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# LATE WISCONSINAN ICE-FLOW RECONSTRUCTION FOR THE CENTRAL GREAT LAKES REGION

By

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ABSTRACT

LATE WISCONSINAN ICE-FLOW RECONSTRUCTION
FOR THE CENTRAL GREAT LAKES REGION

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Tills associated with three Late Wisconsinan ice lobes (Lake Michigan, Huron-Erie, and Saginaw) in Michigan were differentiated based on their heavy mineral assemblages. Using discriminant analysis, the heavy mineral assemblages of tills in Michigan were also associatated with specific source areas on the Canadian Shield. These associations suggest that: 1) The Lake Michigan Lobe flowed southwestward across a region along the north shore of Lake Huron and then into southwestern Michigan. 2) The Huron-Erie Lobe flowed southwestward across a region northeast of Georgian Bay and then southward into southeast Michigan. And 3) the Saginaw Lobe flowed southwestward across both of these regions and then into southcentral Michigan.

Comparison of heavy mineral assemblages from tills in southeastern Michigan with those from younger tills just south of Lake Huron indicates that a significant shift occurred in ice-flow direction during the final retreat of ice from southeastern Michigan.

**to Karen**

## ACKNOWLEDGMENTS

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# INTRODUCTION

The establishment of objective ice-flow reconstructions for the Laurentide ice sheet has been the focus of much recent research in Illinois (Willman, Glass and Frye, 1963), Indiana (Bleuer, 1983), Ohio (Taylor and Faure, 1981), and southern Ontario (Gwyn and Dreimanis, 1979). While most of these investigations have relied on provenance discriminators to reconstruct ice-flow patterns, the flow reconstructions within Michigan are still based mainly on morphologic evidence compiled during the original mapping of the state by Frank Leverett around the turn of the century (Leverett and Taylor, 1915).

The purpose of this paper is four fold: 1) To establish lithologic criteria that can be used to differentiate between tills of the Michigan, Saginaw, and Huron-Erie ice lobes in Michigan. 2) To associate the tills of each lobe with a distinct provenance area on the Canadian Shield. 3) To reconstruct ice-flow patterns in the central Great Lakes region on the basis of these associations. And 4) to compare this reconstruction with those already proposed.

# PREVIOUS ICE FLOW RECONSTRUCTIONS

One of the earliest attempts at ice-flow reconstruction for the central Great Lakes region was by Frank Leverett (Leverett and Taylor, 1915; plate V) aproximately 70 years ago. He based his reconstruction (Figure 1) essentially on the morphology of glacial deposits and suggested that the relative positions of recessional moraines in Indiana and Michigan indicate that ice flowed across the region in three main lobes; the Michigan Lobe, the Saginaw Lobe, and the Huron-Erie Lobe.

In ensuing years, various aspects of till lithology have been used to determine drift provenance and this has resulted in some modifications of Leverett's original reconstruction. For instance, Fullerton (1980) has suggested that the surface drift in southeastern Michigan, central and western Ohio, and central Indiana was deposited by ice that flowed through the Lake Huron basin (Figure 2). He based this reconstruction on the presence of tillite and banded slate indicators, the source of which is most likely northeast of Lake Huron (White, 1939). On the other hand, Bleuer (1983), has suggested that the Erie Lobe flowed through both southeastern Michigan and northern Ohio and extended much farther west into Indiana than was indicated by Leverett (Figure 3). This reconstruction is based on high (> 3) garnet-epidote ratios from the sand sized fraction of till in western Indiana. The source of these


Figure 1. Late Wisconsinan ice-flow in the Great Lakes region, after Leverett and Taylor (1915).

Figure 2. Generalized ice-flow paths, after Fullerton (1980).

| | | | |
|---|---|---|---|
| 1. | Green Bay Lobe | 2. | Michigan Lobe |
| 3. | Saginaw Lobe | 4. | Huron Lobe |
| 5. | Georgian Bay Lobe | 6. | Lake Simcoe sublobe |
| 7. | Ontario Lobe | 8. | Erie Lobe |
| 9. | Grand River sublobe | 10. | Kilbuck sublobe |
| 11. | Scioto sublobe | 12. | Miami sublobe |
| 13. | East White sublobe | 14 | Decatur sublobe |

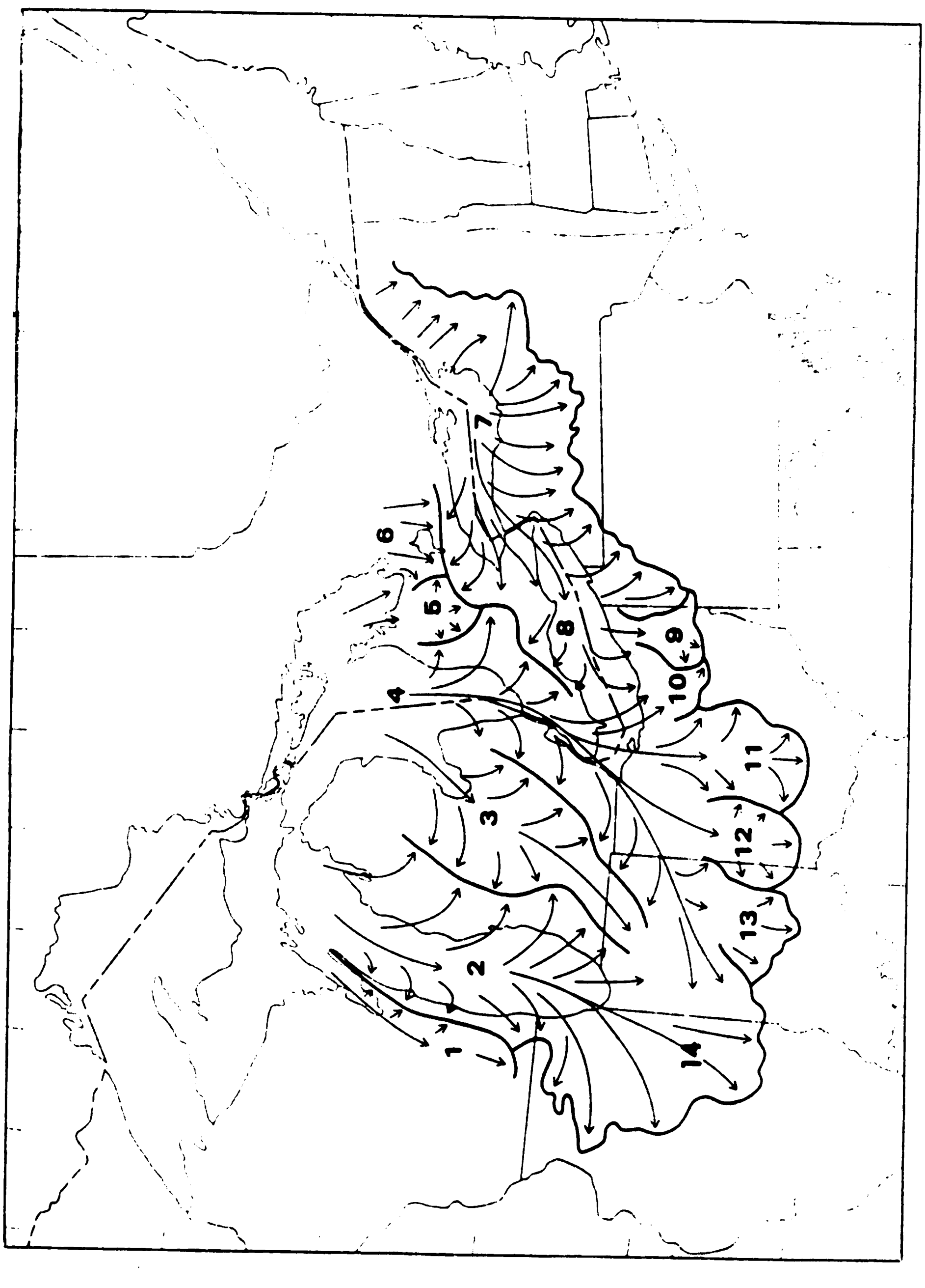
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0 100 200 300 400 KILOMETERS
0 100 200 MILES

Figure 2.

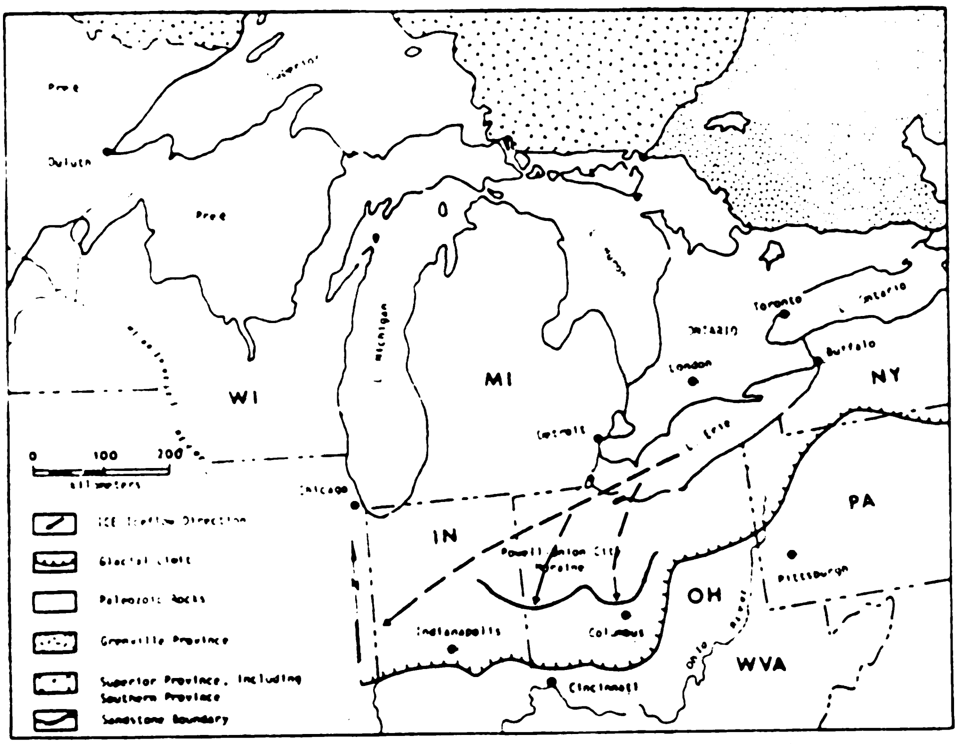


Figure 3. Late Wisconsinan ice-flow reconstructions in Ohio, after Taylor and Faure (1981), and in Indiana, after Bleuer (1983).

two minerals is most likely north and northeast of Lake Ontario (Gwyn and Driemanis, 1979). A similar reconstruction by Taylor and Faure (1981) (Figure 3) was based on the age of detrital feldspar from tills in Ohio. The feldspar dates indicate a Grenville province source and thus transport by the Erie Lobe.

## METHODS

Although indicators, mineral ratios, and radiogenic dates on feldspars provide valuable information regarding ice-flow directions, limitations exist with respect to these methodologies. For example, indicators are generally rare and they can have more than one source area (White, 1939). Likewise, the application of both mineral ratios and feldspar dates can only discriminate between broad regional source areas and thus are of limited use for local reconstructions.

A more precise approach to ice-flow reconstructions has been developed by Gwyn and Driemanis (1979) and was applied to ice-flow in southern Ontario. This method first defines provenance areas by multivariant analysis of heavy mineral assemblages in tills on the Canadian Shield and then classifies assemblages from tills down ice with the assemblages of the source areas. The classifications are then used to reconstruct ice flow patterns. This method is also used for the reconstruction of ice-flow patterns in this investigation.

Data Collection: A total of 31 till samples, 11 associated with the Michigan Lobe, 8 associated with the Saginaw Lobe, and 12 associated with the Huron-Erie Lobe, were collected from exposures in moraines and till plains within the southern half of the lower penninsula of Michigan. Generally these samples were taken at least five feet below the ground surface. The locations of the samples and the moraines from which they were collected are shown in figure 4. The ages of these moraines are believed to be between 15,000 and 13,000 yr B.P. (Farrand and Eschman, 1974; Dreimanis and Goldthwait, 1973; and Dreimanis, 1977).

Heavy minerals from each sample were gravity separated using tetrabromoethane (s.g. 2.95) following the procedure described by Gwyn (1971). Only the fine sand fraction (2 to 3 phi) was studied because it has been demonstrated to be the most diagnostic for heavy mineral studies of till (Gwyn and Dreimanis, 1979). The weight of the heavy minerals was measured and reported as a weight percent of the fine sand fraction. The magnetic minerals were removed with a hand magnet, weighed, and reported as a weight percent of the heavy mineral fraction. The separated heavy minerals were mounted on glass slides with a high refractive index mounting medium

Figure 4. Sample locations with respect to major moraines in southern Michigan.
Abreviations: LBM- Lake Border Moraine, VM- Valparaiso Moraine, KMM- Kalamazoo Moraine Michigan Lobe, KMS- Kalamazoo Moraine Saginaw Lobe, CM- Charlotte Moraine, LM- Lansing Moraine, GLM- Grand Ledge Moraine, MM- Mississinawa Moraine, FWM- Fort Wayne Moraine, DM- Defiance Moraine.

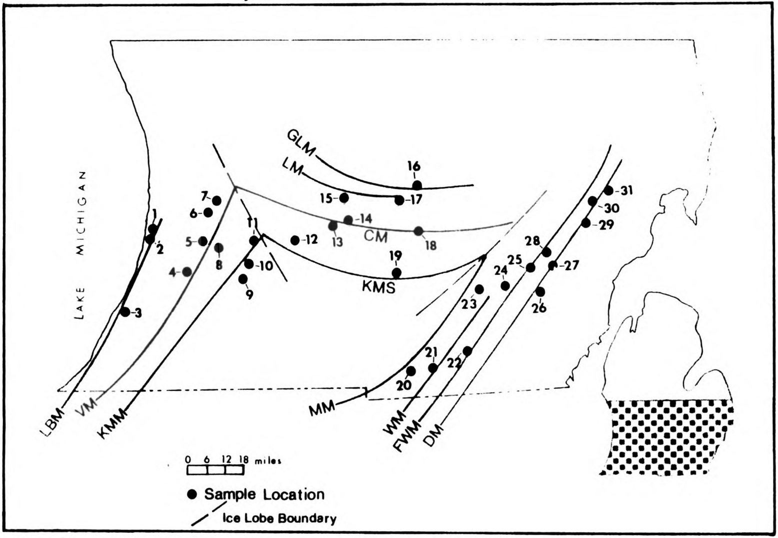
LAKE MICHIGAN
GLM
LM
CM
KMS
LBM
VM
KMM
MM
WM
FWM
DM
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
0 6 12 18 miles
Sample Location
Ice Lobe Boundary

Figure 4.

(Ladd High Mount, R.I. 1.686). On each slide 450 to 500 grains were identified and counted using an Olympus (model BH) petrographic microscope. Heavy minerals were identified optically by their color, refractive index, pleochroism, cleavage, habit, extinction angle, and optic sign. The mineral species identified are listed in table 1. All other mineral species and grains which could not be identified were combined into a category termed "others".

---

Table 1. Heavy mineral species identified.

Hornblende
Tremolite- Actinolite
Orthopyroxenes- Enstatite, Hypersthene
Clinopyroxenes- Augite, Diopside
Garnet
Epidote
Rutile
Sphene
Zircon
Tourmaline
Opaque minerals

---

## HEAVY MINERAL ASSEMBLAGES IN MICHIGAN TILLS

The frequency percent of heavy mineral species occurring in samples from the Michigan, Saginaw, and Huron-Erie lobes in Michigan is shown in table 2. From this data, it is apparent that tills associated with the three lobes can be differentiated on the basis of their heavy mineral assemblages. The Michigan Lobe is characterized by high percentages of epidote and opaque minerals (primarily ilmenite, hematite, and pyrite) and low percentages of clinopyroxene and low weight percent of heavy minerals. High weight percent of heavy minerals, high percentages of hornblende and clinopyroxene, and low percentages of epidote and opaque minerals are characteristic of the Huron-Erie Lobe . The Saginaw Lobe generally has heavy mineral percentages intermediate between the Michigan and Erie Lobes except for garnet which tends to be low.

Table 2. Heavy mineral data from Michigan tills .

| Mineral[1] | Lobe | | | | | |
|---|---|---|---|---|---|---|
| | Michigan | | Saginaw | | Huron-Erie | |
| | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ |
| Opaque Minerals | 20.3 | 6.6 | 12.7 | 2.9 | 6.0 | 1.5 |
| Weight Heavies[2] | 0.9 | 0.3 | 1.5 | 0.2 | 2.5 | 0.8 |
| Rutile | 0.2 | 0.2 | 0.1 | 0.1 | 0.2 | 0.2 |
| Epidote | 7.9 | 1.8 | 5.8 | 1.6 | 5.4 | 1.6 |
| Zircon | 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 |
| Sphene | 0.4 | 0.3 | 0.7 | 0.4 | 0.9 | 0.7 |
| Clinopyroxene | 3.8 | 1.0 | 4.5 | 1.7 | 7.4 | 2.2 |
| Orthopyroxene | 1.2 | 0.4 | 2.5 | 0.9 | 2.3 | 1.2 |
| Tremolite | 0.6 | 0.4 | 1.0 | 0.5 | 0.9 | 1.2 |
| Magnetics Fraction[3] | 5.8 | 3.3 | 5.2 | 2.5 | 5.2 | 2.6 |
| Hornblende | 34.2 | 5.8 | 33.9 | 2.9 | 42.5 | 5.3 |
| Tourmaline | 0.8 | 0.6 | 0.6 | 0.3 | 0.7 | 0.6 |
| Garnet | 8.8 | 2.9 | 7.1 | 1.7 | 9.5 | 2.7 |
| Others | 21.2 | 4.9 | 30.7 | 4.0 | 24.2 | 4.6 |
| Sample Size | 12 | | 8 | | 11 | |

1- In descending order of importance for differentiation of lobes.
2- Units: weight percent of fine sand fraction.
3- Units: weight percent of heavy minerals.

In an attempt to further differentiate between the three lobes the heavy mineral data in table 2 was analyzed using a discriminant analysis computer program (Klecky, 1975). The program mathematically establishes the best combination of mineral variables for differentiating heavy mineral group populations and through a linear discriminant function transforms the heavy mineral data for each sample into a single discriminant score. That score, or transformed variable, represents the samples position along a line defined by the linear discriminant function. The program minimizes the difference between discriminant scores among samples within groups and maximizes the mean discriminant scores between groups. The program also has the capability of classifying ungrouped samples into their most likely group association based on the their discriminant scores.

Discriminant analysis of the heavy mineral assemblage data in table 2 correctly assigned 93 percent of the till samples to their respective lobes. Two samples, 1-1 and 25-1, that were collected from moraines assciated with the Huron-Erie Lobe were classified with the Saginaw Lobe. These samples, which were obtained very near the interlobate area between the Huron-Erie and Saginaw lobes, could have been derived from Huron-Erie Lobe ice that overrode and incorporated older Saginaw Lobe deposits.

## HEAVY MINERAL ASSEMBLAGES IN TILLS ON THE CANADIAN SHIELD

Heavy mineral assemblages of tills on the periphery of the Canadian shield north of the Great Lakes region have been studied by Dreimanis et al. (1957) and by Gwyn and Dreimanis (1979). They found that the most marked change in heavy minerals in tills occurs between the Grenville and the Superior-Southern structural provinces and suggested that these changes are due to "a fundemental difference" in the rocks underlying these two areas. For example, tills in the Superior-Southern province are characterized by a high epidote and occasionally high magnetic and opaque mineral content, and low amounts of garnet, tremolite, sphene, and total heavy mineral content. On the other hand, tills in the Grenville province are generally identified by their high weight percent of heavy minerals and their high content of garnet, tremolite, and to a lesser extent sphene and orthopyroxene . Epidote, opaque minerals, and the magnetic fraction also tend to be lower in the Grenville province than the Superior-Southern province.

Within the Superior-Southern and Grenville provinces several local areas with distinct heavy mineral assemblages have also been suggested by Gwyn and Dreimanis (1979). Two of these occur in the Grenville province; a western area named here "Grenville west" can be identified by abundant garnet and a low purple-red garnet ratio, and an eastern area named here "Grenville east" can be identified by high garnet and tremolite, and a garnet ratio generally greater than one. Two local areas are also located in the Superior-Southern province, one along the north shore of Lake Huron and the other near the Thunder Bay area of Lake Superior. The area on the north shore of Lake Huron is named here "Superior east" and typically has very high percentages of clinopyroxene and relatively low percentages of hornblende and garnet. The "Thunder Bay" assemblage area has high percentages of clinopyroxene and magnetic minerals, however, Gwyn and Dreimanis (1979) have pointed out that this provenance area may be too limited in extent to be a useful provenance area.

From Gwyns' data (1971), two additional provenance areas are proposed. One is the "Province Boundary" area which occurs along the boundary line that separates the Grenville and Superior-Southern provinces. This areas assemblage is identified by its high pecentage of hornblende, intermediate percentages of clinopyroxene, garnet, epidote, opaque minerals and total heavy minerals, and low percentages of magnetic minerals. The other area is located between Thunder Bay and the Superior east area along the northeast shore of Lake Superior. This area, named "Superior west", can be characterized by high epidote and low garnet. Table 3 shows the mean percentages of the heavy minerals in all six areas described above. The

Table 3. Heavy mineral data for Canadian Shield tills.

| Mineral[1] | Provenance | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | T.B. | | S.W. | | S.E. | | P.B. | | G.W. | | G.E. | |
| | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ |
| Garnet | 0.7 | 0.7 | 4.6 | 2.8 | 6.3 | 4.0 | 4.0 | 3.4 | 28.4 | 7.4 | 10.5 | 5.2 |
| Weight Heavies[2] | 1.7 | 1.3 | 0.6 | 0.5 | 0.6 | 0.4 | 1.2 | 0.4 | 2.1 | 0.6 | 1.7 | 0.7 |
| Clinopyroxene | 77.5 | 6.4 | 32.7 | 14.9 | 48.2 | 18.9 | 29.6 | 14.5 | 12.2 | 3.2 | 20.9 | 8.0 |
| Hornblende | 7.1 | 3.4 | 49.5 | 13.2 | 28.3 | 15.0 | 51.9 | 14.5 | 48.5 | 8.7 | 46.7 | 12.0 |
| Epidote | 1.0 | 0.5 | 5.1 | 2.5 | 3.8 | 1.7 | 4.0 | 3.3 | 1.1 | 1.1 | 1.6 | 1.1 |
| Rutile | 0.1 | 0.1 | 0.4 | 0.4 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.6 | 0.5 |
| Magnetics[3] | 7.0 | 5.2 | 4.4 | 1.5 | 6.6 | 8.9 | 0.9 | 2.1 | 2.4 | 2.4 | 5.3 | 3.0 |
| Tremolite | 0.1 | 0.2 | 0.2 | 0.3 | 0.2 | 0.3 | 0.3 | 0.2 | 0.6 | 0.5 | 5.3 | 3.7 |
| Tourmaline | 0.0 | 0.0 | 0.2 | 0.2 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 2.3 | 3.4 |
| Orthopyroxene | 0.4 | 0.4 | 0.7 | 0.5 | 0.6 | 0.4 | 0.3 | 0.2 | 1.8 | 2.6 | 1.2 | 1.7 |
| Sphene | 0.0 | 0.0 | 0.8 | 0.5 | 0.2 | 0.3 | 0.8 | 1.0 | 0.8 | 0.8 | 1.3 | 0.8 |
| Opaques | 14.8 | 7.0 | 6.1 | 2.8 | 10.1 | 4.6 | 7.3 | 3.2 | 6.3 | 2.8 | 9.5 | 6.2 |
| Zircon | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Sample Size | 5 | | 18 | | 20 | | 8 | | 15 | | 23 | |

Abreviations: T.B.- Thunder Bay, S.W.- Superior West, S.E.- Superior East, P.B.- Province Boundary, G.W.- Grenville West, G.E.- Grenville East

1- In descending order of importance for differentiation of provenances.

2- Units: weight percent of heavy minerals in the fine sand fraction.

3- Units: weight percent of magnetic minerals in the heavy mineral separate.

location of these provenance areas is shown in figure 5.

To further substantiate the existence of these six provenance areas, discriminant analysis was performed on the heavy mineral data listed in table 3. Correct assignment of 89 percent of the samples to their respective provenance areas confirms the existance of five of these areas. Correct assignment of only 60 percent of the Thunder Bay area samples suggests that this suite of till samples does not represent a distinct provenace area. Consequently, this area is not considered any further in this study.

## ICE FLOW RECONSTRUCTIONS

On the basis of their discriminant scores, the heavy mineral assembalges of Michigan tills have been classified into the five established provenance assemblages of the Canadian shield. The results of these classifications are summarized in figure 5. The classifications show that the Huron-Erie Lobe assemblage is best asscociated with the assemblage of the Province boundary area. They also show that the assemblage of the Saginaw Lobe is associated with both the assemblages of the Province boundary and the Superior east areas. The assemblage of the Michigan Lobe appears to be primarily associated with the heavy mineral assemblage of the Superior east area.

Figure 5. Late Wisconsinan ice-flow reconstruction for the central Great Lakes region. Samples near the southern shorline of Lake Huron and on the Canadian Shield were collected and analyzed by Gwyn (1971).

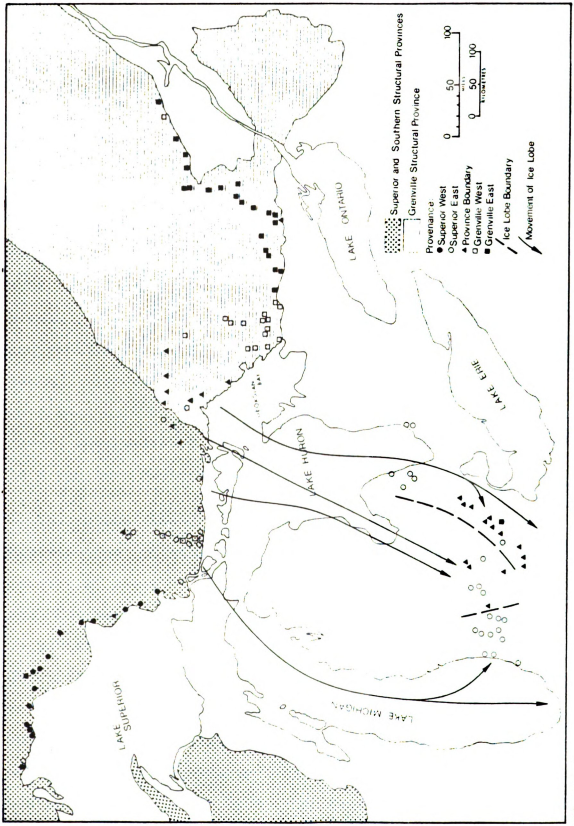
Superior and Southern Structural Provinces
Grenville Structural Province
Provenance:
Superior West
Superior East
Province Boundary
Grenville West
Grenville East
Ice Lobe Boundary
Movement of Ice Lobe
0 50 100
0 50 100
LAKE ONTARIO
LAKE ERIE
LAKE HURON
LAKE MICHIGAN
LAKE SUPERIOR

Figure 5.

From the above classifications late Wisconsinan ice-flow patterns can be reconstructed for the central Great Lakes region (Figure 5). Ice of the Huron-Erie Lobe in Michigan appears to have been derived primarily from the Province boundary area. From here it flowed southwestward through Georgian Bay, then southward into the Huron Basin, and then southwestward into Michigan. Likewise, ice associated with the Saginaw Lobe appears to have been derived primarily from two areas, the Province boundary and Superior east areas. From these areas the ice flowed towards the south and southwest across the Huron Basin and into the Saginaw Basin. Ice of the Michigan Lobe, in Michigan, appears to have been derived mainly from the Superior east area and flowed southwestward into the Lake Michigan Basin, and then into southern Michigan.

The above reconstruction is also supported by the distribution of individual variables. For example, weight percent of heavy minerals, which has been shown by Gwyn and Dreimais (1979) to be one of the most diagnosic variables for discriminating between tills from the Grenville (high weight percent) and Superior-Southern (low weight perecnt) structural provinces, indicates that Huron-Erie Lobe tills in Michigan were derived from the Grenville province because both have high weight percent of heavy minerals. On the other hand, Michigan Lobe tills have a low weight percent of heavy minerals which indicates that they were derived from the Superior-Southern province. Saginaw Lobe tills have intermediate percentages of weight percent heavy minerals which indicates that they were derived from both provinces.

## DISCUSSION

The ice-flow reconstructions presented in Figure 5 agree well with those postulated by Leverett and Taylor (1915); the only exception involves the source of ice in southeastern Michigan. Leverett and Taylor suggest that during the Late Wisconsinan ice from the Erie Basin extended west through southeastern Michigan as far as the Ohio-Indiana state line. This study, however, shows that only ice from the Huron basin extended into southeastern Michigan. This interpretation is supported by Fullertons' reconstruction of ice-flow patterns for the region and by Dreimanis and Goldthwaits' (1973) contention that "the southwestern portion of the so-called Erie Lobe" was actually composed of ice derived from several basins. The reconstruction shown in figure 5 also agrees well with the regional ice-flow reconstruction suggested by Shilts (1980) for the Laurentide ice sheet north of the Great Lakes area. This regional flow pattern appears, however, to have been localy diverted by the basins of the Great Lakes.

A comparison of the classification of heavy mineral assemblages of tills in southeastern Michigan with that of Gwyns' (1971) for tills along the southern shore of Lake Huron suggests a shift in provenance from the Province boundary area to the Superior east area for tills of the Huron ice lobe (Figure 5). This would imply that a major shift in ice flow direction occurred during the retreat of the Huron Lobe from southeastern Michigan into the Huron basin. This shift from a southwestward flow to a southward flow has also been suggested for the Huron Lobe by Dreimanis et al. (1957).

## CONCLUSIONS

The conclusions of this study are as follows:

1) The Michigan, Saginaw, and Huron-Erie lobes in Michigan can be differentiated on the basis of their heavy mineral assemblages. Michigan Lobe tills are characterized by high percentages of epidote and opaque minerals and low percentages of clinopyroxene, and low weight percent of heavy minerals. Huron-Erie Lobe tills are characterized by high weight percent heavy minerals as well as high percentages of hornblende and clinopyroxene and low percentages of epidote and opaque minerals. Tills of the Saginaw Lobe generally have heavy mineral percentages intermediate between those of the Michigan and Erie lobes except for garnet which tends to be low.

2) The heavy mineral assemblage of tills from each of the

three lobes can be associated with distinct provenance areas on the Canadian Shield. The assemblage from Huron-Erie Lobe tills is associated with a provenance area just north of Georgian Bay. The heavy mineral assemblage from tills of the Saginaw Lobe is associated with two provenance areas, one area just north of Georgian Bay and another area on the north shore of Lake Huron. The assemblage from tills of the Michigan Lobe is associated with a provenance area along the northeast shore of Lake Huron.

3) The association of heavy minerals assemblages within Michigan tills with provenance areas on the Canadian shield indicates a general northeast to southwest ice-flow pattern into the Great Lakes region during the late Wisccosinan that was locally modified by the lake basins.

4) Association of heavy mineral assemblages in southeastern Michigan with a provenance area just north of Georgian Bay indicates that during the late Wisconsian the Huron-Erie Lobe in southeastern Michigan was derived from the Huron basin and not from the Erie basin as has been previously suggested.

5) Comparison of heavy mineral assemblages from tills in southeastern Michigan with those from younger tills just south of Lake Huron indicates that these deposits are associated with two diffent provenance areas. This would

suggest that a significant shift occurred in ice flow direction during the final retreat of ice from southeastern Michigan.

I suggest that multivariant analysis of heavy mineral assemblages could also be applied to solving ice-flow reconstructions in other areas. For example, the origin of the Decatur sublobe in east-central Illinois (Figure 2) has been debated. Johnson et al. (1971) and Fullerton (1980) agree with Leverett and Taylor that this sublobe was associated with the Michigan Lobe. In constrast, Dreimanis and Goldthwait (1973) have suggested that both the Saginaw and Huron Lobes contributed ice to the Decatur sublobe while Willman and Frye (1970; 1973) have proposed an Erie lobe origin.

# APPENDICIES

# APPENDIX A

# APPENDIX A

## METHODOLOGY

Collection of Samples: Samples of till were collected from gravel pits, road cuts, and natural exposures. After the first several inches of the exposure were scraped off, dilute hydrocloric acid was poured on the till. If it effervesced, the till was assumed to be unleached and a sample was taken. As the till was shoveled from the oucrop into a zip-loc storage bag, care was taken to avoid highly weathered cobbles and pebbles which might crumble and contaminate the heavy mineral assemblage of the till.

Laboratory Procedure: Approximately 350 to 400 grams of till from each sample was gently crushed using a mortar and pestle. The sample was then sieved to remove cobbles and pebbles and then soaked for 12 hours in a solution of distilled water and Calgon (5 grams of Calgon per litre of water) to defloculate the clays. At this point the sample was wet sieved though a .250 mm sieve which was nested on top of a .125 mm sieve. The fine sand which was caught on the lower sieve was soaked in 20 percent HCl for 12 hours to remove cabonates. The sample was then washed, resieved and dried in an oven.

Heavy minerals were separated from the fine sand fraction of the till by gravity settling in glass separartory funnels. The procedure was as follows:

1) A 500 ml separtory funnel, placed inside a fume cabinet, was filled with 100 ml of tetrabromoethane.

2) The fine sand fraction was poured into the separatory funnel and then agitated thoroughly with a glass rod.

3) After 10 minutes the mixture was stirred again without disturbing the accumulation of heavy minerals that had settled above the valve.

After another 10 minutes, the following procedure was used to drain the separatory funnel:

4) A vacuum funnel apparatus with a #1 Whatman filter paper was placed under the separatory funnel. With the vacuum pump operating, the valve of the separatory funnel was turned to the open position and then closed after all the heavy minerals that had accumulated over the valve had been extracted.

5) Once the tetrabromoethane had drained through the filter paper the funnel was removed and the filtered tetrabromoethane was retuned to its original container.

6) The heavy minerals were washed thououghly with acetone.

7) Steps four through six were repeated for the light mineral fraction.

Magnetic grains were separated from the heavy minerals using a hand magnet covered with a piece of waxed paper. The heavy minerals were then mounted on glass petrographic microscope slide with Ladd High Mount mounting medium.

# APPENDIX B

## APPENDIX B

### Heavy Mineral Data from Individual Samples

| smpl | WHTH | MGNT | HBLD | TRML | OPRX | CPRX | GRNT | EPDT | RUTL | SPHN | ZRCN | TMLN | OPQU | OTHR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | 1.41 | 4.95 | 28.79 | 0.99 | 0.60 | 2.78 | 10.91 | 4.17 | 0.60 | 0.99 | 0.00 | 0.60 | 17.87 | 31.55 |
| 8 | 1.10 | 7.41 | 34.16 | 0.21 | 1.23 | 4.53 | 10.49 | 10.70 | 0.21 | 0.21 | 0.21 | 0.82 | 17.08 | 20.16 |
| 4 | 1.23 | 10.53 | 33.19 | 0.84 | 0.84 | 3.79 | 15.24 | 8.56 | 0.21 | 0.63 | 0.21 | 0.42 | 23.38 | 12.53 |
| 10 | 1.19 | 6.25 | 42.83 | 0.82 | 1.43 | 5.33 | 6.35 | 7.79 | 0.41 | 0.61 | 0.20 | 0.41 | 11.89 | 21.93 |
| 1 | 0.77 | 3.33 | 24.41 | 1.07 | 1.29 | 3.64 | 4.28 | 6.21 | 0.00 | 0.86 | 0.00 | 0.43 | 36.62 | 21.20 |
| 11 | 1.31 | 10.20 | 28.85 | 0.87 | 0.65 | 1.52 | 10.85 | 10.41 | 0.00 | 0.22 | 0.22 | 0.00 | 23.43 | 22.99 |
| 14 | 1.25 | 6.12 | 34.19 | 0.42 | 1.08 | 1.94 | 5.81 | 7.74 | 0.22 | 0.65 | 0.65 | 0.22 | 16.34 | 30.75 |
| 19 | 1.80 | 5.88 | 32.53 | 2.02 | 2.83 | 5.05 | 6.87 | 3.43 | 0.00 | 0.20 | 0.00 | 0.81 | 13.74 | 32.53 |
| 18 | 1.49 | 0.00 | 35.04 | 1.07 | 1.70 | 4.70 | 9.19 | 7.48 | 0.00 | 0.64 | 0.00 | 1.07 | 8.97 | 30.13 |
| 17 | 1.66 | 4.76 | 33.27 | 0.61 | 2.84 | 5.27 | 7.91 | 7.30 | 0.20 | 1.22 | 0.20 | 0.41 | 13.18 | 27.59 |
| 16 | 1.52 | 4.35 | 39.91 | 1.08 | 1.95 | 7.81 | 4.77 | 5.86 | 0.22 | 0.87 | 0.00 | 0.22 | 8.99 | 28.42 |
| 12 | 1.84 | 5.80 | 33.95 | 1.04 | 2.28 | 3.73 | 9.73 | 4.35 | 0.21 | 1.24 | 0.21 | 0.62 | 16.56 | 25.88 |
| 15 | 1.52 | 5.79 | 29.73 | 0.42 | 3.75 | 3.12 | 6.03 | 5.61 | 0.00 | 0.21 | 0.21 | 0.83 | 11.23 | 38.88 |
| 3 | 1.31 | 8.70 | 32.90 | 1.31 | 2.70 | 4.58 | 6.75 | 4.58 | 0.22 | 0.22 | 0.00 | 0.65 | 12.42 | 32.68 |
| 26 | 2.34 | 7.69 | 40.17 | 4.23 | 3.81 | 10.99 | 10.99 | 2.75 | 0.63 | 1.90 | 0.00 | 0.00 | 5.92 | 18.60 |
| 24 | 3.06 | 11.22 | 37.53 | 1.24 | 3.51 | 5.77 | 12.78 | 5.36 | 0.41 | 1.03 | 0.00 | 0.00 | 8.45 | 23.92 |
| 23 | 1.44 | 7.69 | 36.19 | 0.43 | 2.25 | 5.78 | 5.35 | 6.42 | 0.00 | 0.64 | 0.21 | 1.93 | 8.14 | 32.55 |
| 21 | 2.79 | 2.86 | 41.35 | 1.27 | 3.80 | 5.91 | 10.97 | 3.16 | 0.42 | 0.00 | 0.00 | 0.63 | 4.43 | 28.06 |
| 22 | 2.30 | 6.82 | 42.77 | 0.21 | 3.57 | 9.85 | 8.39 | 5.24 | 0.00 | 0.42 | 0.00 | 0.42 | 4.82 | 24.32 |
| 20 | 2.83 | 4.72 | 36.94 | 1.49 | 3.18 | 9.13 | 11.68 | 3.18 | 0.21 | 1.06 | 0.00 | 0.00 | 7.64 | 25.48 |
| 27 | 2.21 | 2.37 | 46.87 | 0.59 | 1.18 | 8.81 | 8.79 | 5.47 | 0.00 | 0.39 | 0.00 | 0.39 | 4.10 | 24.41 |
| 31 | 1.78 | 3.37 | 44.96 | 0.21 | 1.26 | 4.41 | 8.19 | 7.35 | 0.00 | 0.21 | 0.00 | 1.05 | 5.04 | 27.31 |
| 30 | 2.02 | 4.55 | 41.16 | 0.21 | 1.26 | 5.20 | 9.98 | 7.28 | 0.42 | 0.62 | 0.42 | 0.83 | 6.24 | 26.40 |
| 29 | 1.95 | 4.05 | 44.29 | 0.60 | 1.00 | 7.62 | 6.81 | 6.61 | 0.00 | 0.40 | 0.00 | 1.60 | 6.21 | 24.85 |
| 28 | 3.97 | 4.14 | 41.63 | 0.00 | 1.68 | 10.64 | 14.02 | 5.23 | 0.21 | 1.46 | 0.21 | 0.84 | 6.90 | 17.36 |
| 25 | 3.66 | 3.15 | 55.85 | 0.00 | 0.83 | 5.95 | 5.95 | 6.78 | 0.62 | 2.46 | 0.00 | 0.21 | 4.52 | 16.84 |
| 5 | 0.64 | 0.00 | 40.04 | 0.00 | 0.86 | 3.46 | 11.47 | 8.66 | 0.00 | 0.22 | 0.00 | 0.87 | 17.32 | 17.10 |
| 2 | 0.47 | 10.53 | 42.22 | 0.64 | 1.71 | 4.69 | 8.32 | 8.74 | 0.43 | 0.21 | 0.00 | 1.28 | 16.42 | 15.35 |
| 6 | 0.74 | 3.75 | 29.69 | 1.03 | 1.44 | 4.33 | 7.22 | 6.19 | 0.41 | 0.21 | 0.41 | 0.21 | 24.95 | 23.92 |
| 7 | 0.49 | 5.26 | 35.39 | 0.41 | 1.24 | 3.70 | 8.23 | 7.61 | 0.21 | 0.41 | 0.00 | 1.65 | 19.96 | 21.19 |
| 13 | 0.63 | 3.33 | 38.21 | 0.44 | 1.97 | 3.93 | 6.99 | 8.30 | 0.22 | 0.44 | 0.00 | 1.09 | 12.88 | 25.55 |

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