, and by approximately 15,000 (Farrand and Eschman, 1974) to 15,600 (Mörner and Dreimanis, 1973) years BP, the ice margin stood at the position of the Kalamazoo Moraine of the Lake Michigan and Saginaw lobes, and the Mississinnewa Moraine of the Huron-Erie Lobe. Meltwater drainage at that time was

to the southwest, through the Kankakee Torrent (Farrand and Eschman, 1974). The Erie Interstade, a major retreat of the ice that began approximately 15,600 years BP and culminated about 14,800 years BP, is documented for the Huron-Erie Lobe by Mörner and Dreimanis (1973). This retreat, however, has not yet been recognized in the Lake Michigan Lobe (Farrand and Eschman, 1974).

The deglaciation of Allegan County began sometime after 14,800 years BP with the retreat of the Lake Michigan Lobe from the Kalamazoo Moraine. As the ice retreated, kamic and highly collapsed sand and gravel was deposited along the proximal (western) margin of the moraine. These deposits form a belt that is approximately 2 to 5 miles (3 to 8 kilometers) wide in southwestern Barry County, northeastern Kalamazoo County, and southeastern Allegan County, and extends southwestward into Van Buren County and northeastward to the interlobate area of the Kalamazoo moraines of the Lake Michigan and Saginaw ice lobes. In Allegan County, these deposits occur in the extreme eastern part of Gun Plain Township. The coarse texture and kamic, highly collapsed nature of these deposits suggest that they were the result of a stagnating, disintegrating ice margin.

Kamic sand and gravel deposits also occur in the northeastern corner of Allegan County, east of the Outer Valparaiso Moraine. These deposits may represent a continuation of the kamic deposits that occur in the southeast part of the county, or may be interlobate deposits as is suggested by

Leverett (Leverett and Taylor, 1915) and Martin (1955). Only detailed surficial geologic mapping of Barry and Kent counties can provide an answer to this problem.

Following the retreat from the Kalamazoo Moraine, the margin of the Lake Michigan Lobe occupied the position of the Outer Valparaiso Moraine. This moraine represents either a readvance, or a temporary pause in the retreat of the ice front. No conclusive evidence has yet been found that would confirm either possibility. The evidence that does exist, however, tends to support the formation of the moraine as a readvance of the ice. For example, the moraine is composed primarily of a massive, dense till that overlies sand and gravel - a situation that would more likely occur as a result of a readvance of the ice, overriding older outwash deposits and depositing lodgement till on top, than from a receding ice front that would more likely produce a head of outwash with flow till and ablation till common near the crest of the moraine. The occurrence of till overlying sand and gravel deposits was observed at the following locations: NE $\frac{1}{4}$ NE $\frac{1}{4}$ NW $\frac{1}{4}$ sec.13 T1N R12W; NE $\frac{1}{4}$ SE $\frac{1}{4}$ SW $\frac{1}{4}$ sec.9 T3N R11W; SW $\frac{1}{4}$ SW $\frac{1}{4}$ SW $\frac{1}{4}$ sec.22 T4N R11W; NW $\frac{1}{4}$ NW $\frac{1}{4}$ NE $\frac{1}{4}$ sec.17 T4N R11W.

The Outer Valparaiso Moraine is characterized by the occurrence of several gaps in the morainic ridge, the most obvious and extensive being the gap that occurs north of the town of Watson where approximately 3.3 miles (5.3 kilometers) of the moraine is absent. The surficial deposits within this area are comprised mainly of sand, pebbles, and cobbles, and

extend up to five miles (8 kilometers) west of the moraine. These deposits are highly collapsed, and contain numerous kettle lakes and swampy areas. This extensive collapsed outwash deposit probably formed as a large crevasse-filling near the margin of the ice when it occupied the position of the Outer Valparaiso Moraine.

The other gaps in the moraine were most likely formed as a result of the melting of buried masses of ice following the retreat of the ice margin from the Outer Valparaiso Moraine. These occur at the following locations: west of the city of Otsego, where the Kalamazoo River breaches the moraine; immediately east of the city of Wayland and about 1.5 miles (2.4 kilometers) south of the northern border of the county. The surficial materials in these areas are comprised primarily of fine to medium-grained sand. Glacial meltwater, as well as post-glacial drainage, has most likely altered these collapsed areas.

The Shelbyville-Martin Outwash Plain formed when the ice margin stood along the position of the Outer Valparaiso Moraine. The numerous kettle lakes and swampy areas that occur within the outwash plain formed as a result of the melting of ice masses that had broken off the ice margin and were buried in the outwash sediments. The extensive swampy areas and muck deposits that occur in the northern portion of the outwash plain represent large kettle lakes that drained subsequent to the retreat of the ice margin from the Outer Valparaiso Moraine. Meltwater drained southward,

probably along the western edge of the kamic deposits that occur along the western side of the Kalamazoo Moraine. The drainage probably followed roughly the same course as the later Gun Plain Valley Train System, which truncates the Shelbyville-Martin Outwash Plain.

Following the formation of the Outer Valparaiso Moraine and the Shelbyville-Martin Outwash Plain, the ice margin continued to retreat west-northwestward and exposed the till plain that lies between the Inner and Outer Valparaiso moraines. Deposits of stratified sand and silt overly large areas of the till plain east and northeast of the city of Allegan and near the city of Wayland. These sand and silt deposits resulted from the localized ponding of meltwater as the ice margin receded westward. The surface of the till plain that lies south of, and immediately north of the Kalamazoo River is higher in elevation than the portion of the till plain that occurs further to the north, and is generally free of sand and silt deposits at the surface. Kettle lakes, produced from the melting of ice masses that became detached from the glacier as it retreated across the till plain, are common in the till plain south of the Kalamazoo River.

At approximately the same time, the Gun Plain Valley Train System developed. It recieved meltwater mainly from a northeastern source (Saginaw Ice Lobe), but also from the retreating Lake Michigan Lobe via the channel that cuts through the Outer Valparaiso Moraine east of the city of

Wayland. In the southeastern corner of Allegan County near the city of Plainwell, the Gun Plain Valley Train System joined the westward-flowing glacial Kalamazoo River, and continued to flow southwestward between the Outer Valparaiso and Kalamazoo moraines.

Following the retreat of the ice margin from the Outer Valparaiso Moraine, the ice readvanced to the position of the Inner Valparaiso Moraine. Evidence for this readvance can be observed two miles (3.2 kilometers) north of the Allegan County border at Dias Hill in Kent County (sections 19 and 30 T5N R11W) where the Inner Valparaiso Moraine appears to override and truncate the Outer Valparaiso Moraine - a situation that could only occur with a readvance of the Lake Michigan Lobe. The elevation of the surface at the point of intersection of the two moraines is dramatically higher than the surrounding region, which would be expected in an overriding situation. When the ice margin stood at this morainic position, sand and gravel was deposited on the distal side of the moraine, forming the South Monterey Outwash Deposits.

During the retreat of the ice margin from the Inner Valparaiso Moraine, the small till plain that occurs west of the moraine south of the Kalamazoo River was exposed. The northwest-southeast trending drumlins that occur in the western portion of the till plain near the town of Chicora were also exposed at this time. Also, kames were deposited immediately south of these drumlins, and between the Inner

Valparaiso Moraine and the Lake Border Morainic System north of the Kalamazoo River as the ice retreated westward.

As the ice margin continued to recede from the Inner Valparaiso Moraine, a channel referred to by Leverett (Leverett and Taylor, 1915) as the "Ross Channel" developed behind the moraine in southern Kent County and drained meltwater southward into Allegan County. Leverett stated that the extension of this channel southward from the town of Dorr is difficult to interpret, and postulates the following two scenarios: 1) If the ice margin had not retreated far enough westward in Allegan County to allow meltwater to flow between the ice margin and the moraine, flow would have continued southward through the Dorr Channel east of the Inner Valparaiso Moraine, then eastward up the Kalamazoo Valley to Otsego, where the flow again turned southward; 2) If the ice had retreated far enough westward from the Inner Valparaiso Moraine, drainage may have passed through the Ross Channel, and then southwestward between the ice margin and the moraine in Allegan County. This drainage did occur eventually, if not from the beginning (Leverett and Taylor, 1915).

The history of the Dorr Channel cannot be interpreted with any certainty with the present available data. For example, Leverett (Leverett and Taylor, 1915) traced the Ross Channel northward from the town of Dorr to an apron of outwash near Grand Rapids that is at an elevation of approximately 700 feet (213 meters). Divides occur, however,

within the Dorr Channel about 1.5 miles (2.4 kilometers) south of the town of Dorr at an elevation of 710 feet (216 meters), and about three miles (4.8 kilometers) south of the town of Hopkins at an elevation of 725 feet (220 meters). The variability of the elevation of the channel floor is most likely due to several factors that include crustal rebound, the melting of buried ice blocks, and post-glacial drainage alteration. In addition, there may have been more than one stage in the history of the Dorr Channel.

It does appear, however, that the flow of meltwater through the Dorr Channel was westward through the present Kalamazoo Valley - not eastward as Leverett (Leverett and Taylor, 1915) believed. Evidence for a westward flow direction is the presence of two terrace levels in the Kalamazoo Valley between the point of entrance of the Dorr Channel and the western margin of the Inner Valparaiso Moraine. The higher of these terrace levels grades to the floor of the Dorr Channel, and terminates in the lake plain at the western margin of the Inner Valparaiso Moraine. The lower terrace level was produced from the Kalamazoo River, and grades to the mouth of the river at Lake Michigan. The higher terrace also occurs within the gap where the Kalamazoo River breaches the Outer Valparaiso Moraine west of the town of Otsego. This indicates that the glacial Kalamazoo River may have breached the Outer Valparaiso Moraine and joined the westward-flowing Dorr Channel. The Dorr Channel breached the Inner Valparaiso Moraine where the city of Allegan is now located, and resumed a southward flow between the ice

margin and the Inner Valparaiso Moraine. The breaching of the moraine was probably aided by the melting of a large mass of buried ice, which created a sag in the moraine at that location. With further retreat of the ice margin, the Dorr Channel was abandoned and meltwater flowed southward along the entire eastern margin of the Inner Valparaiso Moraine in Allegan County.

While the Dorr Channel was forming, meltwater was ponded between the retreating ice margin and the Inner Valparaiso Moraine in the southern portion of Allegan County. This proglacial lake, referred to by Leverett (Leverett and Taylor, 1915) as "The Lake on the Lower Kalamazoo" and later named Lake Pullman by F.W. Terwilliger (1954), was part of a series of similar lakes that formed a southward-flowing integrated lake system in southwestern Michigan, culminating in the incipient Lake Chicago at the southern end of the Lake Michigan basin (Leverett and Taylor, 1915). This whole system ultimately drained down the Illionios River to the Mississippi. The landward margin of Lake Chicago generally was the Valparaiso Morainic System that looped around the southern end of the Lake Michigan basin. Until late in the formation of the Lake Border Morainic System, incipient Lake Chicago, the level of which was about 640 feet (195 meters), most likely occupied an area entirely outside the present Lake Michigan basin (Leverett and Taylor, 1915; Bretz, 1951).

Leverett (Leverett and Taylor, 1915) found that the small lakes comprising this integrated lake system did not

form easily recognizable beaches that would permit easy mapping. He did determine, however, that Lake Pullman had a surface elevation of approximately 680 feet (207 meters), based on the following evidence: 1) The lake is limited on the east by the Valparaiso Morainic System at an elevation of approximately 680 feet (207 meters); 2) The lake is bordered by a well-defined terrace of the Kalamazoo Valley at 680 feet (207 meters); and 3) An apron of outwash that is graded to the Lake Border Moraine near the town of Fennville occurs at an elevation of about 680 feet (207 meters) (Leverett and Taylor, 1915).

Recent mapping by the author, however, has determined that in Allegan County this lake reached levels as high as 700 feet (213 meters) along the western side of the Inner Valparaiso Moraine, probably early in the lake's development. It initially drained southward through a channel that flowed past the towns of Breedsville and Bangor in Van Buren County, through swampy channels near the town of McDonald, coming to the Paw Paw River near Hartford (Leverett and Taylor, 1915). Topographic maps indicate that the elevation of the drainage threshold at a point about two miles (3.2 kilometers) north of Breedsville was nearly 690 feet (210 meters). When the ice margin had retreated to Covert Ridge of the Lake Border Morainic System, a lower outlet was exposed along the eastern margin of this moraine. The elevation of the drainage threshold for this outlet was about 660 feet (201 meters), near the town of Friendsville in Van Buren County.

Glaciolacustrine deposits occur at elevations up to 650 to 660 feet (198 to 201 meters) along the northeastern portion of Covert Ridge near the town of Burnips.

Most of the area that lies between the Lake Border Morainic System and the Inner Valparaiso Moraine was occupied by this proglacial lake. The kettle lakes and swampy areas that occur in the southern part of the lake plain were produced from the melting of buried ice blocks that became detached from the ice margin as it receded westward across the lake plain. These large masses of ice probably were partially buried in the lake-bottom sediments when the level of the lake was about 700 feet (213 meters) in elevation, and were most likely not totally submerged. As the ice margin continued to recede westward, it exposed the lower outlet along Covert Ridge. The lake level subsequently dropped to about 660 feet (201 meters) - an elevation that is lower than the surface where these collapsed features occur - thus allowing the buried ice blocks to melt without the resulting basins being filled in with lake sediments.

Following the retreat from the Inner Valparaiso Moraine, the margin of the Lake Michigan Ice Lobe occupied the position of the Lake Border Morainic System, the history of which is very complex in Allegan County. For example, two till ridges (Covert Ridge and Zeeland Ridge) occur north of the Kalamazoo River, whereas only one (Covert Ridge) occurs south of the river. Which of the two ridges that occur north of the river is the continuation of the ridge that

occurs south of the river is not known with any certainty - one can only speculate. Leverett (1899) believed that the ice occupied the position of Covert Ridge first, following the retreat from the Valpariaso Morainic System. The ice margin then retreated further westward to form Zeeland Ridge. The portion of Zeeland Ridge that had extended south of the Kalamazoo River would have since been cut away as a result of erosion along Lake Michigan (Lake Chicago).

Alternatively, the portion of Covert Ridge that occurs south of the Kalamazoo River may actually be the continuation of Zeeland Ridge. If this is the case, then this moraine truncates the older, northern portion of Covert Ridge. The crescent-shaped eastward lobation of this moraine into the Kalamazoo Valley may have been due to a pre-existing topographically low area, now occupied by the Kalamazoo River, and would suggest a readvance of the Lake Michigan Lobe. The small ridge of sandy till that lies just east of Covert Ridge near the town of Liesure may represent a remnant of the southward extension of the northern portion of Covert Ridge.

Another possibility is that the southward continuation of the northern portion of Covert Ridge extended southwestward into what is now the Lake Michigan basin, and was subsequently eroded away by the waters of Lake Chicago after the ice had receded to the west. The ice margin would then have readvanced, forming Zeeland Ridge and the southern portion of Covert Ridge.

Morphologic evidence tends to support Leverett's (1899) interpretation that the portions of Covert Ridge that occur north and south of the Kalamazoo River represent time-equivalent ice-edge positions. For example, wave-cut slopes occur on the till plain at the southwestern end of Covert Ridge just north of the Kalamazoo River, and along the western and northern margin of Covert Ridge immediately south of the river. The elevation of the base of these slopes is about 650 feet (198 meters), which suggests they were formed by the erosive action of the waters of Lake Chicago (Glenwood Stage). Since these slopes appear to have been continuous across the river and occur at equal elevations on both sides, they are probably time-equivalent and were formed after the formation of both the southern and northern portions of Covert Ridge. Zeeland Ridge occurs west of the wave-cut slope and would therefore be younger than both portions of Covert Ridge.

The New Salem-Burnips outwash sediments were deposited in the form of small aprons on the distal side of the moraine when the ice margin occupied the position of the northern portion of Covert Ridge. The apron that occurs northwest of the town of Hamilton terminates in the lake plain southwest of the moraine at an elevation of approximately 660 feet (201 meters). The outwash aprons that occur near the towns of Burnips and New Salem terminate at elevations of about 670 to 680 feet (204 to 207 meters). The lower portions of these outwash aprons, however, could well have been deposited subaqueously, therefore making correlations with specific lake

levels tenuous at best.

Sand and gravel that forms the Fennville Outwash Plain was deposited when the ice margin occupied the position of the southern portion of Covert Ridge. The numerous depressions and kettles that occur within this outwash plain, the most obvious being Hutchins Lake, were produced by the melting of several buried ice blocks that had become detached from the retreating ice margin. If the portions of Covert Ridge north and south of the Kalamazoo River represent time-equivalent ice-edge positions, then the Fennville Outwash Plain and the New Salem-Burnips Outwash Deposits are of the same age. If, however, the southern portion of Covert Ridge is time-equivalent to Zeeland Ridge, then the Fennville Outwash Plain is younger than the New Salem-Burnips Outwash.

With the retreat of the Lake Michigan Ice Lobe from the Lake Border Morainic System, the Late Wisconsinan deglaciation of Allegan County was complete. At this time, connections between Lake Pullman and Lake Chicago (Glenwood level) were opened all along the Lake Border System. As these connections were opened, the level of Lake Pullman dropped to that of Lake Chicago (640 feet - 195 meters). Evenson (1972; 1973a) has traced the Glenwood Stage shoreline along the Lake Border Morainic System in Allegan County using localized occurrences of beaches, wave-cut slopes, and transitions from flat to rolling topography, and determined that the Glenwood shoreline occurs at elevations of 650 to 655 feet (198 to 199 meters) in the southern part of the county, and at elevations of 655

to 660 feet (199 to 201 meters) in the northern part. Several of the shoreline features he defined are included on the geologic map, as well as some additional shoreline features recognized by this author. The occurrence of Glenwood level shoreline features at elevations above 640 feet (195 meters), and the general rise in elevation of these features from 650-655 feet (198-199 meters) to 655-660 feet (199-201 meters) from the southern border of Allegan County to the northern border is due to isostatic rebound following the retreat of the Lake Michigan Ice Lobe (Evenson, 1972; 1973).

Mantles of eolian sand that overly portions of the western side of the Inner Valparaiso Moraine, and some of the barchan dunes that occur on the eastern portion of the lake plain west of the moraine probably began to form when the level of Lake Pullman dropped as it merged with Lake Chicago. The drop of the level of Lake Pullman exposed a barren, sandy plain west of the Inner Valparaiso Moraine that provided a source of sand for these eolian deposits.

Lake Chicago stood at the Glenwood level beginning with the retreat of the ice margin from the Valparaiso Morainic System, and remained at that level throughout the formation of the Lake Border Morainic System, and persisted for a period of time after the ice had receded well westward and northward from southwestern Michigan (Bretz, 1959; 1959; 1964; Hough, 1966; Evenson, 1972; 1973; Farrand and Eschman, 1974; Fullerton, 1980). Farrand and Eschman (1974) believe that the Glenwood Stage lasted some 1500 years, and did not drop

to the Calumet level (620 feet - 189 meters) until after the ice had retreated from the Port Huron Moraine, which was built approximately 12,600 years BP. Also, they speculate that a low water stage within the Glenwood Stage could have occurred 13,300 years BP, when the ice margin retreated at least as far north as the Indian River lowlands in the northern part of Michigan's lower peninsula, allowing drainage to pass through to lakes Huron, Erie, and Ontario, and into the St. Lawrence lowlands further to the east (Farrand and Eschman, 1974; Farrand, et al., 1969).

With the drop of Lake Chicago to the 620 foot (189 meter) Calumet Stage, Lake Pullman drained completely. The barchan dunes that occur on the lake plain at elevations below about 650 feet (198 meters) began to form at this time. The source of sand for these eolian sand deposits was the newly exposed barren, sandy lake plain.

Following the Calumet Stage, Lake Chicago dropped to a level of 605 feet (184 meters) (Toleston Stage) due to downcutting of the Chicago outlet (Leverett and Taylor, 1915; Bretz, 1951b; 1959; 1964; Hough, 1958; 1963; 1966; Kelley and Farrand, 1967; Farrand and Eschman, 1974). While extensive Glenwood Stage deposits cover much of the western portion of Allegan County (up to elevations of 650 to 660 feet (198 to 201 meters), Calumet and Toleston Stage deposits occur only in the extreme northwest corner of the county, covering an area of about .75 square miles (1.2 square kilometers) immediately east of the shoreline dune belt and

adjacent to the northern border of the county. Surface elevations below 620 feet (189 meters) also occur locally between Zeeland Ridge and the shoreline dune belt; however any Calumet Stage deposits in these areas have since been masked by post-glacial eolian sand.

With the final retreat of the Lake Michigan Ice Lobe out of the southern peninsula of Michigan and the Straits of Mackinac about 11,500 years BP, the 605 foot (184 meter) Early Lake Algonquin in the Huron basin merged with the 605 foot (184 meter) Toleston Stage of Lake Chicago, forming Main Lake Algonquin. As the ice margin retreated further northward, successively lower outlets east of Georgian Bay were uncovered. The lowest of these outlets was the North Bay Outlet, which resulted in a very low water stage in both the Huron basin (Lake Stanley, 50 to 100 feet - 15 to 30 meters) and in the Lake Michigan basin (Lake Chippewa, 230 feet? - 70 meters). With further retreat of the ice margin, the North Bay Outlet rebounded, causing the drainage to shift to the south. This resulted in the Nipissing (595 feet - 181 meters), Algoma (589 to 591 feet - 179 to 180 meters), and finally the present lake stages (Leverett and Taylor, 1915; Bretz, 1939; Farrand and Eschman, 1974).

POST-PLEISTOCENE HISTORY

As the ice of the Lake Michigan Lobe began to recede from Allegan County, kettle lakes began to develop in

depressions that formed from the melting of buried masses of ice. Several of the kettle lakes remain, scattered throughout the county, while many have since drained, or have become filled with organic matter and form the many swamps and marshes that occur in the county. Kettle lakes and marshes are especially common within the Valparaiso Morainic System and associated till plains and outwash deposits, within the kamic deposits along the eastern border of the county, and in the southern portion of the lake plain that lies between the Lake Border Morainic System and the Inner Valparaiso Moraine. Marshes also occur in the floodplains of rivers and streams throughout the county.

With the retreat of the Lake Michigan Ice Lobe out of southwestern Michigan and the drop of the level of Lake Chicago from the Glenwood Stage, the present drainage pattern in Allegan County began to develop. The Kalamazoo River most likely began to occupy its present course west of the city of Otsego as the ice margin began to retreat from the Inner Valparaiso Moraine, and probably breached Covert Ridge of the Lake Border Morainic System when the level of Lake Chicago dropped to the Calumet Stage. It attained its present course to Lake Michigan as the lake dropped to the Toleston, Nipissing, Algoma, and present levels.

The Kalamazoo River and its major tributaries, the Rabbit River and the Gun River, drain most of the area comprising Allegan County. The extreme northwest corner of the county, north of the northern portion of Covert Ridge, is drained by the Black River, which discharges into Lake Macatawa in

southwestern Ottawa County. The southwest corner of Allegan County is drained by the Black River, which discharges into Lake Michigan at South Haven in Van Buren County.

Following the drop of Lake Chicago to either the Toleston Stage (605 feet - 184 meters), or a later lower level, shoreline dunes began to form along the present Lake Michigan shoreline. Some of these dunes stand more than 200 feet (61 meters) higher than the surrounding region, and form a belt that is generally .5 to .75 miles (.8 to 1.2 kilometers) wide. Many of these dunes possess a well-developed forest cover. The vegetation on some of the dunes, however, has been destroyed by wave action, disease, fire, or by man, thus subjecting these dunes to the effects of wind erosion. Just a small break in the vegetative cover on the windward side of a dune can cause a major blowout and dune migration - a situation that has occurred with several dunes in Allegan County, most notably the Goshorn Dune, which occurs just north of the Kalamazoo River near the town of Saugatuck. This dune has migrated rapidly eastward, and now extends as much as 1.5 miles (2.4 kilometers) inland from the Lake Michigan shoreline (Reinking and Gephart, 1978).

PART II: DIFFERENTIATION AND CORRELATION OF TILLS
USING $\frac{7A}{10A}$ DIFFRACTION RATIOS OF THE CLAY-SIZE
FRACTION OF TILL

In order to determine whether or not semi-quantitative mineralogic analyses of the clay-size fraction of tills can be used to successfully differentiate and/or correlate till units associated with the Lake Michigan Ice Lobe in southwestern Michigan, a reference section was chosen and then sampled extensively in an effort to characterize the clay mineralogy of each till unit exposed. The Glenn Shores section (figures 3 and 5) was used as the reference section not only because it is one of the best exposures of multiple till units in Allegan County, but also because it is the only location in the county where three tills are exposed. In addition, the occurrence of organic material between the lowest till unit (the Glenn Shores Till) and the middle till unit (the Ganges Till) makes this section one of the most important in the Lake Michigan basin since very little is known about the Early and Middle Wisconsinan in this area.

Till that comprises the moraines that occur inland in Allegan County (the Lake Border, Inner Valparaiso, and Outer Valparaiso moraines) was then sampled, and the clay-size fraction analyzed in an attempt to correlate the moraines with the till units exposed in the Glenn Shores section.

SAMPLING PROCEDURE

A total of 63 samples were collected from the three till units that are exposed at the Glenn Shores section - 25 samples from the upper (Saugatuck) till (samples UT 100 - UT 124); 30 from the middle (Ganges) till (samples MT 1 - MT 30); and 8 from the lower (Glenn Shores) till (samples LT 300 - LT 307). In addition, 9 samples of the middle till (samples MT 500 - MT 508) were collected approximately 0.4 miles (0.6 kilometers) south of the Glenn Shores section, and 5 (LT 250 - LT 254) and 8 (LT 200 - LT 207) samples of the lower till unit were collected about 900 feet (274 meters) and about 1400 feet (426 meters), respectively, north of the section (see figure 5). Also, 10 samples (samples 620 - 629) were collected along the shoreline about 1.8 miles (3 kilometers) south of the Glenn Shores section, where Covert Ridge of the Lake Border Morainic System intersects the shoreline. These samples (620 - 629) were collected from a 15 to 20 feet (4.6 meter) thick unit of till near the top of the exposure - presumably the crest of the moraine. All samples collected along the shoreline were taken from fresh exposures of till, and all were unoxidized and unleached.

A total of 35 samples were collected from till that comprises the moraines in Allegan County - 21 samples (LBm 1 - LBm 21) from the Lake Border Morainic System; 9 samples (IVm 1 - IVm 9) from the Inner Valparaiso Moraine; and 5 samples (OVm 1 - OVm 5) from the Outer Valparaiso Moraine.

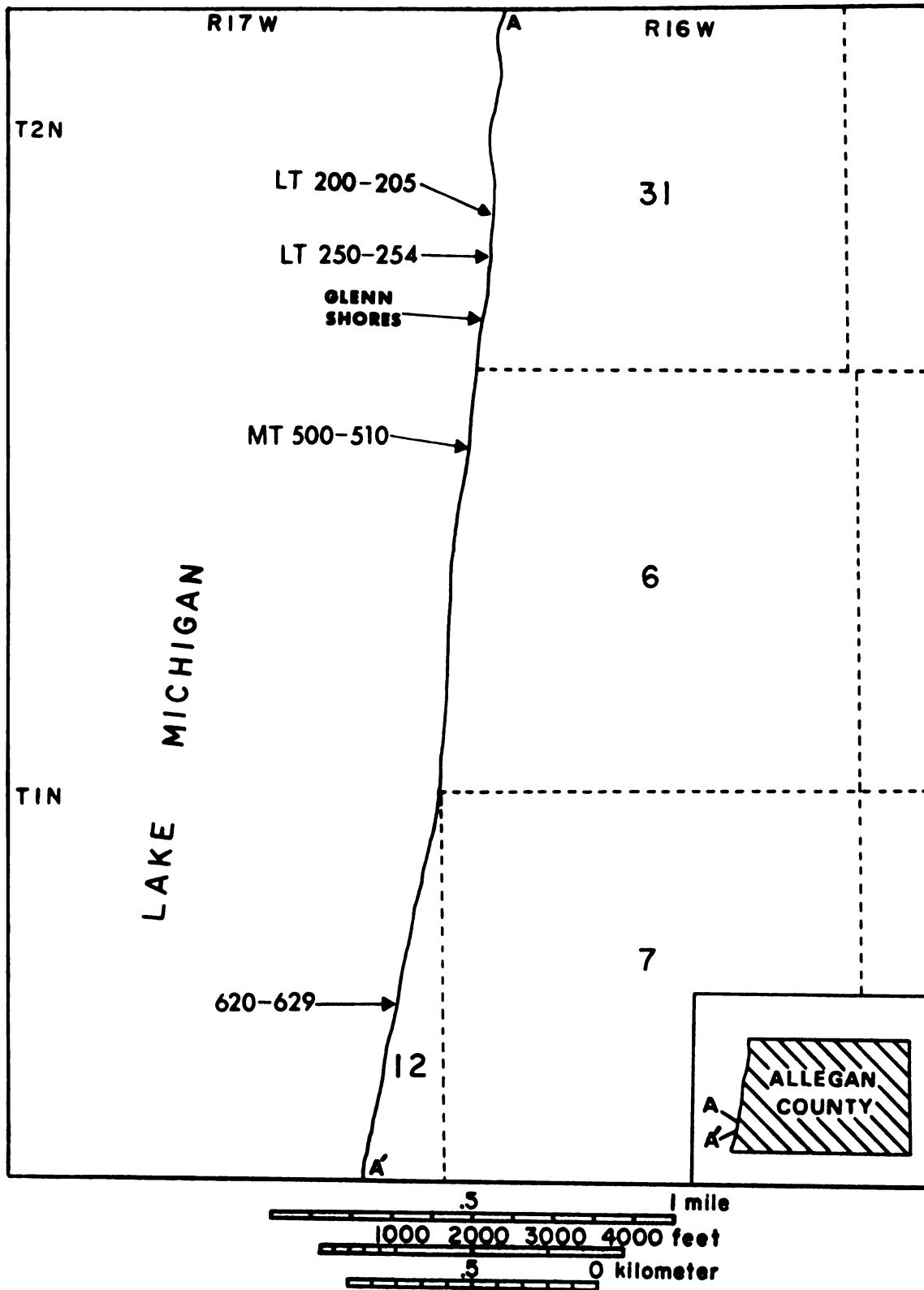


Figure 5: Shoreline sampling locations.

Sampling locations are shown in figure 6. Oxidized, unleached samples were taken generally 5 to 10 feet (1.5 to 3 meters) below the surface in roadcut exposures, using a hand soil auger.

SAMPLE PREPARATION AND X-RAY PROCEDURES

Methods described by Jackson (1958) were used to qualitatively determine which clay minerals are present in the tills that occur in Allegan County. This method of analysis employs several pre-treatments that remove soluble salts, free calcium carbonates, organic matter, and free iron oxides from the sample. The clay-size fraction (< 2 microns) is separated out by gravity fractionation and then deposited on a porous porcelain plate by vacuum suction, thus producing an oriented sample ready for x-ray analysis. Three samples (UT 104, MT 24, and LT 301) were pretreated using the above methods, and were analyzed by x-ray diffraction after each of the following treatments: 1) Mg saturated and glycerol solvated; 2) K saturated and dried at room temperature; 3) K saturated and heated to 300° C; and 4) K saturated and heated to 550° C.

Illite is the only common clay mineral that produces a $10\overset{\circ}{\text{A}}$ peak, and is not affected by the chemical or heat treatments. Kaolinite will produce a $7\overset{\circ}{\text{A}}$ peak that will disappear after heating the sample to 550° C. Vermiculite and chlorite both produce $14\overset{\circ}{\text{A}}$ peaks after Mg saturation and glycerol

solvation, and will produce a smaller second order (002) $7\overset{\circ}{\text{A}}$ peak. Smectite will produce a $17\overset{\circ}{\text{A}}$ to $18\overset{\circ}{\text{A}}$ peak after Mg saturation and glycerol solvation. Both vermiculite and smectite will collapse to $10\overset{\circ}{\text{A}}$ after heating to 300°C .

For the semi-quantitative analysis of the till samples, all of the samples were prepared for x-ray diffraction analysis using the method outlined by Hallberg (in press) of the Iowa Geological Survey. This method was preferred over Jackson's (1958) method because it is much faster and is less expensive, and yet will produce consistent results. The clay-size fraction (< 2 microns) of the till is separated out by gravity fractionation, deposited on a glass slide, dried, and then placed in a dessicator with ethylene glycol to expand the vermiculite to $14\overset{\circ}{\text{A}}$ and the smectite to $17\overset{\circ}{\text{A}}$ - $18\overset{\circ}{\text{A}}$.

Prepared clay slides were scanned from 3 degree to 15 degrees 2θ on a General Electric x-ray diffractometer using a 1° medium range beam slit, a medium range soller, and a 0.2 detector slit. A linear scale was used, the preset count was set at 10K, and the samples were run at either 1,000 or 2,000 counts per second range. The diffraction patterns were analyzed, using techniques outlined by Rieck, et al. (1979), by comparing the intensities of the $10\overset{\circ}{\text{A}}$ (illite) peaks and the $7\overset{\circ}{\text{A}}$ (kaolinite, 002 vermiculite and chlorite) peaks. These peaks were chosen for analysis because they are the most intense in all the samples analyzed. The peak heights were measured to the nearest 0.05 centimeter from an established baseline, and then the $7\overset{\circ}{\text{A}}/10\overset{\circ}{\text{A}}$ peak height

ratio was calculated. This procedure is illustrated in figure 7. After a sample was x-rayed once, the slide was rotated 180° and x-rayed again. In this way, two $\frac{7A}{10A}$ ratios were obtained for each sample. The average of these two ratios was then calculated and used as the ratio value for each particular sample.

RESULTS

Using Jackson's (1958) method for qualitatively determining the clay mineral content of a till sample, it was determined that illite and kaolinite are the dominant clay minerals in all three tills exposed at the Glenn Shores section, and that chlorite occurs in relatively lesser amounts. The occurrence of illite in each sample is indicated by a strong $\frac{10A}{7A}$ peak. The total disappearance of a strong $\frac{7A}{10A}$ peak in each sample after heating to 550° C indicates the occurrence of a significant amount of kaolinite in all three samples. The presence of a $\frac{14A}{10A}$ peak in all three samples after heating to 300° C indicates the occurrence of chlorite, since vermiculite will collapse to $\frac{10A}{7A}$ after this particular heat treatment. The low intensity of the $\frac{14A}{10A}$ peak, relative to the $\frac{7A}{10A}$ and $\frac{10A}{7A}$ peaks, indicates that only small amounts of chlorite are present in each till. A very small $\frac{18A}{10A}$ peak occurs in sample LT 301, indicating the possible occurrence of smectite in the lower till. No $\frac{18A}{10A}$ peaks were detected in samples MT 24 or UT 107. Vermiculite may be present in all three

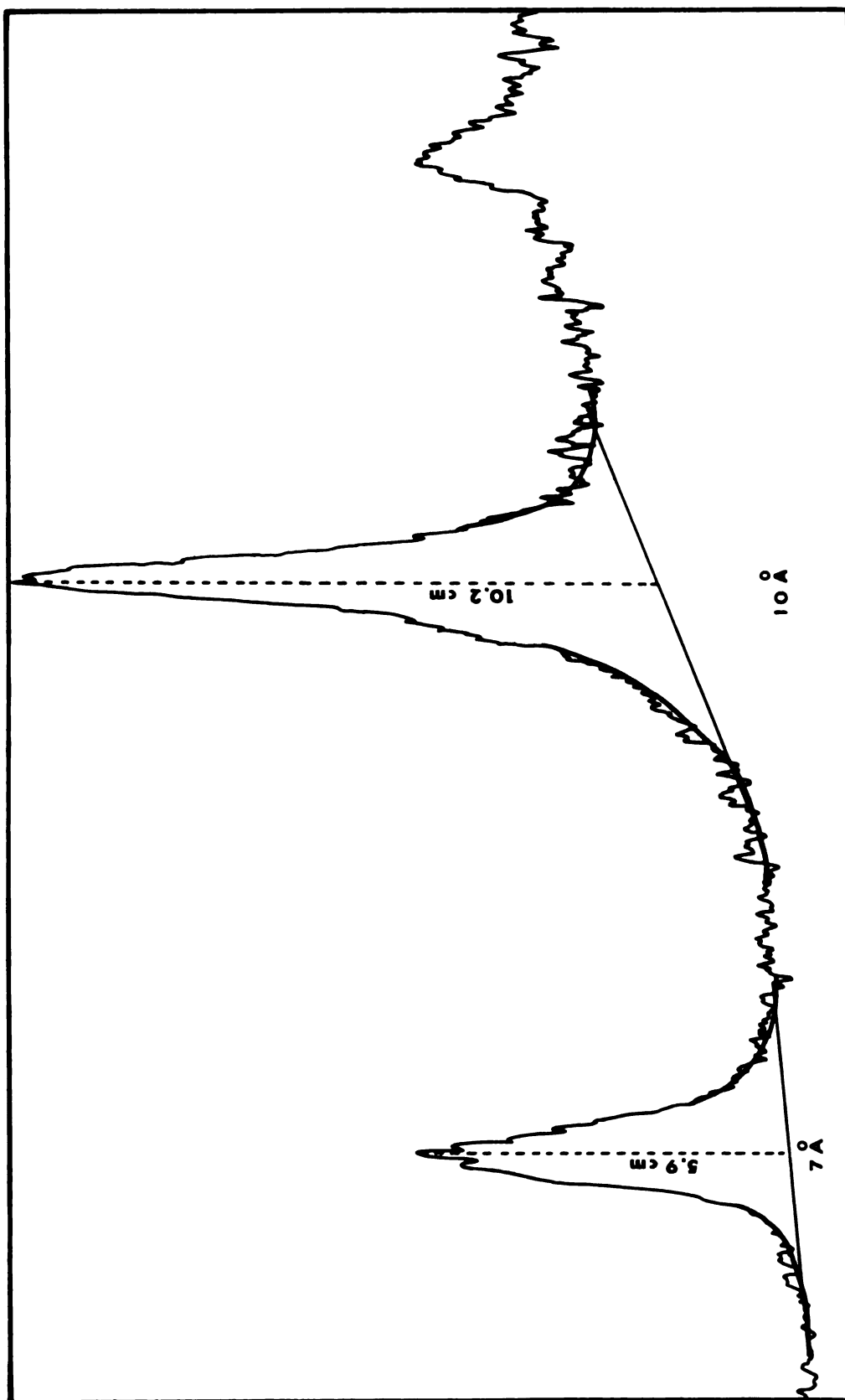


Figure 7: Calculation of 7A and 10A peak heights.

tills, but only in very small amounts since the ^{14}A peak in all three samples did not appear to diminish upon heating to 300°C . These results are consistent with clay mineral analyses of Lake Michigan Lobe tills in Illinois, in which illite is also the dominant clay mineral (Willman et al., 1963).

The calculated $^{7}\text{A}/^{10}\text{A}$ peak height ratios for the samples collected from tills exposed at the Glenn Shores section, as well as the lower and middle till samples that were collected along the shoreline immediately north and south of the Glenn Shores section, are presented in tables 1-3. The results of these analyses indicate the occurrence of three till populations, based on clay mineral compositions, that correspond to the three tills exposed at the Glenn Shores section. Samples collected from the upper till have a mean $^{7}\text{A}/^{10}\text{A}$ peak height ratio of .85 and a standard deviation of .11; samples from the middle till have a mean $^{7}\text{A}/^{10}\text{A}$ ratio of .85 and a standard deviation of .11; and samples of the lower till have a mean $^{7}\text{A}/^{10}\text{A}$ ratio of 1.22 and a standard deviation of .16. This data is presented in figure 8 as a series of histograms, which clearly show the three populations. Application of the t-test to the $^{7}\text{A}/^{10}\text{A}$ ratio values for each of the three tills verifies the existence of three different populations at the 99.9% confidence level.

The $^{7}\text{A}/^{10}\text{A}$ peak height ratios for the three till samples collected from the moraines in Allegan County are listed in tables 4-6. Samples taken from the Lake Border Morainic System have a mean $^{7}\text{A}/^{10}\text{A}$ ratio of .59 and a standard deviation of .11; samples from the Inner Valparaiso Moraine

the following: $\mathcal{P} = \{P_1, P_2, \dots, P_n\}$, where P_i is a polynomial of degree d_i .

Let $\mathcal{P}$ be a set of polynomials. We define the $\mathcal{P}$ -norm of a function f as follows: $\|f\|_{\mathcal{P}} = \max_{P \in \mathcal{P}} \|f - P\|$. This norm measures the maximum error between f and its approximation by a polynomial in $\mathcal{P}$. The $\mathcal{P}$ -norm is a seminorm, meaning it satisfies the properties of a norm except for the definiteness property. The $\mathcal{P}$ -norm is used to measure the quality of polynomial approximations. The $\mathcal{P}$ -norm is also used to define the $\mathcal{P}$ -approximation of a function f , which is the polynomial $P \in \mathcal{P}$ that minimizes the $\mathcal{P}$ -norm of $f - P$. The $\mathcal{P}$ -approximation of f is denoted by $P_{\mathcal{P}}(f)$.

Let $\mathcal{P}$ be a set of polynomials. We define the $\mathcal{P}$ -approximation of a function f as follows: $P_{\mathcal{P}}(f) = \arg \min_{P \in \mathcal{P}} \|f - P\|$.

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TABLE 1

$\frac{0}{7A/10A}$ X-RAY DIFFRACTION RATIOS FOR CLAY-SIZE FRACTION OF TILL
SAMPLES COLLECTED FROM LOWER (GLENN SHORES) TILL

$\frac{0}{7A/10A}$ RATIOS

SAMPLE #	ROTATION #1	ROTATION #2	AVERAGE
LT 200	1.48	1.39	1.44
LT 201	1.19	0.88	1.04
LT 202	1.17	1.13	1.15
LT 203	1.24	1.21	1.23
LT 204	1.53	1.00	1.27
LT 205	1.15	1.14	1.15
LT 206	1.52	1.06	1.29
LT 207	0.92	1.17	1.05
LT 250	1.81	1.14	1.48
LT 251	1.59	1.36	1.48
LT 252	1.12	1.48	1.30
LT 253	1.19	1.54	1.37
LT 254	1.13	0.96	1.05
LT 300	1.33	1.42	1.37
LT 301	1.30	1.29	1.30
LT 302	1.15	0.89	1.02
LT 303	0.93	1.36	1.15
LT 304	0.98	1.14	1.06
LT 305	1.06	1.04	1.05
LT 306	1.29	1.19	1.24
LT 307	0.97	1.11	1.04

TABLE 2

$\frac{0}{7A/10A}$ X-RAY DIFFRACTION RATIOS FOR CLAY-SIZE FRACTION OF TILL
SAMPLES COLLECTED FROM MIDDLE (GANGES) TILL

$\frac{0}{7A/10A}$ RATIOS

SAMPLE #	ROTATION #1	ROTATION #2	AVERAGE
MT 1	0.88	0.76	0.82
MT 2	0.82	0.77	0.80
MT 3	0.79	0.84	0.82

TABLE 2 (cont'd)

$$\frac{0}{7A/10A} \frac{0}{RATIOS}$$

SAMPLE #	ROTATION #1	ROTATION #2	AVERAGE
MT 4	0.76	0.73	0.75
MT 5	0.86	0.77	0.82
MT 6	0.80	0.83	0.82
MT 7	0.97	0.85	0.91
MT 8	1.08	1.03	1.06
MT 9	0.75	0.94	0.85
MT 10	0.96	0.94	0.95
MT 11	0.76	0.75	0.76
MT 12	1.08	0.99	1.04
MT 13	1.04	0.88	0.96
MT 14	1.14	1.04	1.09
MT 15	0.82	0.78	0.80
MT 16	0.91	0.80	0.86
MT 17	0.77	0.74	0.76
MT 18	0.85	0.91	0.88
MT 19	0.82	0.82	0.82
MT 20	1.03	1.00	1.02
MT 21	0.82	0.93	0.88
MT 22	0.95	0.85	0.90
MT 23	0.75	0.77	0.76
MT 24	0.77	0.82	0.80
MT 25	0.74	0.72	0.73
MT 26	0.73	0.65	0.69
MT 27	0.67	0.65	0.66
MT 28	0.89	0.76	0.83
MT 29	0.70	0.77	0.74
MT 30	0.76	0.67	0.72
MT 500	0.99	1.04	1.02
MT 501	0.90	0.86	0.88
MT 502	0.66	0.72	0.69
MT 503	0.92	0.90	0.91
MT 504	1.02	1.10	1.06
MT 505	0.77	0.72	0.75
MT 506	0.98	0.98	0.98
MT 507	0.87	0.92	0.90
MT 508	0.80	0.78	0.79

TABLE 3

⁰ ⁰
7A/10A X-RAY DIFFRACTION RATIOS FOR CLAY-SIZE FRACTION OF TILL
SAMPLES COLLECTED FROM UPPER (SAUGATUCK) TILL

⁰ ⁰ 7A/10A RATIOS			
SAMPLE #	ROTATION #1	ROTATION #2	AVERAGE
UT 100	0.53	0.57	0.55
UT 101	0.57	0.59	0.58
UT 102	0.57	0.49	0.53
UT 103	0.56	0.62	0.59
UT 104	0.62	0.57	0.60
UT 105	0.52	0.63	0.58
UT 106	0.58	0.60	0.59
UT 107	0.60	0.66	0.63
UT 108	0.51	0.51	0.51
UT 109	0.57	0.59	0.58
UT 110	0.51	0.54	0.53
UT 111	0.62	0.53	0.58
UT 112	0.57	0.59	0.58
UT 113	0.63	0.68	0.66
UT 114	0.53	0.53	0.53
UT 115	0.57	0.49	0.53
UT 116	0.60	0.62	0.61
UT 117	0.62	0.65	0.64
UT 118	0.55	0.60	0.58
UT 119	0.59	0.48	0.54
UT 120	0.59	0.56	0.58
UT 121	0.54	0.55	0.55
UT 122	0.72	0.62	0.67
UT 123	0.54	0.52	0.53
UT 124	0.62	0.60	0.61

TABLE 4

⁰ ⁰
7A/10A X-RAY DIFFRACTION RATIOS FOR CLAY-SIZE FRACTION OF TILL
SAMPLES COLLECTED FROM LAKE BORDER MORAINIC SYSTEM

⁰ ⁰ 7A/10A RATIOS			
SAMPLE #	ROTATION #1	ROTATION #2	AVERAGE
LBm 1	0.57	0.58	0.58

TABLE 4 (cont'd)

$$\frac{0}{7A/10A} \frac{0}{RATIOS}$$

SAMPLE #	ROTATION #1	ROTATION #2	AVERAGE
LBm 2	0.65	0.72	0.69
LBm 3	0.55	0.63	0.59
LBm 4	0.57	0.54	0.56
LBm 5	0.70	0.60	0.65
LBm 6	0.67	0.60	0.64
LBm 7	0.66	0.58	0.62
LBm 8	0.52	0.37	0.45
LBm 9	0.65	0.62	0.64
LBm 10	0.48	0.45	0.47
LBm 11	0.39	0.41	0.40
LBm 12	0.48	0.46	0.47
LBm 13	0.96	0.82	0.89
LBm 14	0.59	0.63	0.61
LBm 15	0.72	0.69	0.71
LBm 16	0.63	0.62	0.63
LBm 17	0.65	0.62	0.64
LBm 18	0.67	0.69	0.68
LBm 19	0.55	0.54	0.55
LBm 20	0.49	0.54	0.52
LBm 21	0.53	0.47	0.50

TABLE 5

$$\frac{0}{7A/10A} \frac{0}{X-RAY \text{ DIFFRACTION RATIOS FOR CLAY-SIZE FRACTION OF TILL}} \\ \text{SAMPLES COLLECTED FROM INNER VALPARAISO MORaine}$$

$$\frac{0}{7A/10A} \frac{0}{RATIOS}$$

SAMPLE #	ROTATION #1	ROTATION #2	AVERAGE
IVm 1	0.53	0.62	0.58
IVm 2	0.72	0.60	0.66
IVm 3	0.68	0.66	0.67
IVm 4	0.52	0.51	0.52
IVm 5	0.60	0.66	0.63
IVm 6	0.97	1.04	1.01
IVm 7	0.70	0.91	0.81
IVm 8	0.69	0.68	0.69
IVm 9	0.59	0.74	0.67

20.0

10.0

0.1

0.1

0.1

TABLE 6

$\frac{0}{7A/10A}$ X-RAY DIFFRACTION RATIOS FOR CLAY-SIZE FRACTION OF TILL
SAMPLES COLLECTED FROM OUTER VALPARAISO MORaine

$\frac{0}{7A/10A}$ RATIOS

SAMPLE #	ROTATION #1	ROTATION #2	AVERAGE
OVm 1	0.61	0.67	0.64
OVm 2	0.56	0.43	0.50
OVm 3	0.60	0.71	0.66
OVm 4	0.55	0.51	0.53
OVm 5	0.55	0.58	0.57

TABLE 7

$\frac{0}{7A/10A}$ X-RAY DIFFRACTION RATIOS FOR CLAY-SIZE FRACTION OF TILL
SAMPLES COLLECTED FROM SHORELINE EXPOSURE OF LAKE BORDER MORaine

$\frac{0}{7A/10A}$ RATIOS

SAMPLE #	ROTATION #1	ROTATION #2	AVERAGE
620	0.66	0.61	0.64
621	0.60	0.60	0.60
622	0.64	0.53	0.59
623	0.56	0.63	0.60
624	0.61	0.64	0.63
625	0.79	0.60	0.70
626	0.65	0.69	0.67
627	0.66	0.65	0.66
628	0.60	0.54	0.57
629	0.69	0.62	0.66

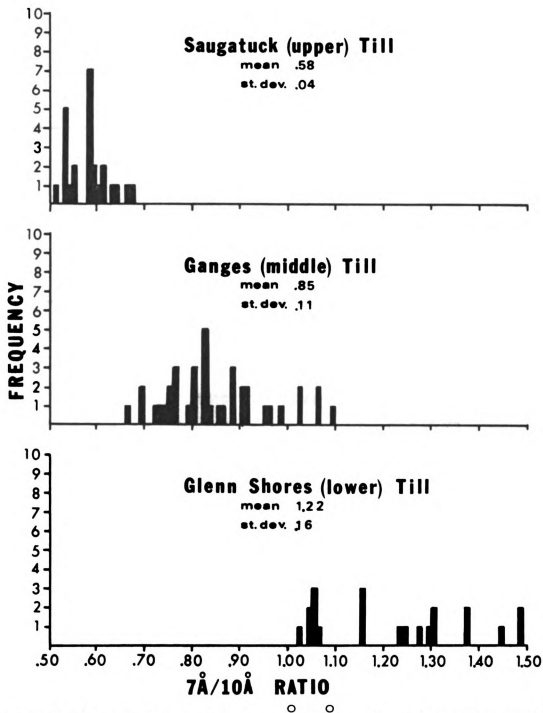


Figure 8: Histogram showing $7\text{\AA}/10\text{\AA}$ ratio values for till collected from shoreline exposures in Allegan County.

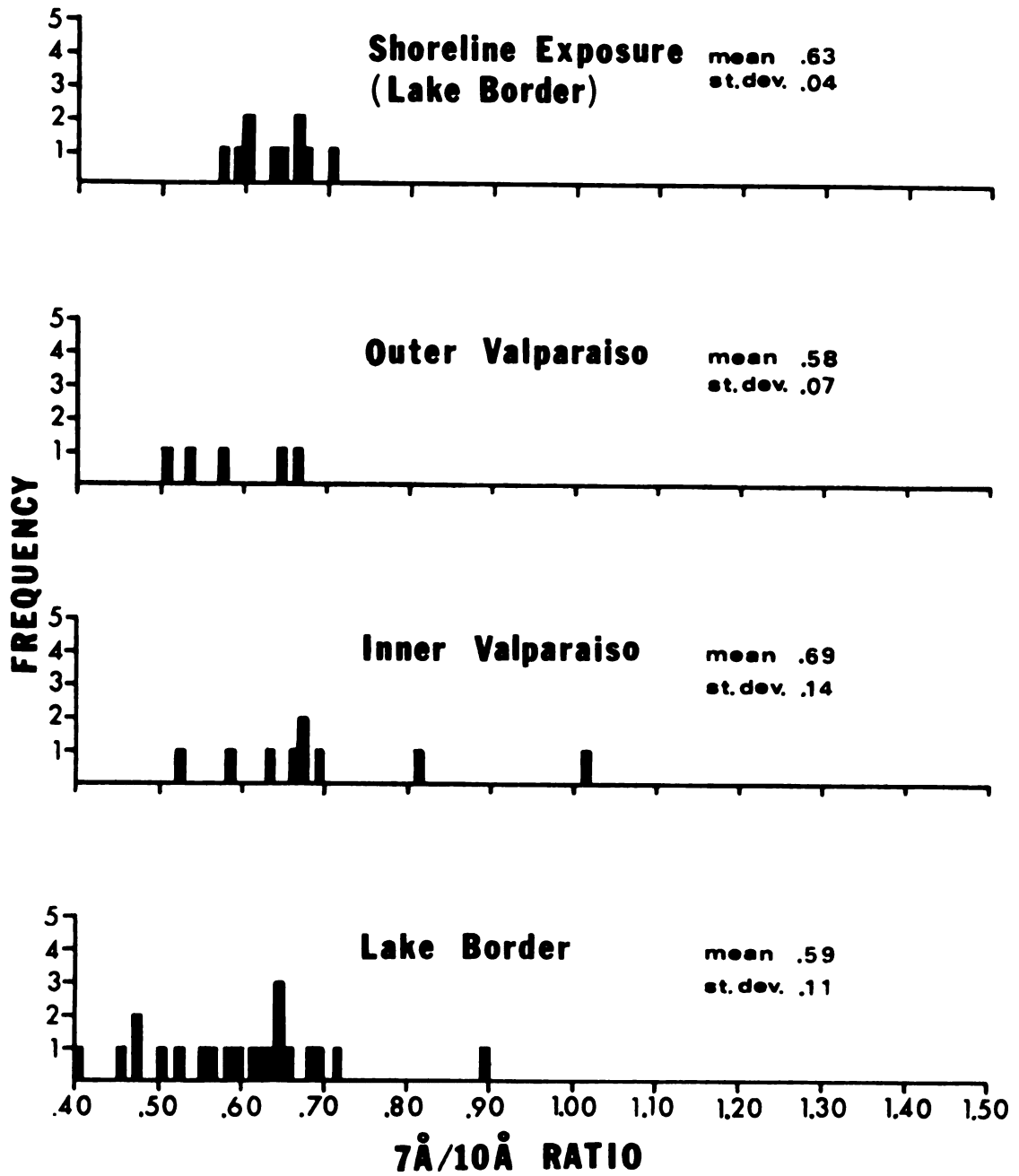


Figure 9: Histogram showing 7Å/10Å ratio values for till collected from moraines in Allegan County.

have a mean $\frac{7A}{10A}$ of 0.69 and a standard deviation of 0.14; and samples collected from the Outer Valparaiso Moraine have a mean $\frac{7A}{10A}$ ratio of 0.58 and a standard deviation of 0.07. Histograms representing this data are shown in figure 9. The $\frac{7A}{10A}$ ratios for samples 620 - 629, collected south of the Glenn Shores section where Covert Ridge intersects the Lake Michigan shoreline (figure 6), are listed in table 7 and are represented as a histogram in figure 7. The mean $\frac{7A}{10A}$ ratio value for these samples is 0.63 and the standard deviation is 0.04.

To determine the variability involved in the preparation and analysis of a till sample, a series of reproducibility tests were performed on three samples (UT 107; MT 25; LT 303) and the coefficient of variability (V) was calculated for each test. To determine the machine variability (V_m) (variability of the x-ray diffractometer and the variability involved in establishing the baseline for peak height measurements), the clay slide was left in the sample holder of the goniometer and x-rayed five times. The variability due to the orientation of clay minerals (V_r) within a prepared sample was determined by rotating a clay slide four times (90° rotations), x-raying the sample after each rotation. The variability involved in the preparation of a till sample (V_p) was determined by splitting a particular sample into five samples, preparing each separately, and x-raying each of these twice (180° rotations). The $\frac{7A}{10A}$ ratios were then calculated for each test.

Based on the three till samples tested, V_m was determined to be 3%-4%, V_r to be 3%-6%, and V_p to be 8%-10%. Obviously, sample preparation produced the largest coefficient of variability in the $\frac{7A}{10A}$ peak height ratios for each particular sample. V_p , however, incorporates both V_m and V_r since each sample is x-rayed 10 times (incorporating V_m) at 10 different orientations (incorporating V_r). Since V_p is by far the most important to consider, it was calculated for several additional till samples. The mean V_p values for each of the three till units exposed at the Glenn Shores section are:

Upper (Saugatuck) Till	9.5%
Middle (Ganges) Till	8.25%
Lower (Glenn Shores) Till	14.0%

DISCUSSION

The $\frac{7A}{10A}$ peak height ratio values for the three till units exposed in the Glenn Shores section show that semi-quantitative clay mineral analyses can indeed be used successfully to differentiate multiple till units exposed in stratigraphic section in southwestern Michigan. Since the uppermost till unit exposed in the Glenn Shores section (the Saugatuck Till) can be physically traced southward to the Lake Border Morainic System (Covert Ridge), a distance of 1.8 miles (3 kilometers), this till unit provides a good

test of whether semi-quantitative clay mineral analyses can also be used to correlate till sheets to till that comprises moraines. A comparison of the $\frac{7A}{10A}$ ratio values for the Saugatuck Till with the ratio values calculated for the till that comprises the Lake Border Morainic System (figures 8 and 9) shows that there is no significant difference between these tills; this is supported by the application of the t-test.

A comparison of the $\frac{7A}{10A}$ peak height ratios for the samples collected from the three till units exposed in the Glenn Shores section with the values for those samples collected from the Inner and Outer Valparaiso moraines in Allegan County (figures 8 and 9) clearly shows that the clay mineral content of the till that comprises these moraines is also most similar to that of the uppermost till at the Glenn Shores section (the Saugatuck Till). In fact, application of the t-test shows that there is no significant difference between samples collected from the Lake Border Morainic System, the Outer Valparaiso Moraine, and the Saugatuck Till. The t-test shows, however, that samples collected from the Inner Valparaiso Moraine are significantly different from the uppermost (Saugatuck) till, but are clearly more closely associated with this till than with the other two tills exposed at Glenn Shores. If the two anomalously high ratio values are excluded from the Inner Valparaiso Moraine values, the mean $\frac{7A}{10A}$ ratio value for this till is lowered to 0.63 - very close to that of the Saugatuck Till.

It is not surprising that the clay mineral composition of the tills that comprise the Outer Valparaiso Moraine, Inner Valparaiso Moraine, Lake Border Morainic System, and the Saugatuck (upper) Till are similar. This is because the Inner and Outer Valparaiso moraines, the Lake Border Morainic System, and the Saugatuck Till were all formed after the Erie Interstade during a progressive retreat of the ice. The clay mineral composition of the till that comprises these moraines and the uppermost till unit at Glenn Shores would be expected to change significantly only if this progressive retreat were interrupted by a later interstade.

If the middle (Ganges) till is also Late Wisconsinian in age, it may correlate to older, pre-Erie Interstade moraines of the Lake Michigan Lobe. For example, if the lacustrine sand deposits that separate the Saugatuck and Ganges tills represent an open lake in the Lake Michigan basin during the Erie Interstade, then the Ganges Till may correlate to either or both the Kalamazoo and Tekonsha moraines. If the Erie Interstade began as a retreat from the Tekonsha Moraine and ended with a readvance to the Kalamazoo Moraine, then the till comprising the Tekonsha Moraine may correlate to the Ganges Till and the till comprising the Kalamazoo Moraine would most likely correlate to the Saugatuck. If, however, the Erie Interstade began as a retreat from the Kalamazoo Moraine and ended with a readvance to the Outer Valparaiso Moraine, then the till comprising both the Tekonsha and Kalamazoo moraines should correlate to the Ganges (middle) Till. If either of the above correlations can be made in

future clay mineralogy studies, the Erie Interstade could be well defined for the Lake Michigan Ice Lobe, a significant contribution to the Pleistocene history of the Great Lakes region.

The reason for the difference in the clay mineral compositions of the three tills exposed in the Glenn Shores section is not known with any certainty, but appears to be related to significant glacial retreats. This is suggested by the occurrence of lacustrine sediments between the till units. In fact, the retreat of the ice following the deposition of the Ganges Till was great enough to allow northward and eastward drainage through the Straits of Mackinac or the Indian River lowlands (Gephart, et al., 1982). Each time one of these lakes developed in the Lake Michigan basin, sediment from different source areas may have been washed in and deposited on the lake bottom. Each subsequent advance of the ice margin would then have incorporated these lake sediments into the ice and re-deposited them as till with a unique clay mineral composition.

Another possibility is that the lower two tills exposed at the Glenn Shores section were deposited from either the Saginaw or Huron-Erie lobes, rather than from the Lake Michigan Lobe. Since the ice would have advanced over different source areas, the composition of the lower and middle tills might be expected to differ significantly from the uppermost till unit at the section, derived from the Lake Michigan Lobe. This explanation can only be tested by independent provenience

indicators (i.e. strontium/rubidium ratio of feldspars and/or heavy mineral assemblages).

Also, the difference in the clay mineral compositions of the three tills exposed in the Glenn Shores section may be the result of some sort of pedogenic or weathering effect. For example, kaolinite has been produced in the laboratory by dissolving aluminosilicate minerals, mainly labradorite, microcline, and augite, in organic acids. Silica and aluminum dissolve into solution, then re-combine to form kaolinite (Huang and Keller, 1970; Linares and Huertas, 1971; Hem and Lind, 1974). This explanation for the clay mineral differences in tills at the Glenn Shores section is unlikely, however, because of the short time intervals in which these processes could have taken place. Also, the till units at the Glenn Shores section are composed of dense clay-rich till, and are as much as 20 feet (6 meters) thick, making weathering throughout the till unlikely. In addition, vertical sampling of each till unit has shown no consistent vertical change or trend in the clay mineral composition with a particular till sheet that would suggest pedogenic clay mineral alteration.

SUMMARY AND CONCLUSIONS

The surficial deposits in Allegan County, Michigan are comprised mostly of drift associated with the progressive Late Wisconsin retreat of the Lake Michigan Ice Lobe. The deglaciation of the county occurred during the approximate period 14,800 to 13,800 years BP (Farrand and Eschman, 1974), and resulted in the formation of four moraines in Allegan County - the Outer and Inner Valparaiso moraines, and Covert Ridge and Zeeland Ridge of the Lake Border Morainic System, all of which roughly parallel the present Lake Michigan shoreline. Outwash deposits, lacustrine sediments, and till plains separate these moraines.

Pre-Late Wisconsin drift deposits are not exposed at the surface in Allegan County, but can be observed along the Lake Michigan shoreline in the southern part of the county. A sequence of tills and lacustrine sediments exposed in the Glenn Shores section about one mile (1.6 kilometers) southwest of the village of Glenn record several fluctuations of glacial ice during the Wisconsin.

The three till units exposed in the Glenn Shores section were sampled in order to determine whether or not these tills can be differentiated on the basis of clay mineral composition.

Till that comprises the moraines that occur further inland was also sampled, in order to determine if the till sheets exposed at Glenn Shores can be correlated to the moraines on the basis of clay mineral composition. Based on semi-quantitative clay mineral analyses of these till samples, the following conclusions have been determined:

- 1) The dominant clay minerals that comprise the three till units exposed in the Glenn Shores section are illite and kaolinite. Chlorite and vermiculite occur in much lesser amounts and do not significantly affect the $\frac{7A}{10A}$ peaks.
- 2) The illite content of the till increases with respect to kaolinite, from the lowermost till unit at Glenn Shores (Glenn Shores Till) to the uppermost till unit (Saugatuck Till).
- 3) The three till units exposed in the Glenn Shores section can be differentiated on the basis of $\frac{7A}{10A}$ peak height ratios. Application of the t-test shows that the three till units are significantly different, based on their clay mineral composition, to the 99.9% confidence level. The mean $\frac{7A}{10A}$ ratios for the three tills exposed at Glenn Shores are:

Upper (Saugatuck) Till:	0.58
Middle (Ganges) Till:	0.85
Lower (Glenn Shores) Till:	1.22
- 4) The Saugatuck Till can be traced laterally for a distance of 1.8 miles (3 kilometers) to a shoreline exposure

of the Lake Boarder Moraine, using semi-quantitative clay mineral analyses.

- 5) The clay mineral compositions of till that comprise all of the moraines that occur in Allegan County (the Lake Boarder Morainic System, the Inner Valparaiso Moraine, and the Outer Valparaiso Moraine) are all most similar to that of the Saugatuck (upper) Till at Glenn Shores. The Saugatuck Till is therefore related to each of the moraines in Allegan County - a situation that would be expected with a progressive retreat of glacial ice.

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