PRE-WOODFORDIAN DRIFTS OF NORTH-CENTRAL WISCONSIN

BY

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Abstract

The Border Drift of parts of Lincoln, Langlade and Marathon Counties, north-central Wisconsin is comprised of two till units, distinguished from each other and adjacent late Woodfordian deposits on the basis of pebble lithologies, ice flow directions, and semi-quantitative clay mineralogy. The two units are informally named the Merrill and Wausau drifts (LaBerge, 1971). Stratigraphically, the Merrill drift overlies the Wausau drift, but the distribution of the older unit beneath the Merrill drift is patchy, and in most exposures only the younger unit is recognized. Till clast fabrics suggest a SSE ice flow direction for the Merrill till. Ice flow directions for the Wausau drift are ambiguous. Boulder trains indicate an easterly flow direction, while the only till fabric indicates an east to south-southeast flow direction. The degree of weathering of the clay fraction of the Merrill till indicates that it underwent a period of sub-aerial weathering before deposition of the relatively unweathered late Woodfordian drifts. The Wausau drift shows a greater degree of weathering than the Merrill drift and represents an earlier, separate ice advance. Black (1959) suggests a late Altonian age for the single Border Drift of west-central Wisconsin which may correlate with the Merrill till.

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF ILLUSTRATIONS

TABLE OF ILLUSTRATIONS (continued)

Introduction

A major glacial feature of the mid-western United States is the prominent Woodfordian end moraine complex extending from New York through Minnesota. In Wisconsin, correlation of the glacial drift outside the Woodfordian moraines is difficult. Topography is subdued, the drift is often thin and draped over bedrock and no end moraines mark positions of former ice margins. In north-central Wisconsin this extra-morainal drift is termed the Border Drift (Hole, 1943).

The area of the Border Drift discussed in this paper lies in front and south of the marked re-entrant of the Woodfordian end moraines in Lincoln, Langlade, and Marathon Counties, Wisconsin (Fig. 1). The drift is usually less than five or six meters thick, thinning toward the boundary of the "Driftless Area" to the southwest where it disappears with no obvious topographic discontinuity (Hole, 1943). It is primarily ground moraine, with outwash filling the major stream valleys. Topography is controlled by bedrock relief, and major glacial landforms are rare.

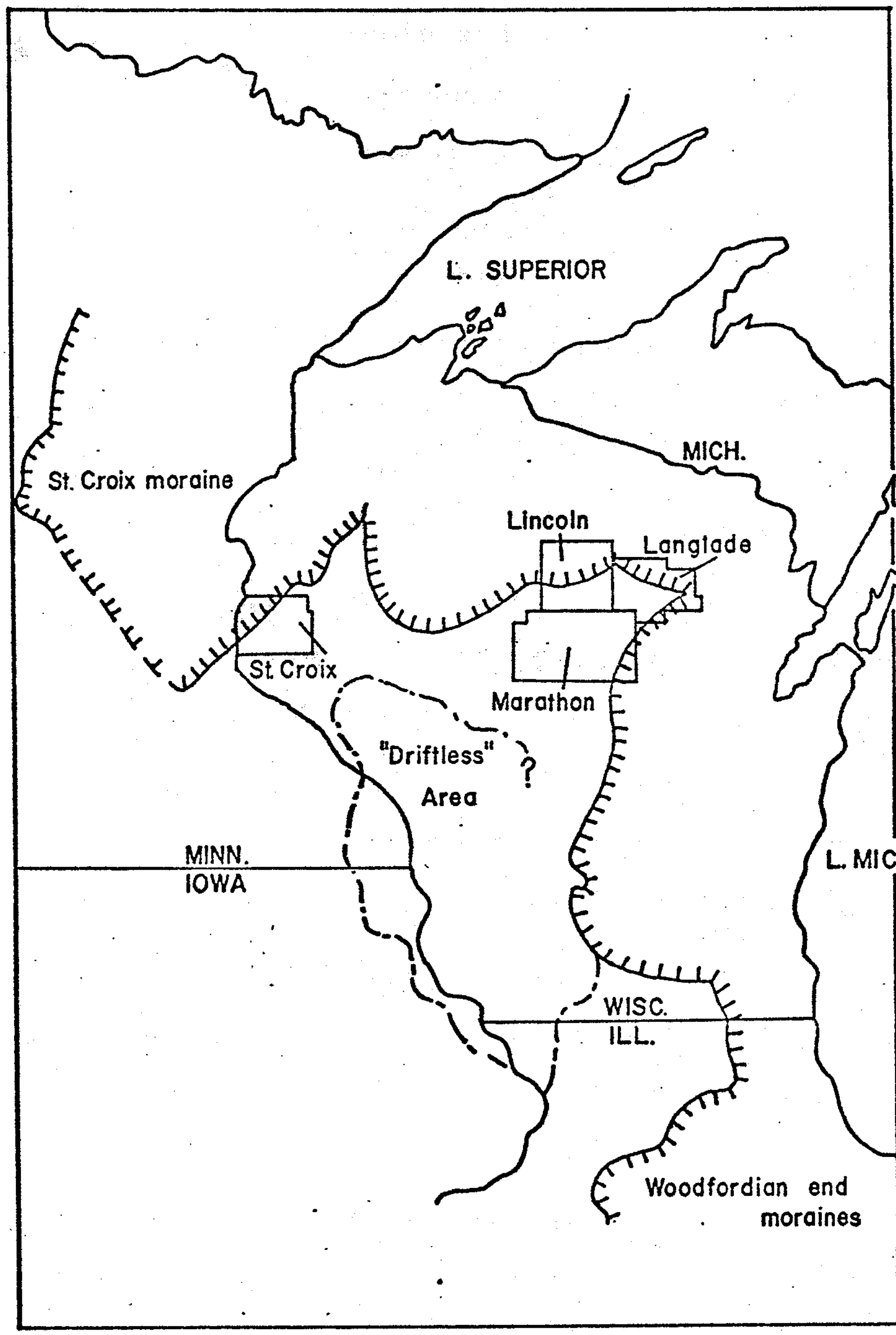


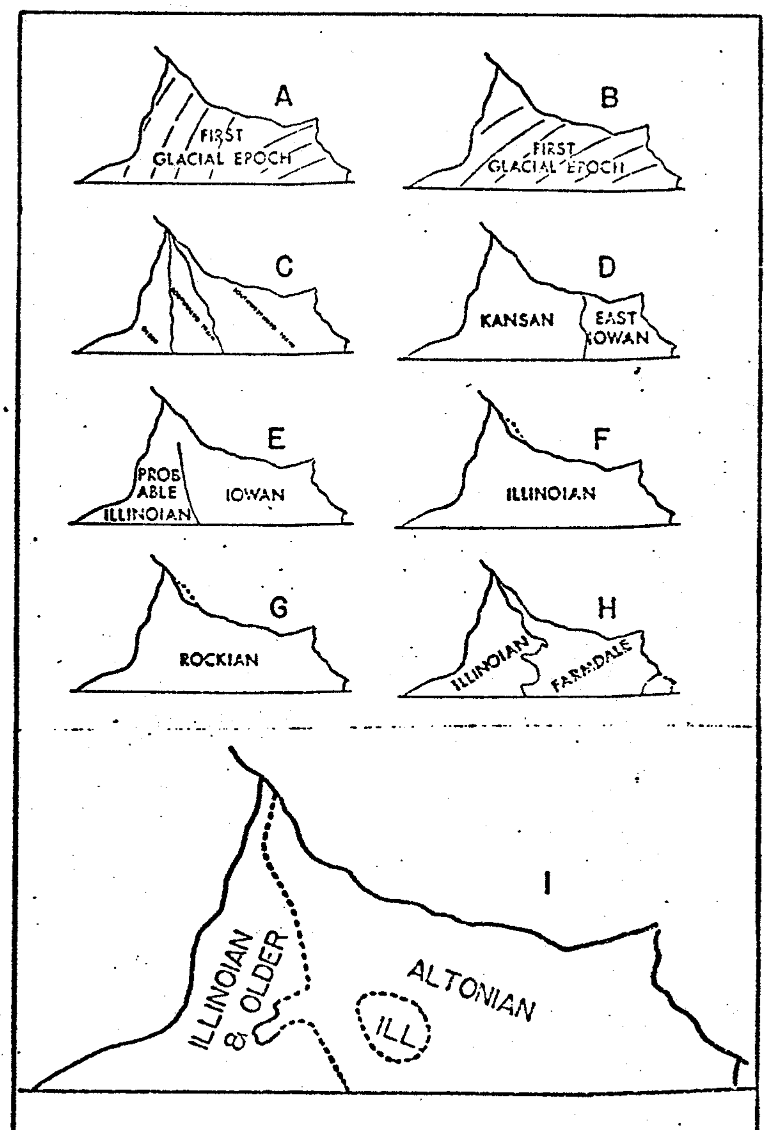
Figure 1. Woodfordian end moraines of Illinois, Wisconsin, and Minnesota.

Previous Investigations

Southeastern Wisconsin, Illinois, and Minnesota

In northwestern Illinois and southeastern Wisconsin tills of several ages are exposed at the surface between the prominent late Woodfordian end moraines and the "Driftless Area". This area has been studied by many investigators, and their work is summarized in Figures 2A and 2B. The more recent interpretations agree that there are drifts of at least two different ages, early Wisconsin and Illinoian, exposed at the surface beyond the late Woodfordian moraines.

Leighton and Brophy (1966) mapped four drifts beyond the West Chicago moraine (Cary), correlating them with the Tazewell, Iowan, and Farmdale Wisconsin sub-stages, and the Illinoian stage. Kempton and Hackett (1968) studied the subsurface stratigraphy of northeastern Illinois and divided the early Wisconsin Winnebago drift into three units of early, middle, and late Altonian age. The uppermost Altonian is bracketed by two organic silts, the older Plano silt and the younger Robein silt. Radiocarbon dates give a range of 41,000 ± 1,500 years BP (Grn-4408) to 32,600 ± 520 years BP (Grn-4468) for the Plano silt, and greater than 27,850 years BP to 20,000 ± 400 years BP (I-2519) for the Robein silt (Willman and Frye, 1970). In northwestern Illinois, Frye, et. al., (1969) distinguish eight drifts at the surface (Fig. 3). The Altonian sub-stage is represented by the Argyle

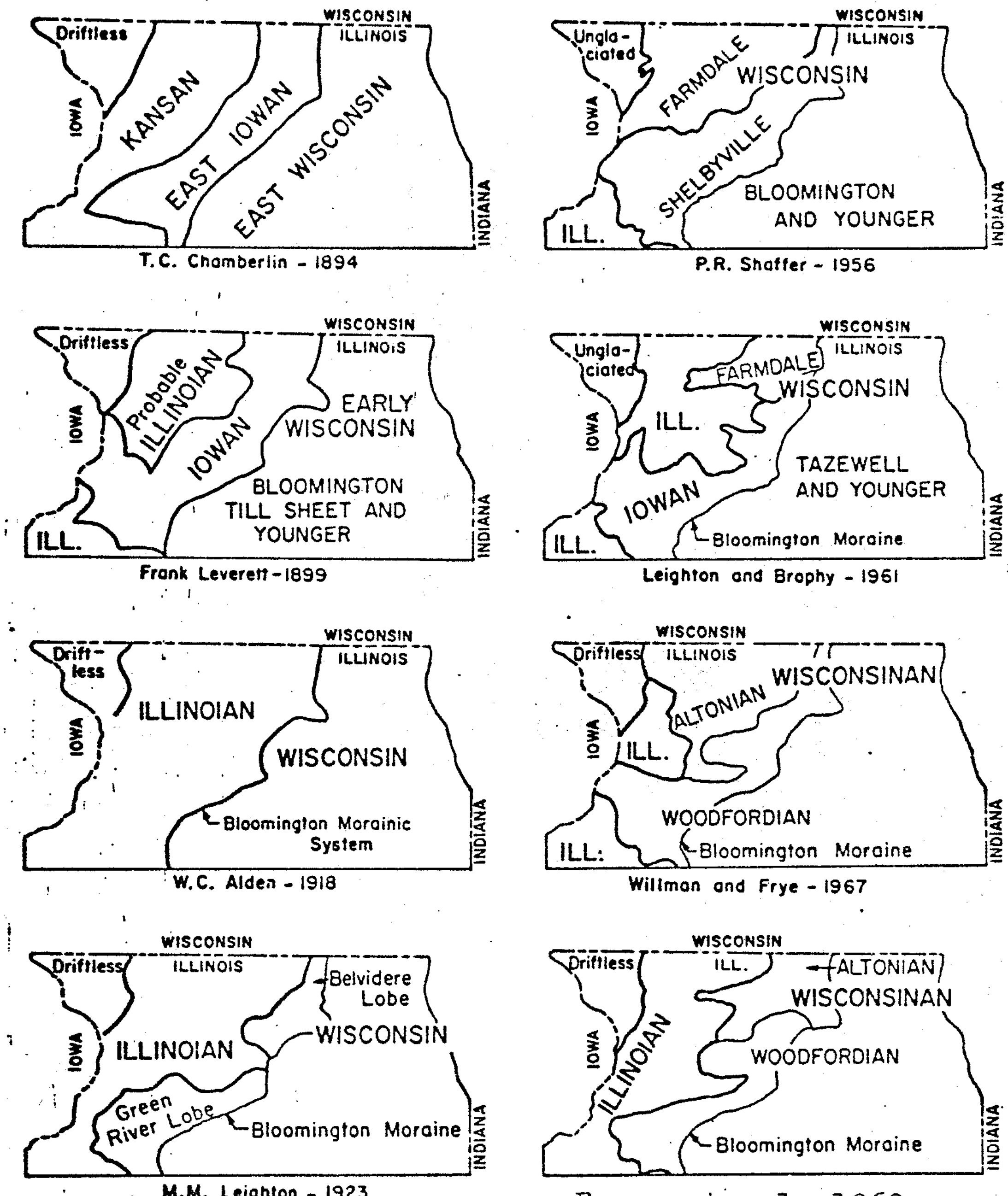


A. Chamberlin(1877) E. Leverett(1899)
B. Chamberlin(1883) F. Alden(1918)
C. Buell(1895) G. Black(1962)
D. Chamberlin(1894) H. Leighton & Brophy(1966)
I. Bleur(1971)

Figure 2A. Generalized maps showing major changes in previous mapping and classification of the glacial drifts of southeastern Wisconsin.

(from Bleuer, 1971)

GLACIAL TILLS OF NORTHWESTERN ILLINOIS



Frye, et. al.-1969

Figure 2B. Generalized maps showing major changes in previous mapping and classification of the glacial drift of northeastern Illinois.

(from Frye,et. al., 1969)

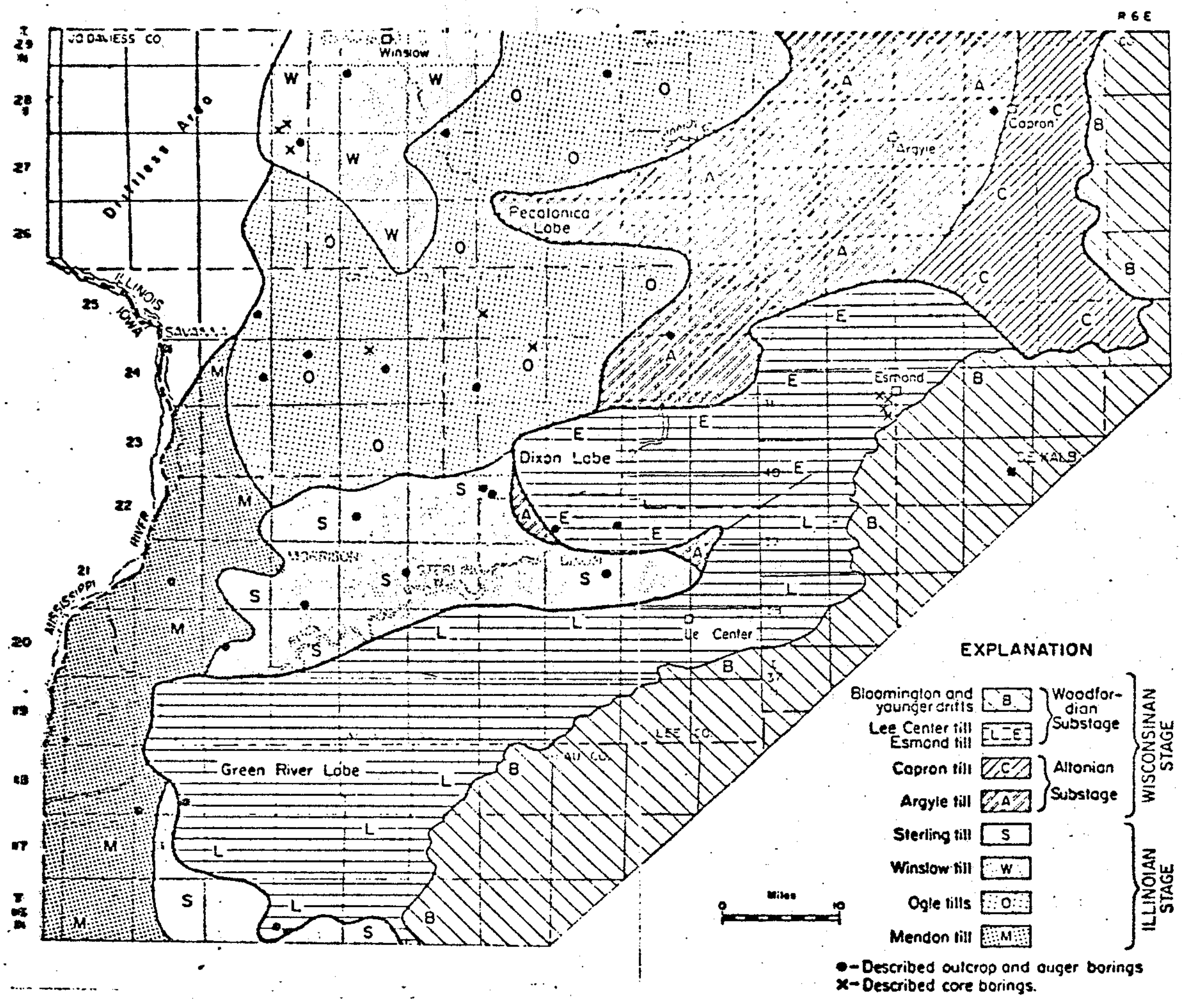


Figure 3. Glacial drifts of northeastern Illinois according to Frye, et. al., (1969).

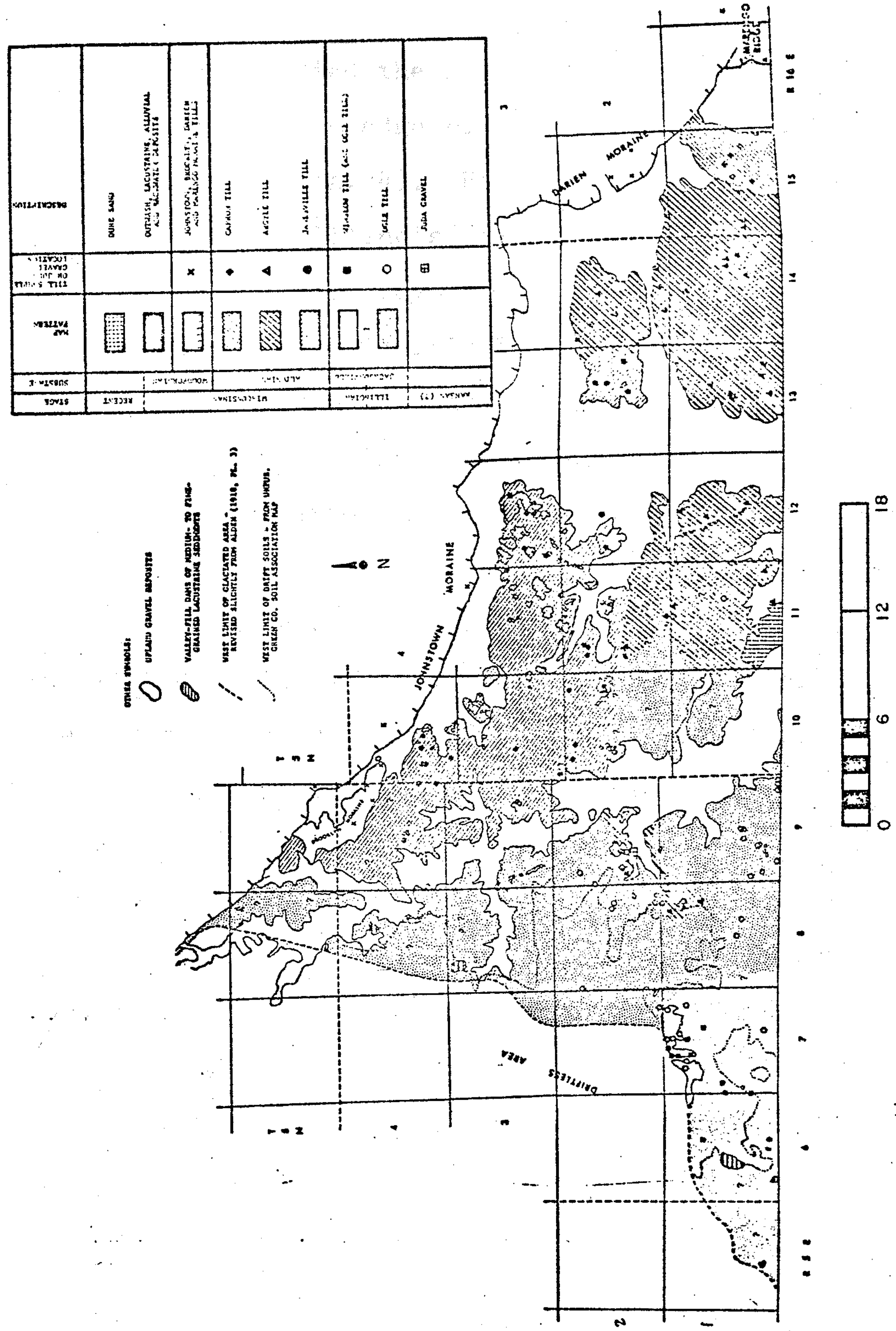


Figure 4. Glacial drifts of southeastern Wisconsin according to Bleuer (1971).

and Capron tills, and the Esmond and Lee Center tills are early Woodfordian in age.

Bleuer (1971) studied the area between the Johnstown and Darien moraines and the edge of the "Driftless Area" in southeastern Wisconsin (Fig. 4). He maps two Altonian tills, the Argyle and Capron of Illinois, and an earlier Altonian drift, the Janesville till. Beyond the Altonian border are the Winslow and Ogle tills of Illinoian age, and a small patch of older gravels, tentatively assigned a Kansan age. Between the Woodfordian terminal moraines and the "Driftless Area" he distinguishes seven units recording five major ice advances from the east.

In southeast Minnesota little information is available on the age of the drift. The St. Croix moraine is Woodfordian age (Wright and Watts, 1969). Ruhe (1969) maps early Woodfordian (Tazewell) drift at the edge of the "Driftless Area" near the Minnesota-Iowa border.

In west-central Wisconsin, Black (1959) distinguishes both early Woodfordian (Tazewell) and Altonian drifts beyond the late Woodfordian (Cary) end moraine. Two radiocarbon dates from west-central Wisconsin are reported by Black and Rubin (1968). In St. Croix County, till with erratic wood dated at 29,000 ± 1,000 years BP (W-747) and 30,650 ± 1,650 years BP, also includes peat from pre-glacial ponds dated at greater than 45,000 years BP (W-1788). The wood is interpreted by Black to represent a spruce forest overrun by advancing ice. Black's opinion is that the dates from St.

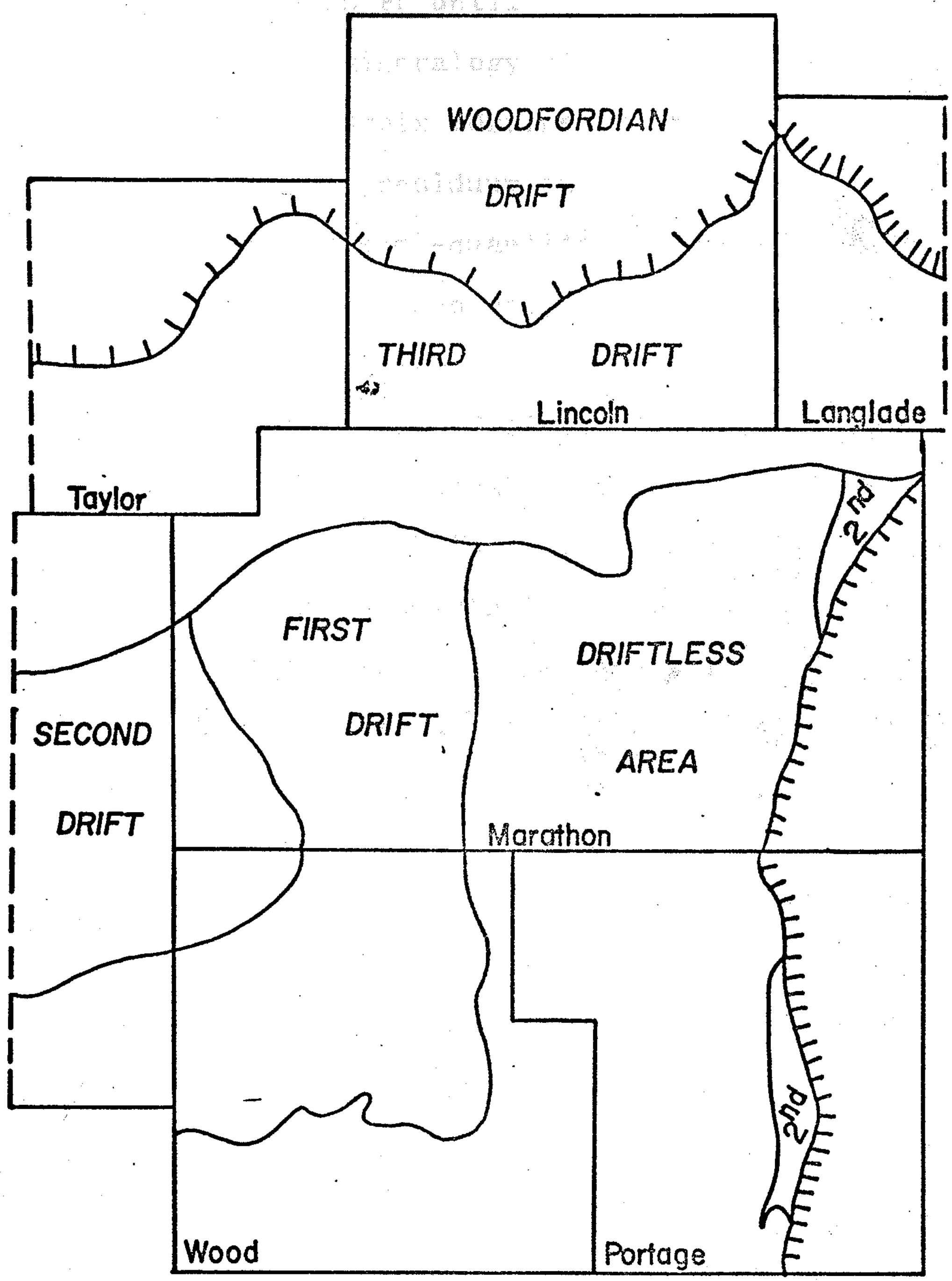


Figure 5. Glacial drifts of north-central Wisconsin according to Weidman (1907).

Croix county imply west-central Wisconsin was ice-free from greater than 45,000 years BP until 31,000 years BP. Akers (1961) studied the clay mineralogy of the tills and bedrock residuum beyond the St. Croix moraine in west-central Wisconsin and of the bedrock residuum in the northwestern "Driftless Area". Using semi-quantitative techniques he was unable to distinguish more than one Border Drift beyond the St. Croix moraine.

At the southern border of Wisconsin, glacial deposits outside the late Woodfordian terminal moraines represent five ice advances of Wisconsin, Illinoian, and possibly Kansan ages. At the Wisconsin-Minnesota border, only two ice advances are suggested by two Wisconsin age tills. Either the older units are buried beneath late Wisconsin age drifts in northern Wisconsin, or the glacial histories of the two regions differ greatly.

North-central Wisconsin

Relying primarily on topography, T.C. Chamberlin (1882) recognized the difference between the more irregular topography and higher relief of the Woodfordian drift and the low relief of the drift beyond the moraines. He states (1882, p. 720) that the topography outside the moraines is due to relatively thin drift draped over the underlying bedrock topography.

Weidman (1907) divides the pre-Woodfordian drift into three units: the First, Second, and Third drifts (Fig. 5).

As criteria he cites differences in degree of weathering of clasts and till, maturity of topography and drainage, consolidation of the till units, and relative preservation of glacial features. The Third drift, which is equivalent to most of the Border Drift within the study area, is described as more like the Woodfordian drifts than the older drifts in degree of erosion, but is more eroded than the Woodfordian deposits. As to the degree of weathering of the Third drift he states (Weidman, 1907, p. 485), "On the whole, this drift appears to be about as fresh and unconsolidated as the Wisconsin" (Woodfordian). The Second drift is distinguished from the Third in the greater degree of weathering of clasts, and its yellow-brown color, compared to the red-brown color of the Third drift. Weidman considered the area of very thin or no till in the Wisconsin River lowland in Marathon County to be driftless due to his failure to recognize erratics or other glacial deposits in this region. The First drift is assigned a pre-Kansan age, the Second Kansan, and the Third an early Wisconsin (Iowan) age (Weidman, 1913).

Thwaites (1943), using soil profiles as a criterion, fails to distinguish the boundaries between Weidman's three drifts. He also disagrees with Weidman's opinion that the Wisconsin River valley in Marathon County is driftless. He notes the soils in the area are often developed on bedrock or loess, but that the large number of erratics indicates the area was glaciated. He suggests the possibility of drifts of two ages in Marathon County, the patchy drift of Weidman's driftless area being older than the areas surrounding it. Thwaites feels the extra-morainic drifts were deposited by two nearly synchronous ice lobes from the north and east. To Thwaites, the moderate amount of erosion suggests an Iowan age for the drift. The irregular southern border of the extra-morainic drift is attributed to post-glacial erosion rather than glacial deposition. Admitting that the contact between the morainal and extra-morainal drifts had never been observed, Thwaites states it "is evident...that the time between the two was at least long enough for all residual ice to melt and that there is a distinct difference in amount of weathering under comparable topographic conditions" (Thwaites, 1943, p. 120).

Hole (1943) discusses in great detail many of the arguments for and against multiple Border drifts and the age of the drift. In discussing the number of drifts, Hole is impressed by six observations:

1. The thickening of the drift is gradual from south to north as could have been produced by the retreat of a single ice mass.
2. There are no terminal moraines.
3. No till has been found beneath buried soils.
4. Most erratics are equally unweathered throughout the area.
5. The silty texture of the southern portions of the Border Drift may be due to local material encountered by the ice, rather than great age.

6. The heterogeneity of the drift does not give evidence of any zonal or regional discontinuities.

Hole concludes that there is little evidence for multiple drifts, and suggests that the Border Drift represents a single ice advance (Fig. 6).

Hole discusses several possibilities for the age of the drift, but does not express a strong opinion whether the drift is late Woodfordian (Cary) or older. He does state that the drift is undoubtably Wisconsin and possibly late Woodfordian (Cary), suggesting there may not be a great difference in age between the Woodfordian units and the Border Drift. Arguments (Hole, 1943) for early Woodfordian (Iowan, Tazewell) and late Woodfordian (Cary) are presented below:

1. Early Woodfordian (Iowan)
   - A. The topography is similar to the early Woodfordian (Iowan) of southeast Minnesota.
   - B. The loess mantle is very similar to loess on the early Woodfordian (Iowan) of Minnesota.
   - C. Most of the erratics are undecomposed, meaning the drift is not Illinoian.
   - D. The Border Drift lies outside the late Woodfordian (Cary) moraine, hence is older than late Woodfordian (Cary).
2. Early Woodfordian (Tazewell)
   - A. Topography is controlled by bedrock and the silty composition of the drift. Topography has no relation to the age of the drift.

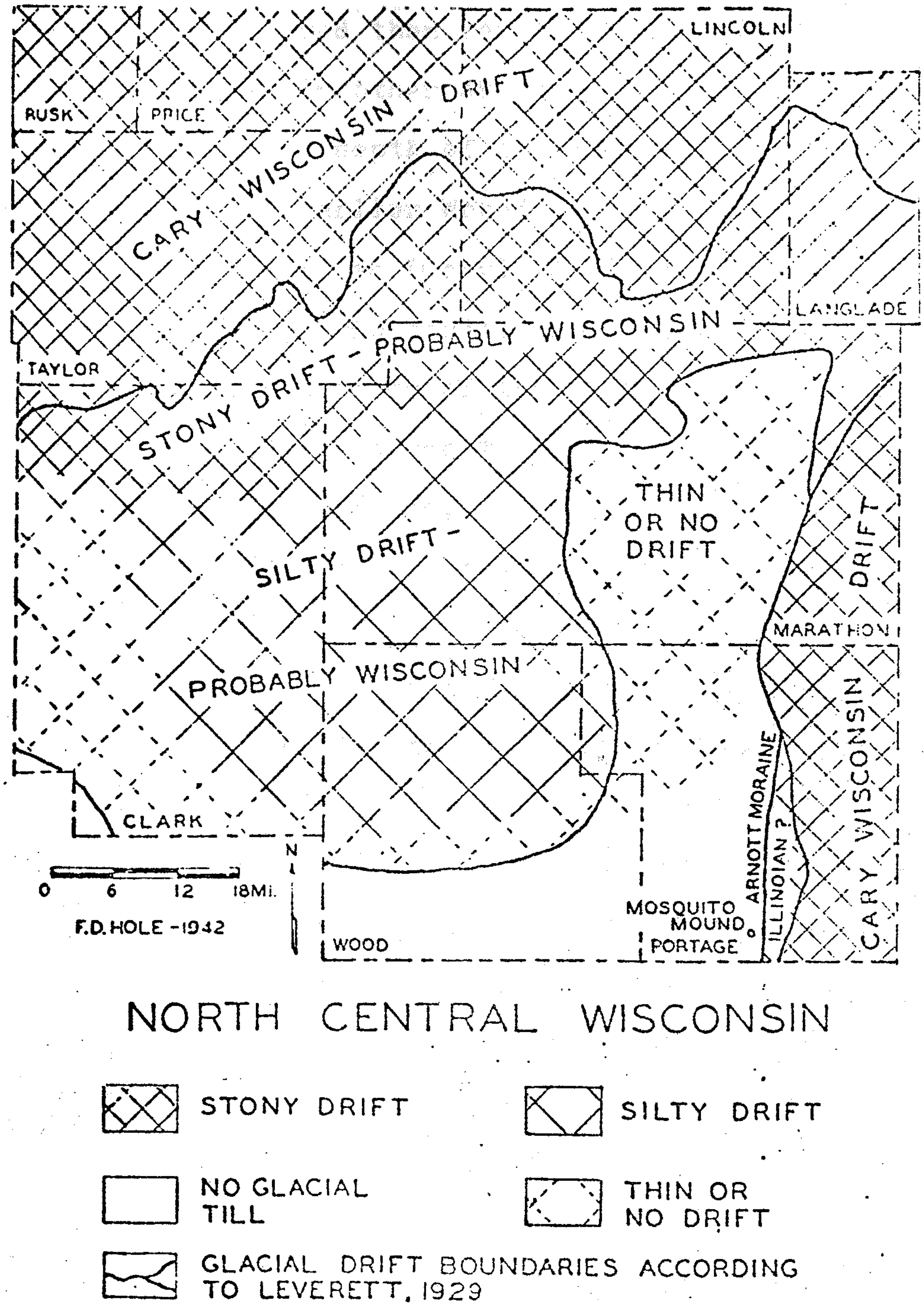


Figure 6. Glacial drifts of north-central Wisconsin according to Hole (1943).

B. The Border Drift is no more eroded or weathered than earlier Woodfordian (Tazewell) drift in other areas.

C. Average depth of leaching is not reliable to prove earlier Woodfordian (Iowan) age.

3. Late Woodfordian (Cary)

A. There is no significant, abrupt change in the character of the drift from the southern limit to the north of the late Woodfordian (Cary) moraine.

B. Most of the minerals in the drift are unweathered.

C. There is no evidence that the loess north of the moraine is younger than loess south of the moraine.

Black and Rubin (1968) report three radiocarbon dates from Walworth and Waukesha Counties in southeast Wisconsin which date a late Altonian ice advance. The deposits are in overridden outwash and sandy till. The dates of 29,000 ± 900 years BP (W-903), 30,000 ± 1,000 years BP (W-901) and 31,800 ± 1,200 years BP (W-638) agree well with dates for the Capron till, the latest Altonian till of Illinois. A radiocarbon date from west-central Wisconsin is also reported by Black and Rubin. Two samples of silty-clay pond deposits on bedrock below the single Border Drift near Marshfield, Wisconsin give dates of greater than 45,000 years BP (W-1370, Nuclear Sci. and Eng. Lab.).

Olup (1969) studied the petrology of the glacial drift in northern Marathon County, Wisconsin. His study area includes Weidman's First, Second, and Third drifts, late Woodfordian deposits, and Weidman's "driftless" area in the Wisconsin River valley. Using size distribution, qualitative clay mineralogy, pebble counts, color, and calcium carbonate equivalent content, Olup is able to distinguish only one pre-late Woodfordian till. He tentatively correlates this unit with Black's late Altonian (Rockian) ice advance, approximately 30,000 years BP (Black, 1965) of west-central Wisconsin. This unit is equivalent to both the Merrill and Wausau drifts.

LaBerge (1970, 1971) maps two drift units in Marathon and Lincoln Counties (Fig. 7). The till east of Wausau, informally named the Wausau drift, is a thin veneer over the pre-Cambrian bedrock. Cobbles in this unit have a very close correlation to the underlying bedrock. Commonly 75% or more of a rock pile is one lithology that coincides with bedrock outcrops which may be present. The presence of iron formation and algal jasper from northern Minnesota or northern Wisconsin-Michigan indicates glacial transport. Boulder trains suggest that this unit was deposited by ice flowing from the west. North of the Wausau drift in the area mapped as the Third drift by Weidman is another till unit, informally named the Merrill drift. It differs from the Wausau drift in the lack of similarity between the lithology of rockpiles and outcrops in the area. The smaller number of outcrops in the area of the

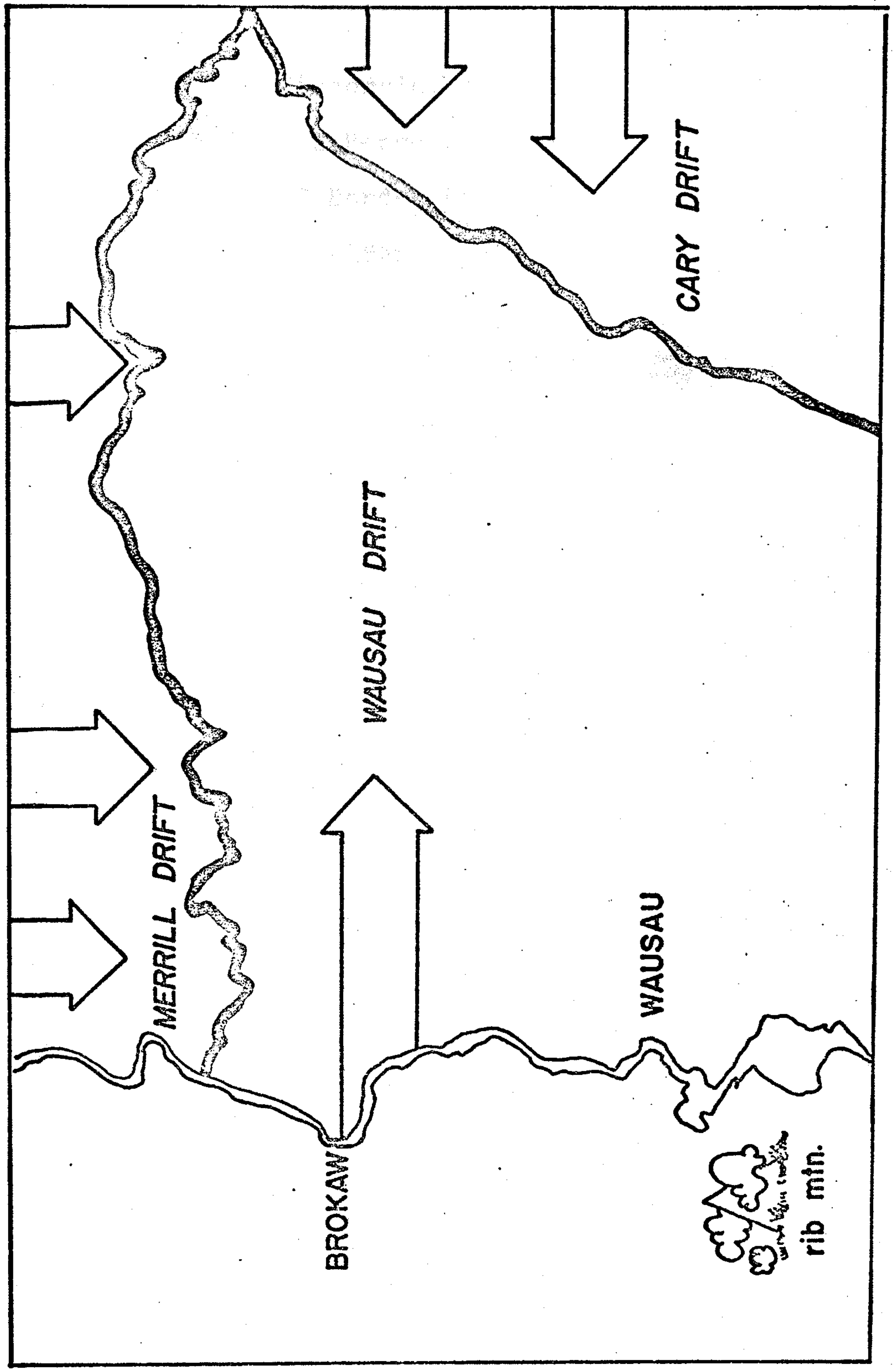


Figure 7. Glacial drifts of the Wausau, Wisconsin area according to La Berge (1971).

Merrill drift implies a greater thickness than the Wausau drift.

In north-central Wisconsin, previous work by Weidman, Thwaites, Hole, Olup, and LaBerge has been concerned with the questions of the number of Border Drifts and the age or ages of the drift. Weidman and LaBerge suggest multiple Border Drifts. However, their definitions of units differ, LaBerge's Wausau drift being equivalent to Weidman's driftless area. LaBerge states only that the Wausau is older than the Merrill drift, which in turn is older than late Woodfordian. Weidman assigns an early Wisconsin age to the Third or Merrill drift. Thwaites, Hole, and Olup see no evidence for multiple Border Drifts based on degree of weathering, homogeneity of the drift, lack of obvious topographic discontinuities, and in Olup's case, the failure of several analytical procedures to differentiate Weidman's units. Hole states that the drift is Wisconsin in age, but may not be much older than the late Woodfordian drifts. Olup correlates his single Border Drift to that of west-central Wisconsin which Black and Rubin (1968) have dated at approximately 30,000 years BP.

The present study includes data not collected by earlier workers. Till clast fabrics were measured in both the Merrill and Wausau drifts and provide new evidence for the origin of the Border Drift. Semi-quantitative clay mineralogy was the primary tool used to distinguish units and also provides indication of relative age. The data obtained support

LaBerge's conclusion that there are two units in the Border Drift, the Merrill and Wausau drifts.

Field and Laboratory Procedures

Introduction

Field and laboratory studies were conducted during the summer of 1972 and the winter of 1972-73. Field work consisted of a reconnaissance survey of the study area (Fig. 8), measurement of till fabrics, completion of thirty-six auger borings (Fig. 9), and collection of samples from outcrops and drill holes. Laboratory analysis included mechanical analysis of the sand/silt/clay composition of 19 samples of Border Drift, and determination of the qualitative and quantitative mineralogy of the less than two micron fraction by x-ray diffraction techniques of 26 Border Drift samples and 25 samples of the late Woodfordian tills.

Methods

Color

The color of the Border Drift samples was determined using a standard Munsell soil color chart. The color of each sample was determined in the laboratory under artificial light. Samples were moistened and compared to the color charts and the wet color recorded.

Mechanical Analysis

Mechanical analysis of 19 Border Drift samples was completed using standard dry sieving and Buyocos hydrometer techniques as described by Royse (1970). Appendix D presents

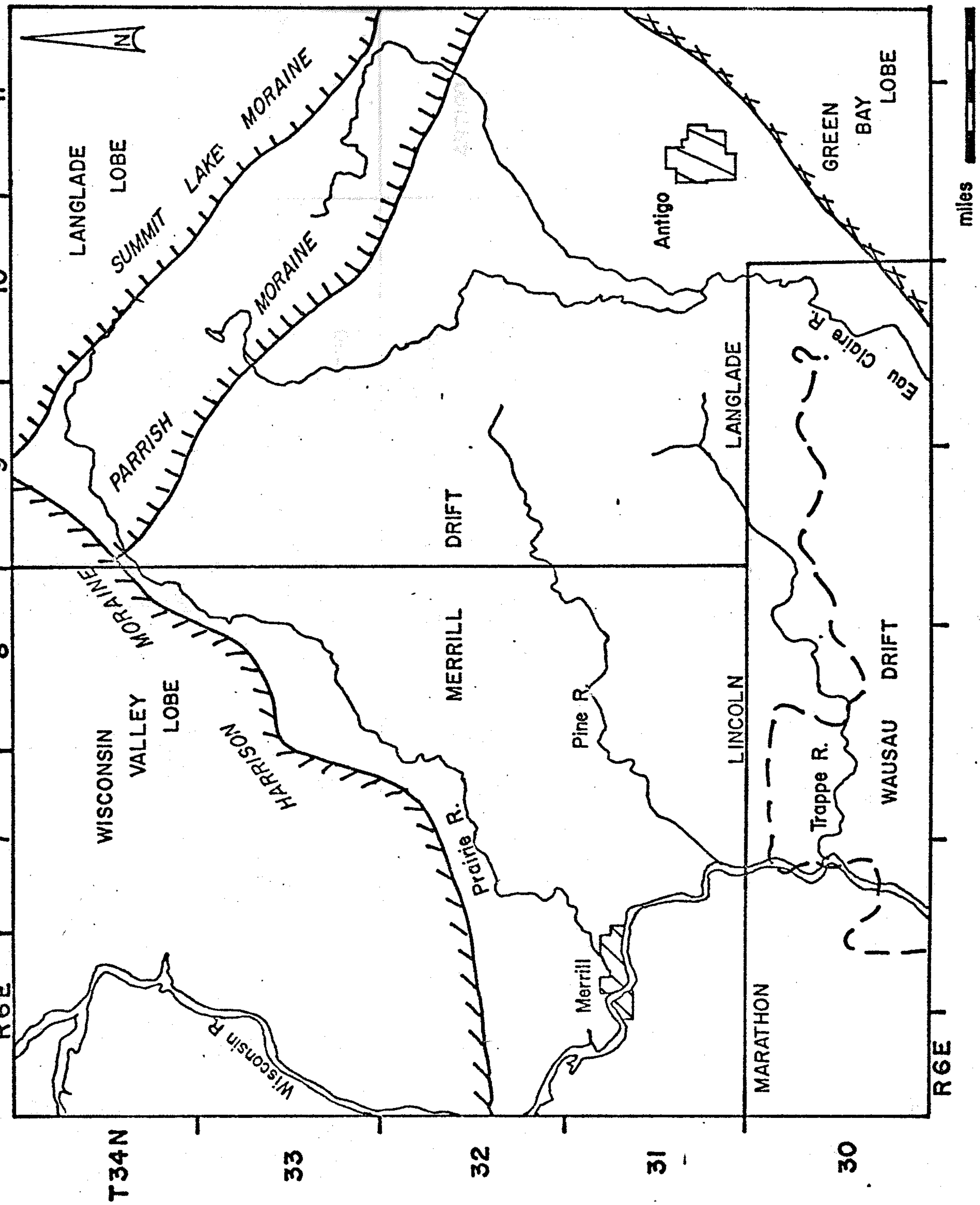


Figure 8. Glacial deposits of north-central Wisconsin.

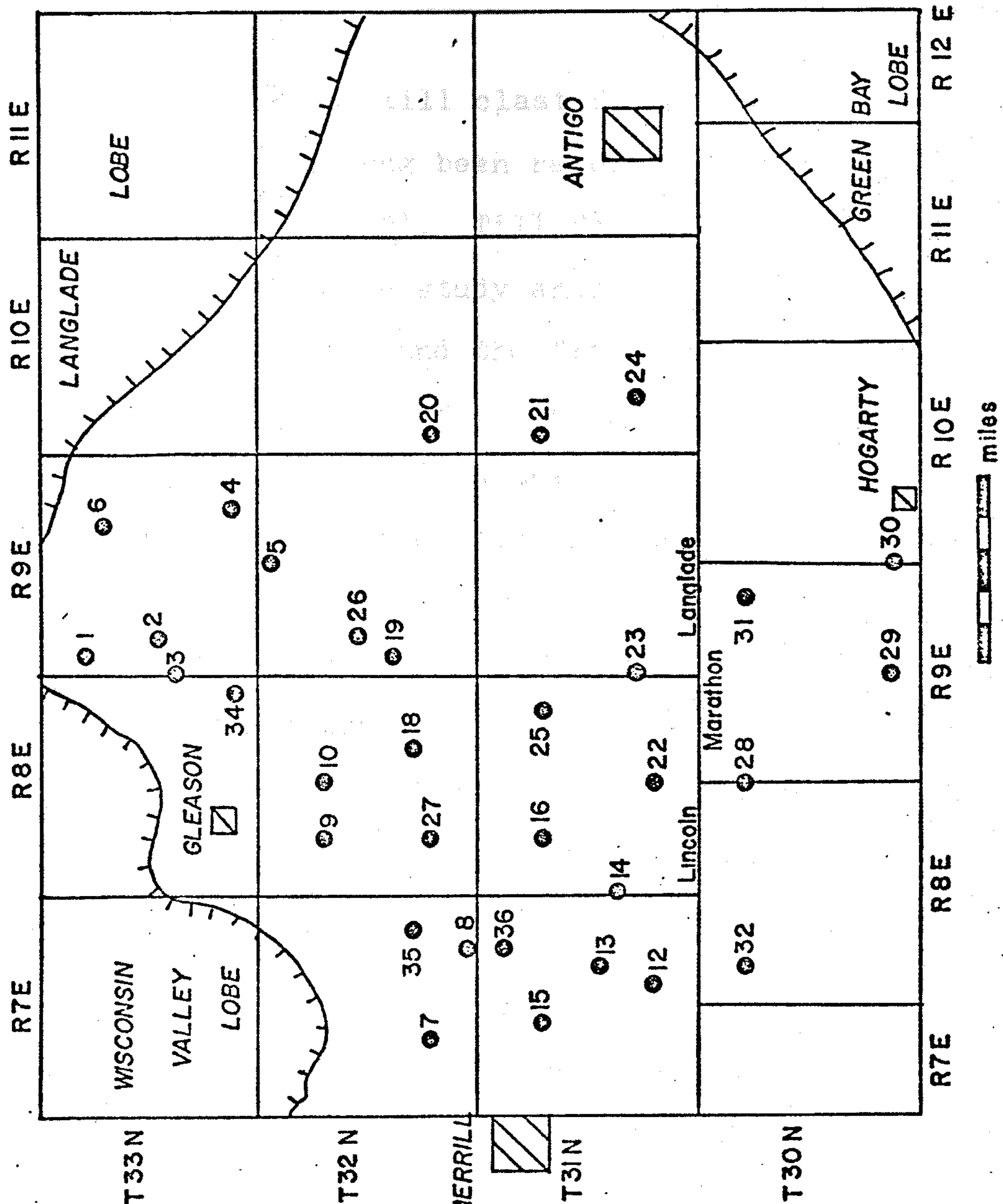


Figure 9. Location of drill sites.

a complete flow chart of the method of grain size analysis used in this study.

Till Fabrics

The usefulness of till clast fabrics for determining ice flow direction has long been recognized (Miller, 1884; Bell, 1888; Harrison, 1957). Till fabrics were measured at five localities within the study area (Fig. 10). Four of the outcrops are Merrill till and the fifth is an older unit, possibly the Wausau drift. Fifty pebbles having a long axis at least 1.5 times greater than the short axis and a minimum length of 2 cm were measured at each site. Care was taken to avoid till which may have been reoriented by slump or soil creep. The azimuth and dip of the clasts were printed as equal area stereo net plots according to Kamb's (1959) plotting method. The stereo net plots were generated by a computer program (Corbato, in Mickelson, 1971).

Clay Minerals

The less than two micron clay fraction of 26 Merrill and Wausau samples and 25 samples of the late Woodfordian tills were analyzed by x-ray diffraction. Samples were collected from outcrops and auger borings below the B horizon of the soil at depths of 2 to 25 feet. The late Woodfordian samples are all basal tills collected from outcrops, while the majority of the Border Drift samples are from auger borings (App. B).

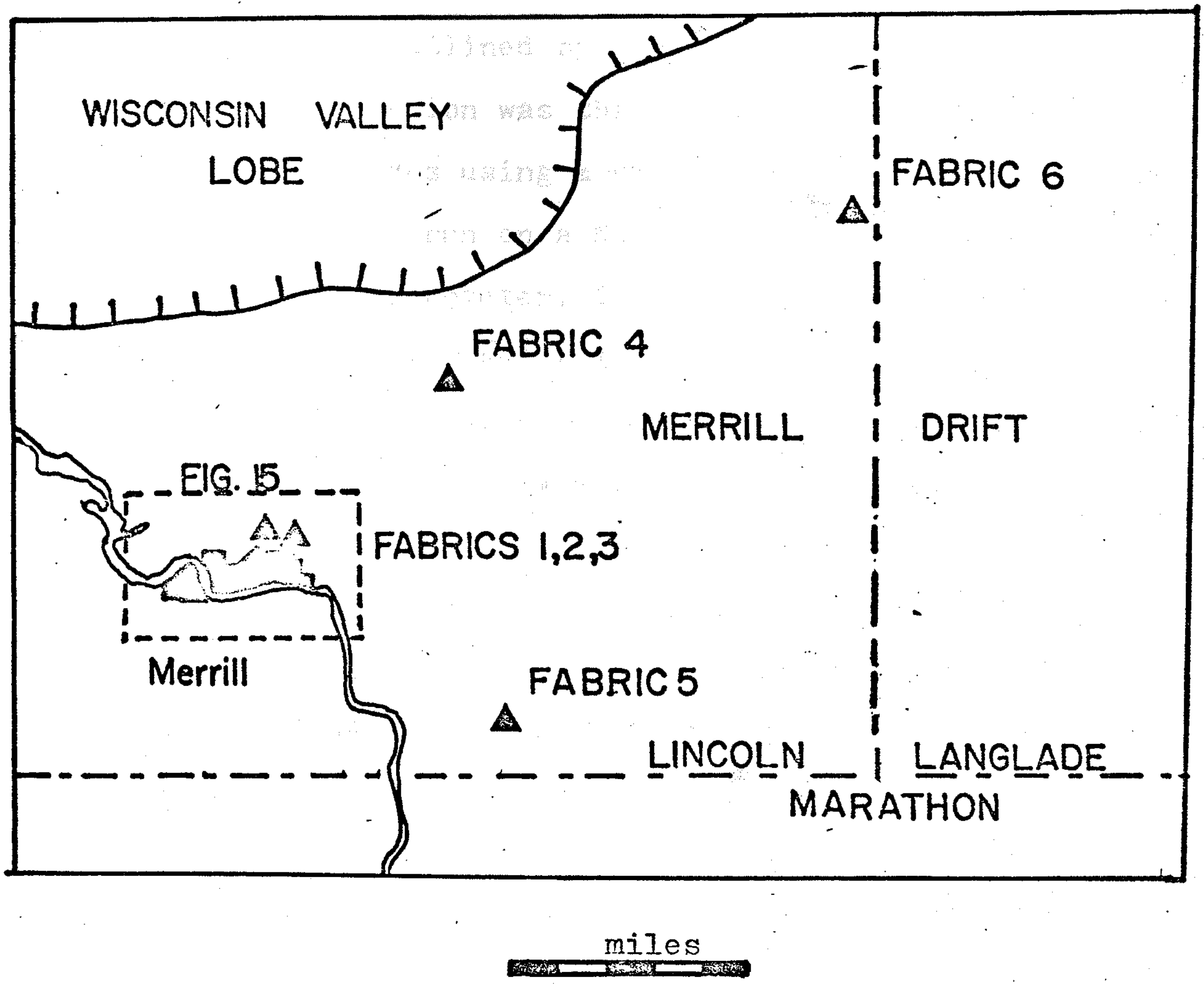


Figure 10. Till fabric sites.

The silt and clay fraction of each sample was pretreated for removal of organic matter and free iron oxides according to the method outlined by Jackson (1956). The less than two micron clay fraction was then separated by centrifuge and mounted on glass slides using a smear technique (Gibbs, 1965). All analyses were run on a Norelco x-ray diffractometer with a carbon monochrometer, 1 degree divergence slit, a scan rate of 1° 2θ/minute, and a time constant of 2.

Diffraction patterns were made under conditions of water saturated air, dry air, glycerol treatment, and after heating to 300°C and 550°C. High humidity, water saturated air conditions were obtained by bubbling a stream of air through distilled water and into the sample chamber. Dry air conditions were achieved by passing the stream of air through a column of Drierite, a commercial dessicant, and into the sample chamber. Saturated and dry air runs were allowed to equilibrate for 15 minutes before beginning an analysis. Glycerol expansion was achieved by wetting the sample with a 10% solution of glycerol in ethyl alcohol, and allowing it to equilibrate overnight in a glycerol saturated atmosphere. Heat treated samples were heated to 300°C and 550°C for $\frac{1}{2}$ hour, then cooled and run under dry air. A few samples heated to 300°C were run under saturated air to check for reversible dehydration reactions. Ten samples were heated at 80°C for 4 hours in 2N HCl to dissolve chlorite to aid in distinguishing it from kaolinite (Brindley, 1961).

Mineral Identification and Semi-Quantitative Analysis

Qualitative and semi-quantitative determinations of clay minerals are difficult, particularly when several species are present and have been subjected to weathering reactions (Grim, 1968). Qualitative mineralogy was determined from the characteristic basal reflections of the various minerals (Grim, 1968; Jackson, 1956). Semi-quantitative analysis was attempted for the major clay mineral groups using a scheme proposed by Johns, et. al. (1954) and described in detail by Darby (1971). In this method the area of the diffractogram peak characteristic for each mineral is compared to the area of the 10 Å (001) illite peak. As a result of the different reflectivities of clay minerals, it is necessary to multiply the area of each characteristic peak by an empirically derived reflectivity factor (RF) in order to compare it to illite. The relative per cent of each mineral is obtained by multiplying its peak area by the proper RF, and dividing by the illite peak area from the same diffractogram to obtain the peak area ratio. The reflectivity factors were calculated by S.W. Bailey of the University of Wisconsin (pers. comm., 1973). The peak area ratio, divided by the sum of the peak area ratios of all of the minerals quantified, multiplied by 100, equals the relative percent of that mineral. A general equation is given below, and Table 1 diagrams the quantification procedure for several samples.

Table 1

CLAY MINERAL QUANTIFICATION

	ILLITE 10 Å	KAO.-CHL. 7 Å	VERMICULITE 14 Å	SMECTITE 17 Å
LINC 253				
peak area	110 s	60 d	0 d	180 e
	90 e		180 e	
peak area·RF / 10A area	$(\frac{110}{110})$	$(\frac{60^d}{110^s})\cdot.25$	$(\frac{180^e}{90^e}-\frac{0}{110})\cdot.25$	$(\frac{180^e}{90^e})\cdot.22$
peak area ratio	1	.136	.50	.440
clay %	48	16	61	8
LN 2				
peak area	203^s	341^d	225^d	61^e
	210^e		126^e	
peak area·RF / 10A area	$\frac{203^s}{203^s}$	$(\frac{341^d}{203^s})\cdot.25$	$(\frac{126^e}{210^e}-\frac{225^d}{203^s})\cdot.25$	$(\frac{61^e}{210^e})\cdot.22$
peak area ratio	1	.42	0	.073
clay %	68	28	0	4

saturated air = s dry air = d treated with glycerol = e

$$\text{relative \% mineral Z} = \frac{\dfrac{\text{peak area x } (RF_Z)}{10 \text{ Å illite peak}}}{\text{sum of peak areas of all minerals quantified}} \times 100 .$$

Similar quantitative methods have been used by Berry and Johns (1966), Biscaye (1965), Griffin, et. al. (1968), and Guggenheim and Bailey (1973).

Any quantification scheme must define the mineral species to be quantified so that their peak areas may be measured. In the case of tills which have undergone weathering or may have incorporated older soils, this is not an easy task. In this report, illite, chlorite, kaolinite, vermiculite, and expandable lattice minerals are quantified. Mixed-layer complexes, while common, are not included due to the difficulty in definition. The major mineral species discussed in this paper are defined by the following criteria.

Illite

The term illite is used in the general sense and includes all mica polytypes. Illite is recognized by well-defined peaks at 10 Å (001), 5 Å (002), and 3.34 Å (003) which are unaffected by heating to 300°C and do not expand with glycerol. The 10 Å (001) was used for quantification. Since all other minerals are compared to illite, the peak area ratio is always one.

Chlorite-Kaolinite

Chlorite is recognized by peaks at 14, 7, and 4.7 Å. These peaks disappear after treatment with 2N HCl, do not collapse to 10 or 12 Å under dry air or heating to 300°C, and do not expand beyond 14 Å with glycerol. The (002) 7 Å peak is used to calculate the relative percentage of chlorite. Kaolinite is recognized by peaks at 7 and 3.57 Å which are unaffected by dry air, heating to 300°C, treatment with glycerol, and which remain after treatment with 2N HCl. Ten samples were treated with acid to distinguish chlorite from kaolinite. It was determined that in all units, the percentage of chlorite was very low, always less than 5%, and comprised approximately 10% of the total 7 Å peak. According to Bailey (pers. comm., 1973) the reflectivity of the chlorite (002) peak is 13 times that of the (001) illite peak, and the 7 Å kaolinite reflectivity is three times that of illite. Using the data obtained from the acid treated samples, an average reflectivity of four times that of illite was calculated for the combined chlorite (002) and kaolinite (001) peaks. This gives a RF of .25 for the 7 Å peak. Chlorite and kaolinite were quantified together using this average RF.

Vermiculite

Vermiculite is identified by a 14 Å saturated air peak which collapses to 11-12 Å under dry air, 10 Å after heating to 300°C, and readily rehydrates to 14 Å under saturated air. It does not expand beyond 15 Å after treatment with glycerol.

The peak area ratio of the 14 Å dry air peak subtracted from the peak area ratio of the 14 Å glycerol peak is used for quantification. Vermiculite has a reflectivity 4 times that of the (001) illite peak, yielding a RF of .25.

Expandable Layer Minerals

"Expandables", or smectites, are defined as all minerals which have a basal reflection at 17-18 Å after treatment with glycerol, collapse reversibly to 10 Å under dry air, and irreversibly after heating to 300°C. The 17 Å glycerol peak area ratio is used for quantification. The RF used for smectite was .22.

Mixed-layer Complexes

Peaks between 10 and 14 Å and at 17-30 Å under saturated air which collapse under dry air are attributed to randomly interstratified mixed-layer complexes. In the tills studied the most common species were chlorite-vermiculite and illite-expandables. No attempt was made at quantification except in very general terms.

Other Minerals

Several other minerals in the less than two micron fraction were identified by their characteristic basal reflections. Quartz was identified at 4.27 Å and at 3.34 Å where it combines with the illite (003) peak, amphibole at 8.5 Å, potassium feldspar at 3.24 Å, 3.19 Å for plagioclase, calcite at 3.03 Å, and 2.88 Å for dolomite. No attempt was made at quantification of these phases, but rough estimates of relative percent may be made from the peak heights given for each sample in Appendix B.

Stratigraphy

The glacial deposits in north-central Wisconsin may be divided into two groups, the Border Drift and the late Woodfordian deposits. Within the study area, the late Woodfordian morainal complex makes two major reentrants (Fig. 8). The late Woodfordian drifts were deposited by three ice lobes: the Wisconsin Valley lobe in the north, the Langlade lobe in the northwest, and the Green Bay lobe in the southeast. Nelson (1973) has informally named the Wisconsin Valley lobe terminal moraine in this area the Harrison moraine. The Langlade lobe has two end moraines representing two separate advances. The oldest and outermost is the Parrish moraine, and the younger, inner moraine is the Summit Lake moraine (Thwaites, 1943). Reentrant relationships and till fabrics suggest to Nelson (1973) that the Parrish moraine represents the oldest advance, followed by the Harrison moraine, and finally the Summit Lake moraine is the youngest of the three. In the southeast, the Langlade and Green Bay lobes also form a major reentrant. Based on till fabrics, pebble lithologies, patterns of melt-water channels, and outcrop stratigraphy, Mickelson (pers. comm., 1973) has concluded that the outer moraine of the Green Bay lobe represents an earlier advance than either of the Langlade lobe moraines (Nelson, Mickelson, Stewart; 1973). Till fabrics suggest a southeast ice flow direction for the Harrison moraine, southwest for the Summit and Parrish moraines, and northwest for the Green Bay lobe.

The topographic features of the late Woodfordian deposits are described by Nelson (1973) and Thwaites (1943). In the morainal belts (Fig. 11) relief is 100-300 feet. The glacial features are ice-contact and ice-stagnation forms such as kettles, kames, crevasse fillings, and thick ablation debris. The morainal belts are characterized by many small lakes and bogs, hummocky linear ridges, and high relief. Behind the moraines relief varies from 5-10 feet in poorly drained outwash to the 50-100 foot relief of ice-contact deposits. At Irma, 11 miles north of Merrill, quartzite bedrock forms several hills standing 200-300 feet above the surrounding ground moraine and outwash, but in general, bedrock outcrops are rare.

The deposits beyond the prominent late Woodfordian moraines are termed the Border Drift (Hole, 1943). Hole and Olup (1969) both suggest that the Border Drift is a single unit. Hole feels the lack of buried soils, terminal moraines, and lithologic discontinuities, either in vertical section or regionally, argues for a single Border Drift. Olup's major point is the petrologic homogeneity of the drifts in Marathon County. On the basis of pebble and coarse fraction lithology, carbonate equivalent percentages, magnetic susceptability, qualitative clay mineralogy, and color, he is unable to distinguish more than one unit beyond the late Woodfordian moraines.

LaBerge (1971) suggests that there are two units within the Border Drift. The oldest unit, informally termed the

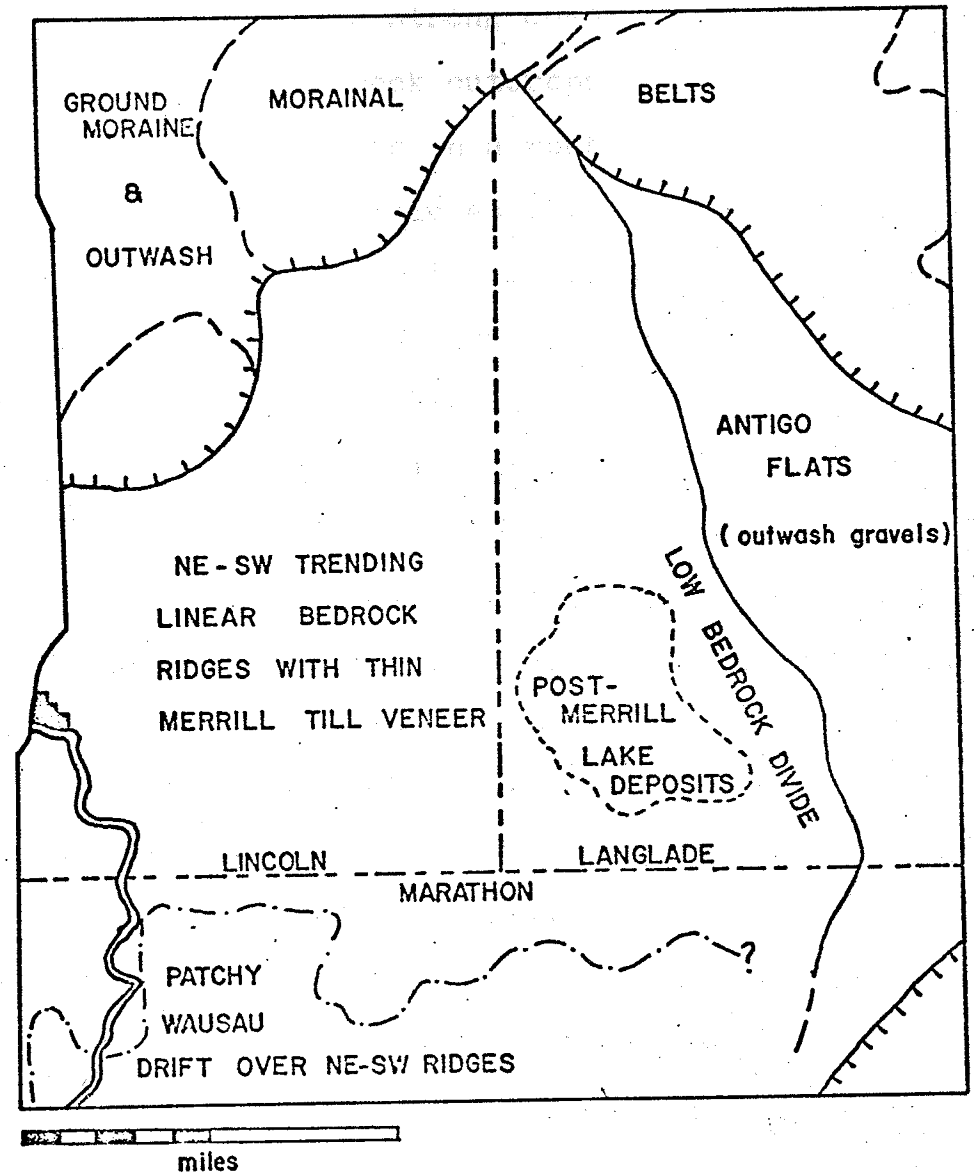


Figure 11. Physiographic map of north-central Wisconsin.

Wausau drift, roughly corresponds to Weidman's Driftless Area east of Wausau. The younger unit, informally termed the Merrill drift, is equivalent to Weidman's Third drift. LaBerge's evidence is the strong correlation of rock pile lithologies to local bedrock outcrops within the Wausau drift. As many as 70% of the rocks in a rockpile correlate with local bedrock. The other 30% includes obvious erratics such as iron formation and algal jasper with an inferred source of Minnesota or northern Michigan-Wisconsin. Cobbles in rockpiles within the Merrill drift do not correlate well with local bedrock. This lack of correlation may be due to the greater thickness of the Merrill drift reducing the influence of local bedrock on cobble lithology. Better evidence is provided by several boulder trains of quartzite, nepheline syenite, and tuff which indicate a westerly ice flow direction for the Wausau drift (LaBerge, 1971). Evidence presented in this report suggests a SSE ice flow direction for the Merrill drift, and a difference in the quantitative clay mineralogy of the two units, supporting LaBerge's contention that the Border Drift is comprised of two units.

The Merrill drift covers much of the study area (Fig. 8). The till unit associated with it is called the Merrill till throughout this paper. The best exposures of the Merrill till are in the vicinity of Merrill (App. A-1, A-2, A-3). The border between the Merrill and Wausau drifts is irregular and indistinct, the Merrill till simply thinning to a few feet at the border between the units. In Figure 8, the border between the two drifts is drawn where residual soils developed on bedrock merge with soils developed on till or loess (LaBerge, 1971). The Wausau drift is very thin and patchy, often no more than a few erratics on top of bedrock (Olup, 1969). There are four possible exposures of the Wausau drift within the study area and two drill sites where Wausau drift was encountered beneath Merrill till. The best exposures are in road cuts along the new US Highway 51, between Merrill and Wausau (Fig. 12).

The area outside the Woodfordian end moraines may be divided into three physiographic provinces: the rolling, fluvial topography of the west, post-Merrill lake deposits, and the Antigo flats. South of Merrill, bedrock ridges trending SW-NE with relief of 100-200 feet typify the mature landscape near the Wisconsin River. Drainage is well-integrated, with few bogs or marshes, and no lakes or ponds along stream courses. Bedrock outcrops are not common, but are more frequent than in areas of late Woodfordian deposits. Merrill till caps the ridges as a thin veneer 3 to 15 feet thick, thinning to the south. The major stream valleys are filled with outwash deposits 10-40 feet in thickness. Relief decreases eastward away from the Wisconsin River, the prominent ridges merging into the gently rolling, somewhat poorly drained lands bordering the lake deposits and the Antigo flats (Fig. 11).

Post-Merrill lake deposits cover approximately 55 square miles in Ackley and Vilas townships, Langlade County. The bed of the former lake is very flat, relief being 10 feet or less.

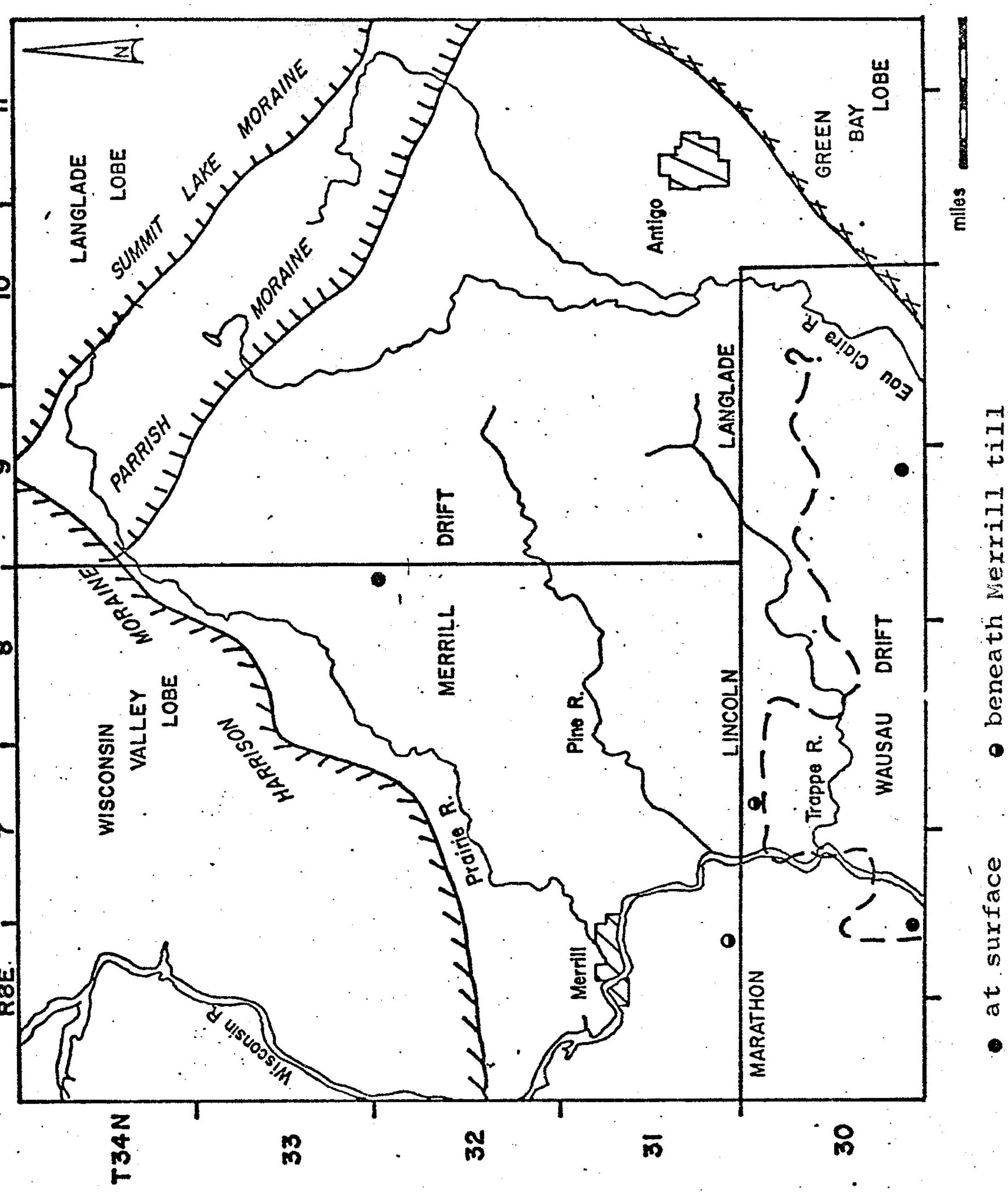


Figure 12. Location of Wausau till outcrops and drill holes where Wausau till was found beneath Merrill till.

Much of the area is poorly drained bog and swamp used for the growing of pulpwood. Drilling indicates that at least 24 feet of lake clays underlie some parts of the basin. The former lake is bordered on the west by the ridge province of the Wisconsin River, and on the east by a low bedrock drainage divide. This bedrock divide separates the lake deposits from the Antigo flats which are at a lower elevation than the former lake. The age and origin of the deposits are uncertain, but they probably post-date the Merrill till.

The Antigo flats are a low lying, very flat region of outwash gravels from the Langlade and Green Bay glacial lobes. The province is roughly triangular in shape, being widest near Antigo. It is bordered on the west and south by the late Woodfordian moraines and on the east by the ridge province and glacial lake deposits. Well logs near Antigo indicate outwash thicknesses of 100 feet or more.

Results

Late Woodfordian Drift

Color

The average wet color of the Wisconsin Valley lobe basal till is 5 YR 4/6 (reddish brown). The average wet color of the Langlade lobe basal till is 7.5 YR 4/5 (brown). The color of the whole till is variable for both lobes and is not diagnostic. The suspended silt and clay fraction color, however, is very constant, being 7.5 YR 4/5 (brown) for the Langlade lobe and 5 YR 4/6 (reddish brown) for the Wisconsin Valley lobe (Nelson, 1973). The color of the Green Bay lobe till is generally 5 YR 4/6 (reddish brown) (Nelson, Mickelson, Stewart; 1973).

Mechanical Analysis

The three late Woodfordian drifts are indistinguishable on the basis of sand/silt/clay percentages (Fig. 13). The mean sand/silt/clay percentages for the late Woodfordian tills are 78/17/5.

Till Fabric Analysis

Nelson (1973) reports in detail on till fabrics from both the Wisconsin Valley lobe and Langlade lobe. The ice flow direction of the basal till in the Harrison moraine is southeast, and the ice flow direction of the basal till in the Parrish and Summit Lake moraines is southwest. The ice flow

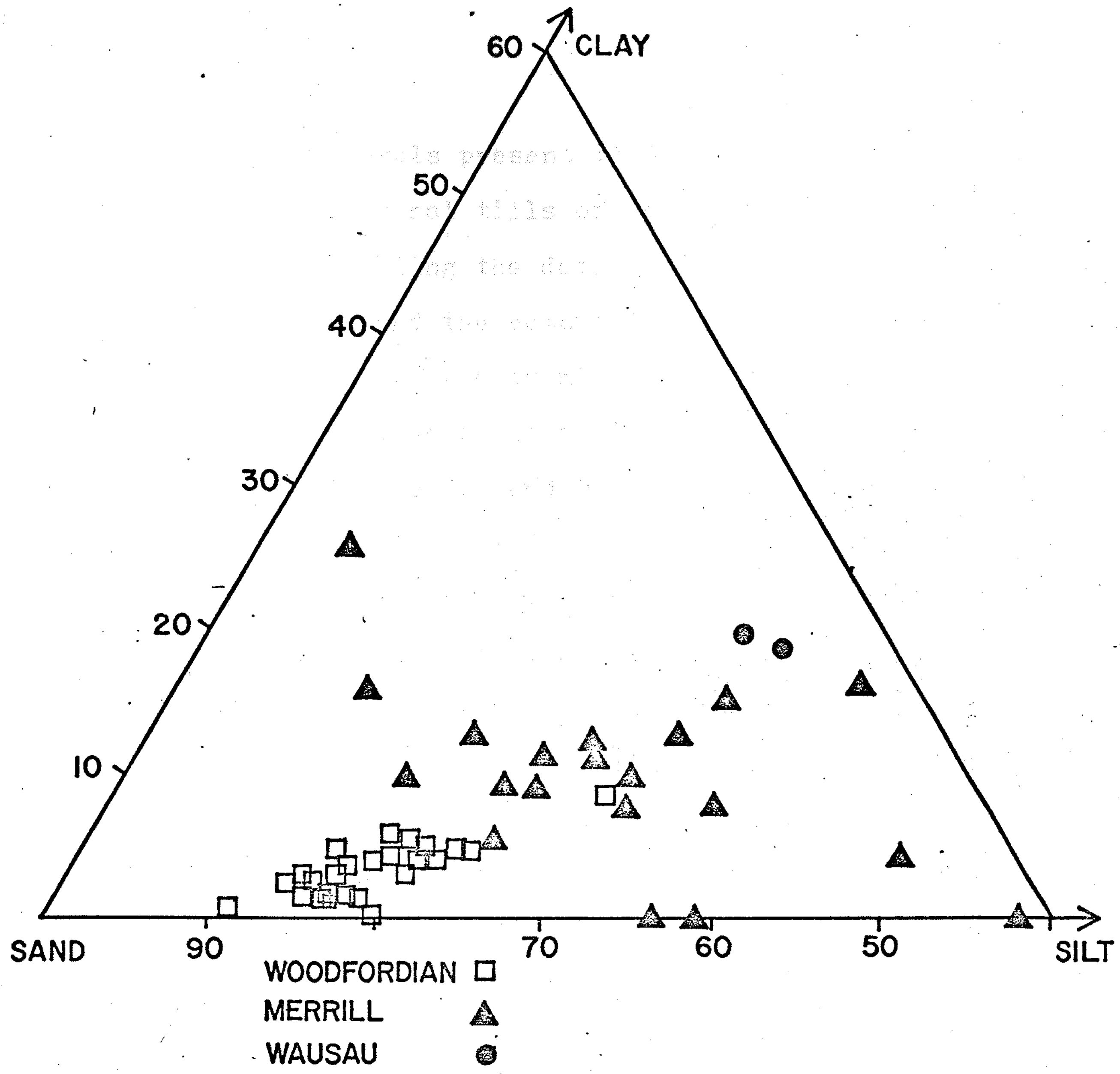


Figure 13. Mechanical analyses of the Woodfordian, Merrill, and Wausau tills.

direction of the Green Bay lobe is northwest (Nelson, Mickelson, and Stewart; 1973).

Clay Minerals

The list of minerals present in the less than two micron fraction of the basal tills of the three Woodfordian lobes is lengthy, reflecting the detrital nature of much of the clay size fraction and the complexity of the pre-Cambrian bedrock (App. E). The major clay minerals include mica (illite)*, predominantly as biotite (Bailey, pers. comm., 1973); chlorite; kaolinite; expandable layer clay minerals; minor vermiculite; and some mixed layer complexes (App. F). The mixed layer complexes are not quantitatively important in the Woodfordian drifts, but are present. A broad band between 10 and 14 Å under saturated air which collapses to 10 Å under dry air, and partially expands to 17 Å after treatment with glycerol is probably a random illite-smectite complex. Chlorite-vermiculite interlayering is suggested by a slight shift of the 14 Å peak under conditions of dry and saturated air. Non-clay minerals present are quartz, potassium feldspar, plagioclase, amphibole, and minor calcite and dolomite. Calcite was detectable in 2 of 10 Langlade lobe samples, 1 of 10 Wisconsin Valley lobe samples, and 1 of 5 Green Bay lobe samples. Dolomite was detectable in 2 Langlade lobe, 1 Wisconsin Valley lobe, and 2 Green Bay lobe samples.

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*Illite as defined in this report includes all mica polytypes. The definition is not restricted to muscovite, the mineral often implied by the term "illite".

The relative percentages of illite, chlorite-kaolinite, vermiculite, and smectite of all three late Woodfordian lobes are very similar and the tills are indistinguishable on the basis of semi-quantitative clay mineralogy. Average values are given in Table 2, and individual analyses are included in Appendix B. The low average vermiculite values are misleading as most Langlade and Wisconsin Valley lobe samples contain no vermiculite. However, 4 out of 20 have 3-11% vermiculite. Vermiculite is somewhat more prevalent in the Green Bay lobe, 3 out of 5 samples having 3-14% vermiculite.

The predominance of mica in the clay mineral assemblage is probably due to the influence of the igneous and metamorphic rocks which comprise the local bedrock and that of source areas to the north and northeast. In the area sampled, the bedrock is similar among all three lobes, but dolomitic cobbles in the Green Bay lobe are evidence of the influence of the early Paleozoic sediments to the east. Akers (1961) found the Paleozoic limestones and dolomites of west-central Wisconsin contain predominantly illite and smectite with minor amounts of vermiculite. That the illite, vermiculite, and smectite values of all three Woodfordian drifts are similar implies that the clay mineral contribution of the Paleozoic rocks was either minimal or very similar to that of the local bedrock. The comparatively low vermiculite and smectite values suggest that these units are relatively unweathered or young, and that unweathered bedrock, rather than older soils

TABLE 2
QUANTITATIVE CLAY MINERALOGY

	mica	kaolin-chlorite	vermiculite	smectite	# of samples
WISC. VALLEY LOBE					
relative %	66	21	2	12	10
std. deviation	8	5	3	6	
relative std. dev.(%)	12	24	150	60	
LANGLADE LOBE					
relative %	71	18	1	11	10
std. deviation	9	3	3	6	
relative std. dev.(%)	13	17	300	55	
GRN. BAY LOBE					
relative %	69	13	5	14	5
std. deviation	6	3	5	5	
relative std. dev.(%)	9	23	100	36	
MERRILL TILL					
relative %	51	9	23	16	23
std. deviation	8	4	9	5	
relative std. dev.(%)	16	44	39	31	
WAUSAU TILL					
relative %	26	5	25	44	2
std. deviation	4	0	4	0	
relative std. dev.(%)	15	0	16	0	

overridden by the advancing ice, was the major source of the clay fraction for these units.

Merrill Till

Color

The color of the Merrill till is usually very distinctive in the field. The wet color of 26 samples ranges from 10 R 3/4 (dark red) to 5 YR 3/4 (reddish brown), with the majority of the samples being 2.5 YR 3/3-4/3 (dark reddish brown). This is in contrast to the lighter, less red, 5 YR 4/6 color of the Wisconsin Valley lobe, and 7.5 YR 4/5 color of the Langlade lobe (Nelson, 1973).

Mechanical Analysis

The Merrill till is somewhat siltier and more clay rich than the Woodfordian drifts with a mean sand/silt/clay composition of 60/30/10 (Fig. 13). The higher silt and clay content is noticeable in the field as is the general tendency for the Merrill drift to have a lower percentage of boulders and cobbles than the Woodfordian drifts. The percentage of boulders and cobbles in the Merrill till is at a maximum near the border of the Wisconsin Valley lobe and decreases to the south. This tendency was also noted by Hole (1943) for the Border Drift to the west in western Marathon, Clark, and Wood Counties. Hole feels that the finer texture of the Border Drift may be due in part to the incorporation of older soils during the advance of the Border Drift ice.

Till Fabric Analysis

Five till fabrics were measured at four outcrops of the Merrill till (Fig. 10) within the study area. Fabrics 1 and 2 were measured in a gravel pit just north of Merrill (Fig. 10, App. A-1). The pit is cut into the down-ice face of a recessional moraine (Weidman, 1907) that extends in a NE-SW direction (Fig. 14). The morainal ridge has a relief of 50 feet, and is composed of ice-contact stratified drift interbedded with Merrill till. Fabric 1 is from the upper unit of two till bands separated by clean sand and Fabric 2 is from the lower unit. Both fabrics indicate an ice flow direction from the NNW, approximately perpendicular to the trend of the morainal ridge (Fig. 15A).

Fabrics 3 and 4 were also measured in Merrill till. Fabric 3 was taken from a cut on the south side of the Prairie River in Merrill (Fig. 14). Two feet of loess caps Merrill till 4-5 feet thick overlying 15 feet of clean sand which extends to the bottom of the section (App. A-3). The fabric indicates an ice flow direction from the NW. Fabric 4 was measured in a gravel pit five miles NE of Merrill. Four to six feet of Merrill till overlies cobbly sand and gravel in a section similar to the Prairie River cut (Fig. 10, App. A-4). The ice flow indicated is SSE (Fig. 15B).

Fabric 5 is from a gravel pit five miles southeast of Merrill near the Pine River. The till here is very thin, only three feet of weathered Merrill till lying directly on deeply weathered coarse granite (Fig. 10, App. A-5). The fabric

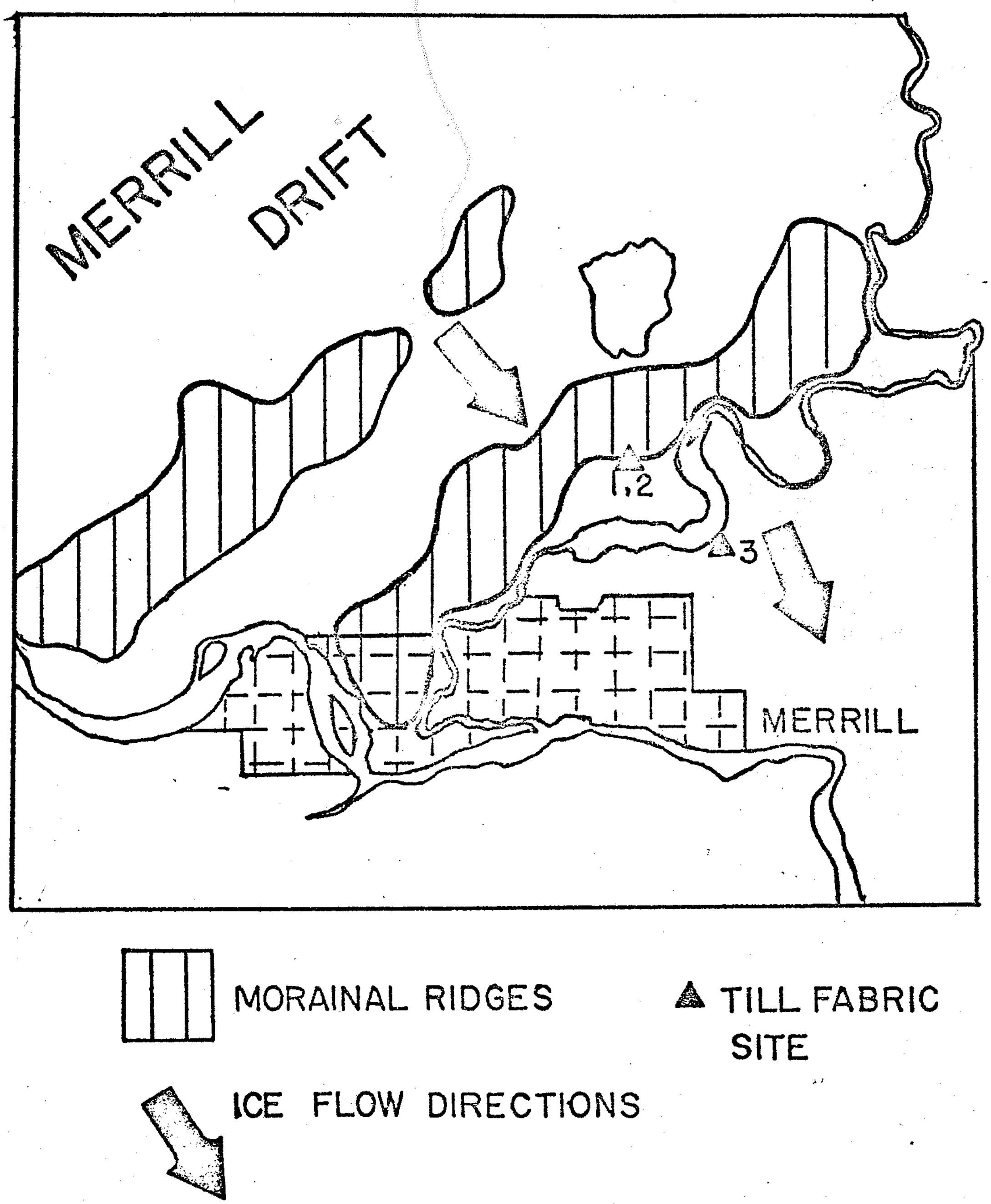

Figure 14. Relationships between morainal ridges and till fabrics near Merrill, Wisconsin.

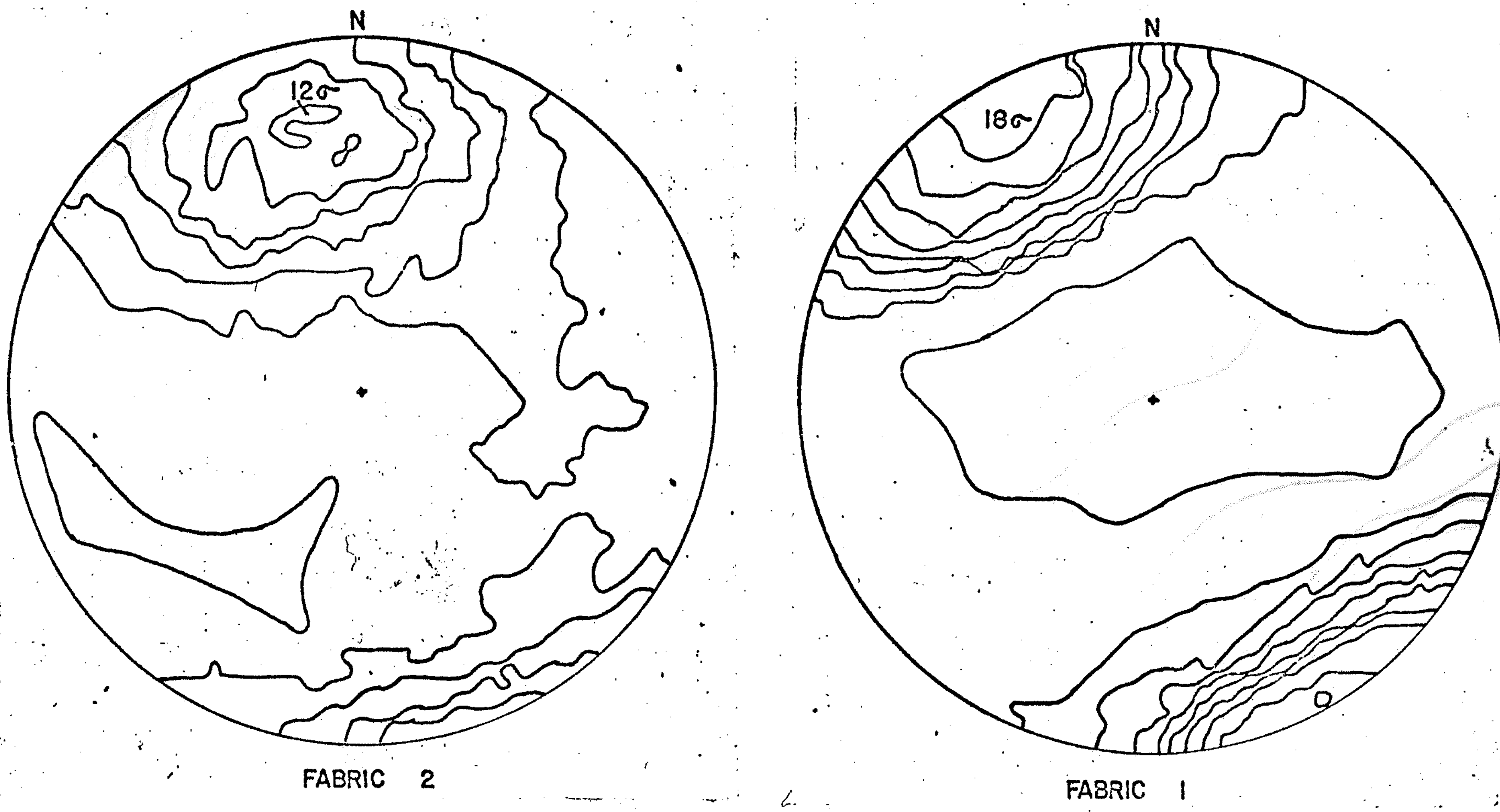

Figure 15A. Lower hemisphere, equal area stereo net plots of till clast fabrics. First contour is 1 sigma, contour interval is 2 sigma.

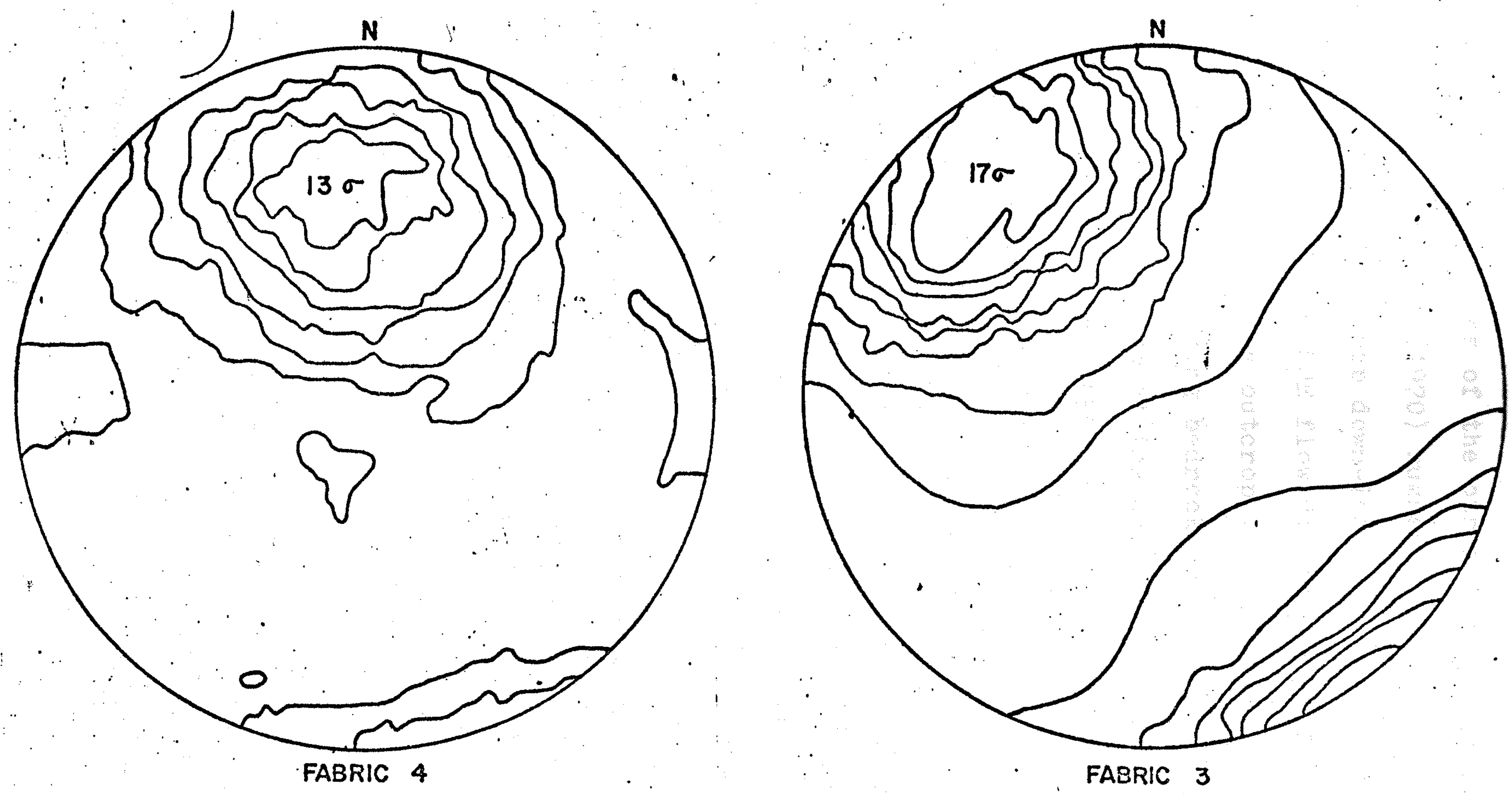

Figure 15B. Lower hemisphere, equal area stereo net plots of till clast fabrics. First contour is 1 sigma, contour interval is 2 sigma.

differs from the fabrics of the other three outcrops of the Merrill till. Lindsey (1970) suggests that it is possible to form a fabric with a steep down-ice dip, but the NNE azimuth does not agree with the SSE flow directions indicated by Fabrics 1 through 4. The outcrop is located on the south side of a northeasterly trending bedrock spur. This spur may have influenced local ice flow at the depositional interface enough to develop the SSW fabric (Fig. 15C).

Clay Minerals

The qualitative mineralogy of the less than two micron fraction of the Merrill till is very similar to the Woodfordian tills. The major qualitative difference is the increased occurrence of mixed layer complexes, and the high percentage of vermiculite in all 26 samples of the Border Drift. Calcite is somewhat more common than in the Woodfordian drifts, being detected in 10 of 26 samples. No dolomite was found in the Merrill till. The reason for the occurrence of calcite in 10 of 23 samples of Merrill till is not apparent. In the field, all samples of the Merrill till tested did not effervesce with 10% HCl. Hole (1943) reports calcareous Border Drift near Marshfield, Wisconsin, possibly related to Paleozoic sandstone outliers. It is possible that the Merrill till may have a more westerly source than the Woodfordian drifts. This may have increased the influence of the calcareous Paleozoic rocks of western Wisconsin or Paleozoic outliers to the northwest. In the field within the area

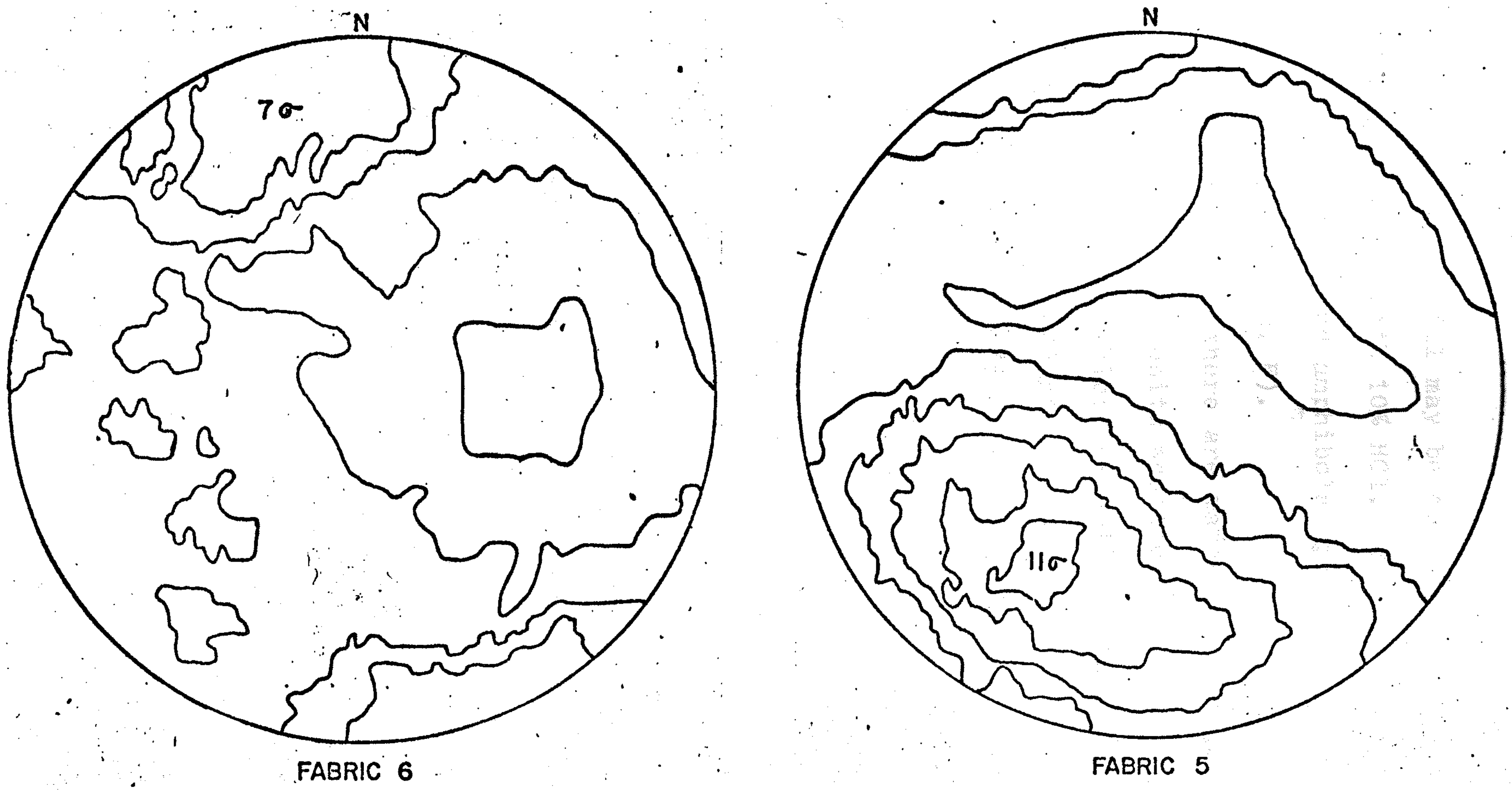

Figure 15C. Lower hemisphere, equal area stereo net plots of till clast fabrics, First contour is 1 sigma, contour interval is 2 sigma.

sampled, the Merrill till may be considered non-calcareous, as it does not react with 10% HCl. Potassium feldspar, plagioclase, quartz, and amphibole are present as in the Woodfordian drifts (App. F).

Quantitatively, there are major differences between the late Woodfordian deposits and the Merrill till. The percentages of illite and chlorite-kaolinite are lower, while vermiculite is more abundant and found in every sample. There is no significant difference in the relative amount of smectite. The decrease in illite and the increase in vermiculite may be linked to a difference in the degree of weathering between the Merrill and late Woodfordian drifts. Vermiculite has a hydrated mica structure and can be formed from the weathering of illite in soils (Carroll, 1970). Alteration of chlorite can also produce vermiculite (Willman, et. al., 1963). However, in these units the relative percentage of chlorite is very low and is possibly related to the widespread occurrence of low-chlorite granitic intrusives in the local bedrock. The contribution of smectite to the clay mineral assemblage by the weathering of chlorite is minor. The final end product of the weathering of illite is smectite, vermiculite being an intermediate step. In the Merrill till both the illite and chlorite-kaolinite values are lower than those of the late Woodfordian drift. This could be expected if the Merrill till originally had a clay mineral composition similar to the younger drift and has been subjected to a longer period of weathering.

The difference may also be due to the incorporation of old weathered soils overrun by the Merrill drift ice and incorporated into the till. Such older soils would have a greater influence on a thinner unit such as the Merrill till than the thicker late Woodfordian drift. A thin unit has a lower volume of material than a thicker unit and overridden materials might be expected to have a stronger influence on the mineralogy of a thin till, since their relative volume would be greater. However, older soils would also contain expandable layer clays in the upper horizons (Willman, et. al., 1963). The addition of soil materials to a till should add not only vermiculite but smectite as well. The smectite values for the Merrill till are not significantly higher than for the late Woodfordian units. This suggests that the source of the vermiculite is not overridden pre-glacial soils.

A third explanation is that the differences in clay mineralogy are due to a difference in local bedrock. However, in a region of complex bedrock geology (LaBerge, 1971) the semi-quantitative differences in the clay mineralogy of the Woodfordian and Border drifts are consistent over a very large area. Also, samples from within one mile of the Woodfordian border show the same differences as samples collected twelve miles away, suggesting that bedrock veriation is not a factor.

It is interesting to note that the values for chlorite-kaolinite are also lower in the Merrill till. As mentioned earlier chlorite is unstable in most soils and alters readily to vermiculite (Frye, et. al., 1969). If the lower illite and higher vermiculite values are due to weathering, it is reasonable to assume that chlorite alteration would also have occurred as the alteration of illite is a slower process (Willman, et. al., 1961). However, the chlorite values obtained from the acid-treated samples are too low to account for observed decrease in chlorite-kaolinite values, even if all chlorite had altered to vermiculite (Table 2). If true, it is possible that the use of 2N HCl to quantitatively distinguish between chlorite and kaolinite may not be valid for these samples. Ostrom (1961) found that well-crystallized chlorites were stable in 10N HCl for 72 hours, and Brindley (1961) states that while the method may be useful, many factors influence the acid solubility of chlorite and such a procedure should be used with caution. If the variation of the chlorite-kaolinite values is due to chlorite alteration, then chlorite must comprise more of the 7 Å peak than indicated by the data in Table 2.

The high kaolinite values are not geologically unreasonable, although they may be analytically suspect to some degree. Kaolinite may be considered a "mature" weathering product representing either intense weathering or a long period of relatively stable conditions (Grim, 1968). Normally it is associated with warm, moist environments (Carroll, 1971) but it has been found in temperate and Arctic environments (Biscaye, 1965; Darby, 1971). Kaolinite can also be a product of hydrothermal alteration, but it is unlikely that the consistent kaolinite values over a large area of complex bedrock geology would be due to this. Chemical weathering of acidic feldspars is the usual source of kaolinite. In this area, much of the bedrock is coarse-grained granite, a possible source of kaolinite. There is some doubt as to whether there has been sufficient intensity or time of weathering during the Pleistocene to produce a kaolinitic weathering regime. Paleo-temperature curves (Emiliani, 1966) show that the present interglacial is as warm as the Sangamon interglacial, and that interglacial periods have been numerous but short term events during the Pleistocene. However, there is evidence of warm, intense weathering regimes during pre-glacial times. If this is the case, kaolinite could be derived from a weathering residuum formed on the pre-Cambrian bedrock surface during an intense period of weathering. Dury (1971) describes deep weathering profiles (duricrusts) developed on the Paleozoic sediments of SW Wisconsin. Buckley (1901) describes residual clay deposits several feet thick supporting brick factories in Merrill, Antigo, and Tomahawk. Most of the brick pits were worked in 2-5 feet of yellow clay containing granite chips from the underlying bedrock. Buckley also reports on the very thick (forty feet) profiles developed on pre-Cambrian schists and gneisses under Paleozoic sandstones near Black River Falls and Eau Claire, Wisconsin. These clays are very high in kaolin and were used commercially for porcelain. Several miles northeast of Merrill a shallow pit exposed three feet of

Merrill till overlying at least three feet of a highly weathered clay with the distinctive coloration and texture of a biotite gneiss. Also, the coarse-grained granites of the region are often disaggregated to depths of greater than seven or eight feet. To the southeast, within the Green Bay lobe, the relief of the weathering surface between weathered and unweathered granite is irregular. Small, steep-sided hills with relief of 10-20 feet are not uncommon and are comparable to tors (Anderson, pers. comm., 1973). It is possible that a more intense weathering regime existed in this area during pre-glacial time, and the residuum produced has contributed kaolinite to the clay mineral assemblage.

Wausau Till

Color

The four possible samples of the Wausau till vary in color from 2.5 YR 3/6 (dark reddish brown) to 5 YR 4/6 (reddish brown), most being 5 YR 2/3-4/6.

Mechanical Analysis

Two samples of Wausau till were analyzed (Fig. 13, App. B). Both have a finer texture than either the Merrill or Woodfordian units. The average texture of the two samples is 45% sand, 35% silt, and 18% clay.

Till Fabric Analysis

Fabric 6 was measured in a small gravel pit twelve miles west of Merrill within the border of the Merrill drift

(Fig. 10). The pit is located on the south side of a low, drumlinoid hill which trends roughly north-south. Two feet of loess overlies a mottled, orange-red, deeply weathered till two to three feet thick (App. A-5). The fabric is weak, with a maximum contour of seven sigma. The mean azimuth is NNW, and the mean dip is very low, less than two degrees. However, LaBerge (1970; 1971) reports that boulder trains indicate a westward ice flow for the Wausau drift. Because this site was overrun by Merrill drift ice, the weak fabric with secondary westerly modes may imply reorientation of an older, westerly fabric by later ice coming from the north (Fig. 15C).

Clay Minerals

The qualitative mineralogy of the Wausau till is most similar to that of the Merrill till. Quantitatively the units differ significantly (App. F). The Wausau till has the lowest illite and highest smectite values of all the units sampled. The average vermiculite value is identical to the Merrill drift, but the chlorite-kaolinite value is somewhat lower (Table 2). This would be expected if the quantitative differences were due to <u>in situ</u> weathering rather than incorporation of older soil or local bedrock differences. Stratigraphically the Wausau is the oldest unit in the area and it has the highest percentage of weathering products in the clay size fraction. Drill hole #31 (Fig. 9) penetrates both the Merrill till and the underlying Wausau till. MAR 205, the younger unit, has 22% smectite while MAR 206, two feet lower, has 35% smectite. As in the case of the Merrill till, the most probable origin of the present clay mineralogy is the sub-aerial weathering of an original high-illite, low-smectite till over a period of time significantly longer than for the Merrill or late Woodfordian drifts.

Discussion

Origin of the Merrill and Wausau Drifts

The till fabrics discussed earlier are the best evidence for the source of the ice which deposited the Merrill till. Of the five fabrics measured in the Merrill till, four show SSE ice flow directions. The fabrics are very strong and only Fabric 5 shows other than a northwesterly source for the Merrill drift ice. Additional support for a NW origin is the NNW trend of the two morainal ridges of the Merrill drift north of Merrill (Fig. 14). Fabrics 1 and 2, measured in the face of one of the ridges, show an ice flow direction perpendicular to the trend of the moraines. LaBerge (pers. comm., 1973) also reports a large boulder of Powell kyanite within the Merrill drift two miles west of Fabric 4. The nearest outcrop of this distinctive rock is 100 miles to the northwest near Powell, Wisconsin.

Within the study area, there is little evidence for the origin of the ice which deposited the Wausau drift. Fabric 6, measured in an outcrop of the Wausau till is ambiguous. It is a weak fabric, with many secondary modes. The strongest part of the fabric indicates a SE ice flow direction, However, as this exposure was overrun by Merrill drift ice it is possible that the pebbles have been reoriented and the original fabric lost. The best evidence for the source of the Wausau drift ice is the boulder trains of quartzite, tuff, and nepheline syenite reported by LaBerge (1971) which indicate that the last movement of the Wausau drift ice was from the west.

Age of Units

Topography

Chamberlin (1882) noted the marked difference between the late Woodfordian deposits and the older deposits beyond the Woodfordian end moraines. In north-central Wisconsin the boundary between the two areas of glacial drift forms a discontinuity expressed by relief, drainage patterns, and apparent topographic maturity. Figure 16 is a series of profiles across this boundary.

Drainage patterns developed on the late Woodfordian deposits are characterized by many ponds and bogs along the stream channels, poorly integrated stream systems, and many undrained swamps and lakes. The least well developed drainage occurs within the morainal belts. The deranged drainage pattern and the strong influence of glacial features on stream flow patterns imply both recent glaciation and glacial drift thick enough to subdue the effect of bedrock topography. The well-integrated drainage and rolling topography of the Border Drift suggest a greater age than the poorly drained depositional topography of the late Woodfordian deposits. Chamberlin (1882) recognized that the marked difference in topography is the result of variations in the thickness of the glacial deposits which blanket the ancient pre-Cambrian bedrock surface.

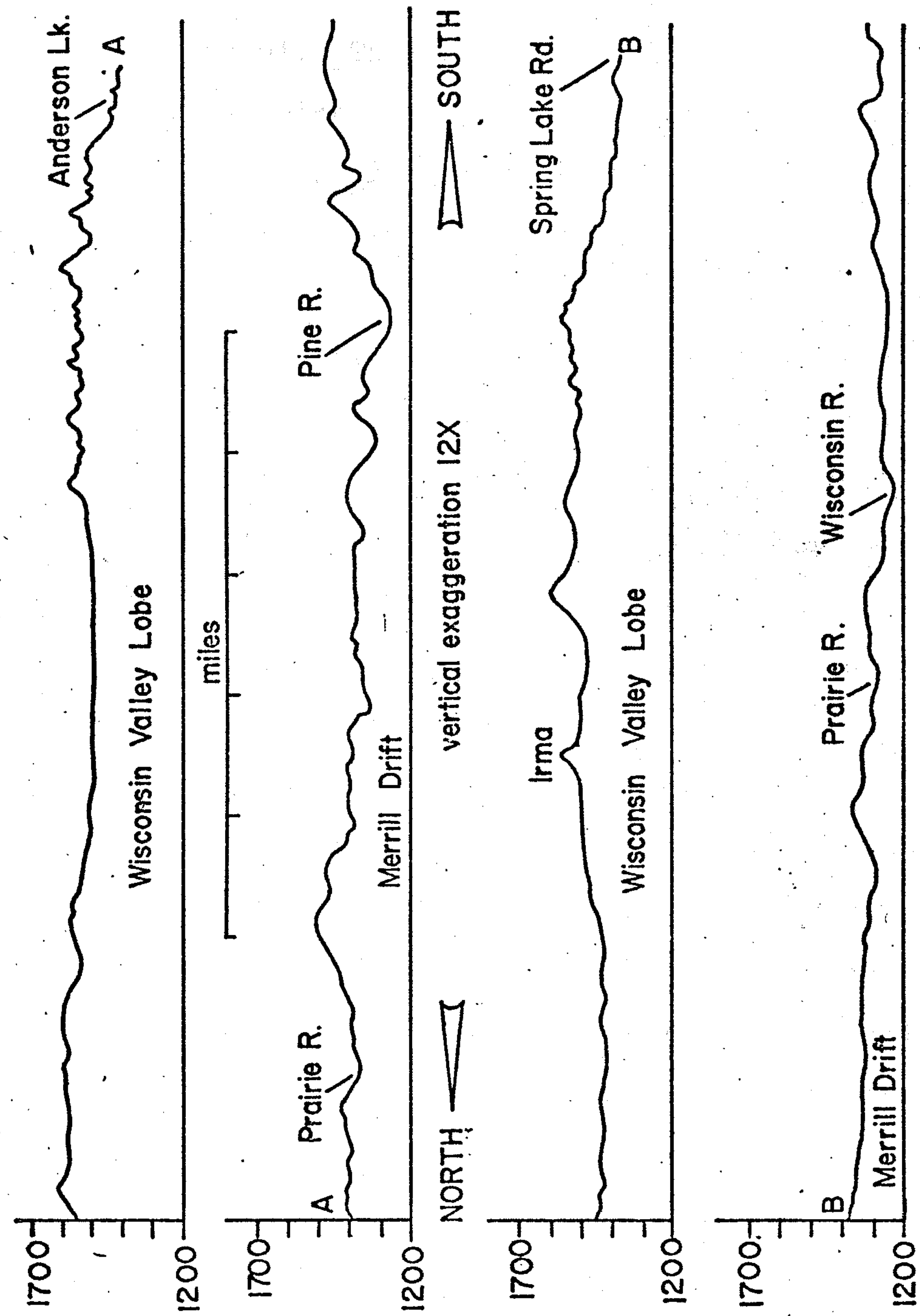

Figure 16. Topographic profiles across the Late Woodfordian boundary in north-central Wisconsin.

The late Woodfordian deposits are thick enough to subdue the original bedrock relief, resulting in deranged drainage and glacial landforms. The Border Drift is a thin sheet of till and outwash draped over a mature erosional surface developed on the pre-Cambrian basement. The result is a landscape of apparent erosional maturity inherited from the bedrock topography. The variation of landforms between the Border Drift and the late Woodfordian drifts is striking, but is not necessarily due to a great difference in age.

The thinness of the Border Drift can be explained by two hypotheses. The first is that the drift was deposited as a thin sheet of ground moraine. The gradual thinning of the drift from north to south suggests this is a possibility. A rapid advance and retreat of a relatively clean ice mass can explain both the thinness of the drift and the absence of end moraines. In this case, the Merrill drift could be very young, even an earlier advance of the Wisconsin Valley lobe. The second hypothesis is that the thinness of the drift is due to erosion. This would also explain the lack of glacial features and the subdued, rolling topography. This hypothesis implies a greater age for the Merrill drift than the late Woodfordian deposits. Evidence from the mineralogy and degree of weathering of the Merrill and late Woodfordian drifts is compatible with either of the two hypotheses. The patchy distribution and high degree of weathering of the Wausau till suggests the second hypothesis may be the best explanation for its thinness.

Clay Minerals

The semi-quantitative clay mineralogy of the late Woodfordian deposits and the two Border Drifts provide evidence of the relative ages of the units. The Border Drifts are distinguished from the late Woodfordian deposits by very high vermiculite and smectite contents. The Wausau drift is differentiated from the Merrill drift by a higher percentage of expandable layer clays. While the evidence is not completely unambiguous, it can be argued that these differences in semi-quantitative clay mineralogy reflect differences in the ages of the units.

Clay minerals show varying degrees of susceptability to alteration by weathering processes. In a weathering zone, chlorite is readily altered to vermiculite, while the stepwise alteration of illite to vermiculite and smectite is a much slower process (Droeste, 1959; Frye, et. al., 1969). Because of the predominance of illite in the tills studied, the weathering sequence of illite-vermiculite-smectite is of great importance in determining the weathering history of the units. If it is reasonable to assume that most of the vermiculite and smectite are weathering products of the *in situ* alteration of illite, and to a lesser extent chlorite, then the rates of alteration of the two minerals can provide information on the relative length of time a till has been exposed to sub-aerial weathering.

There are two possible origins for the vermiculite and smectite in a till. The first, as already suggested, is an *in situ* weathering of illite and chlorite. The other source is the incorporation of soil clays from well developed and highly weathered soils as a glacier advances over a region not recently glaciated. If the Merrill and Wausau tills were originally deposited as very thin units, a few feet of older soil would have a greater influence on the clay mineralogy than in the case of much thicker drift units such as the late Woodfordian deposits. This can explain the higher percentage of weathering products in the thinner Border Drifts. However there is an argument which suggests that *in situ* weathering is the more important process.

In a closed system, where all the values are made to sum to 100, the simple increase in one component will decrease the values for all other components by a proportionate amount. If the increase is not a simple addition, but rather an alteration of one component to another, only the values of the two components will change; the other components will remain the same. If a plot of the parent material, illite, vs. the weathering product, smectite, is made the graph (Fig. 17A) supports the *in situ* weathering mechanism. The graph of illite vs. expandables is not random, but shows the expected relationship; samples high in illite are correspondingly low in expandables. The concurrent decrease in the parent material and increase in the weathering product suggests that simple detrital additions to a closed system are not causing the variations in the percentages. Figure 17B is a plot of a stable component, kaolinite, vs. a weathering product,

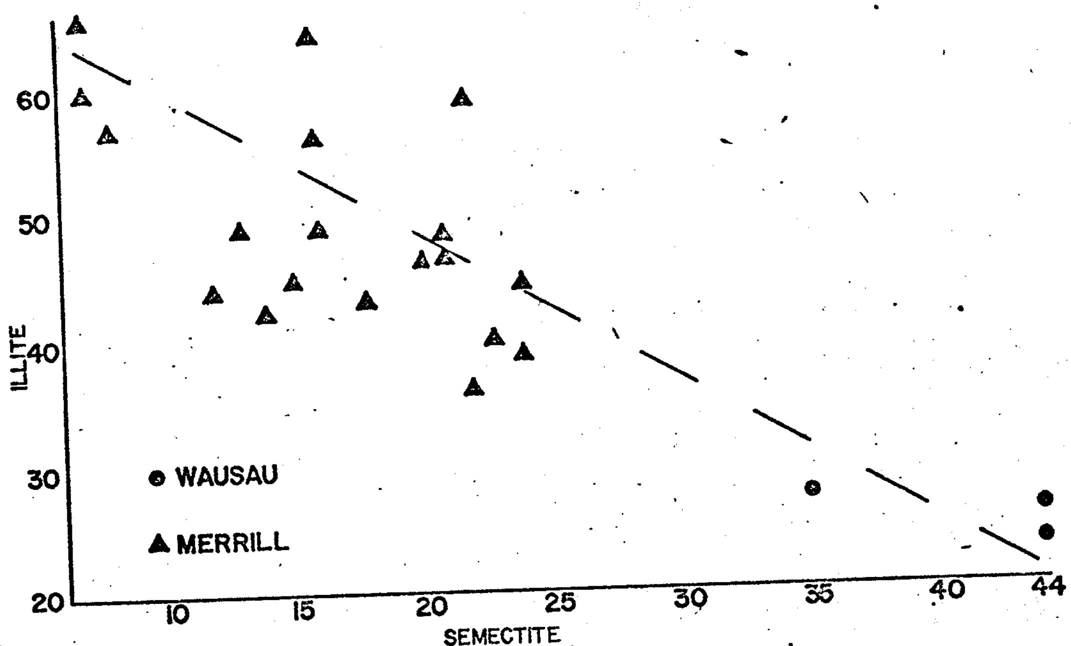

Figure 17A. Percentage of parent material illite vs. weathering product vermiculite.

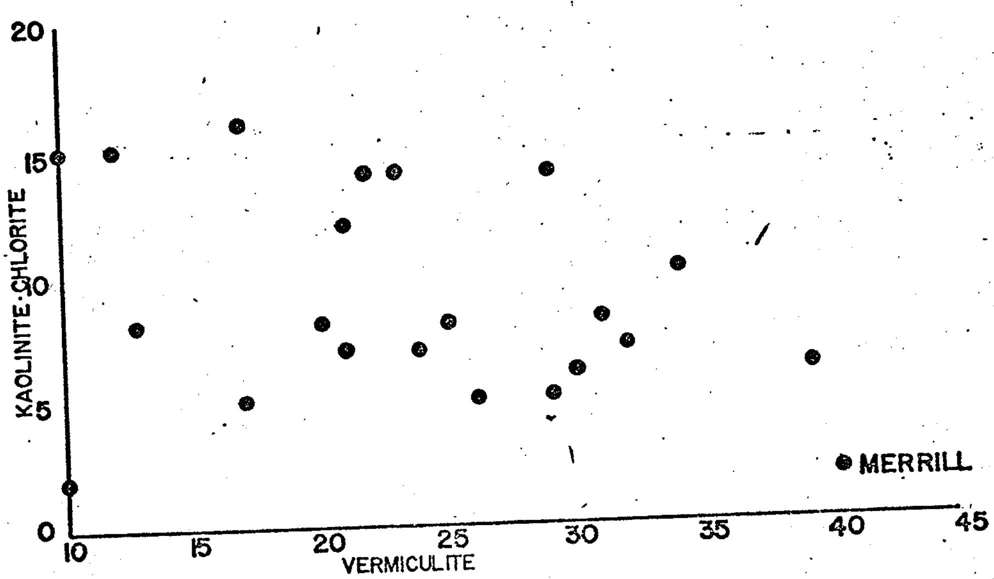

Figure 17B. Percentage of stable component kaolinite vs. weathering product vermiculite.

vermiculite. Despite the wide variation in the percentage of the weathering product, the stable component remains relatively constant. If the increase in smectite were due to simple addition, the kaolinite percentage would decrease as smectite increased.

It is a logical assumption that the weathering of a till starts at the surface and proceeds downward. The till near the surface has undergone the longest period of weathering, and will contain the highest percentage of weathering products. In a till which has weathered in situ, there is a linear relationship between depth below the surface and degree of weathering. If the weathering products and parent materials were derived from the incorporation of pre-glacial soils, no definite relationship between depth and percentage of weathering products or parent materials would be expected. Figure 17C is a plot of vermiculite vs. sample depth, and Figure 17D is a plot of illite vs. sample depth, both for the Merrill till. The samples plotted are from different sections and some of the scatter can be explained by variation in weathering intensities under different environmental conditions. In both cases there is a well defined relationship between relative abundance and sample depth. The percentage of vermiculite increases near the surface while illite decreases upward. In contrast, Figure 17E, a plot of illite vs. depth for the Woodfordian drifts, shows no such relationship. This is a further suggestion that the difference between the tills in the percentage of weathering products is due to in

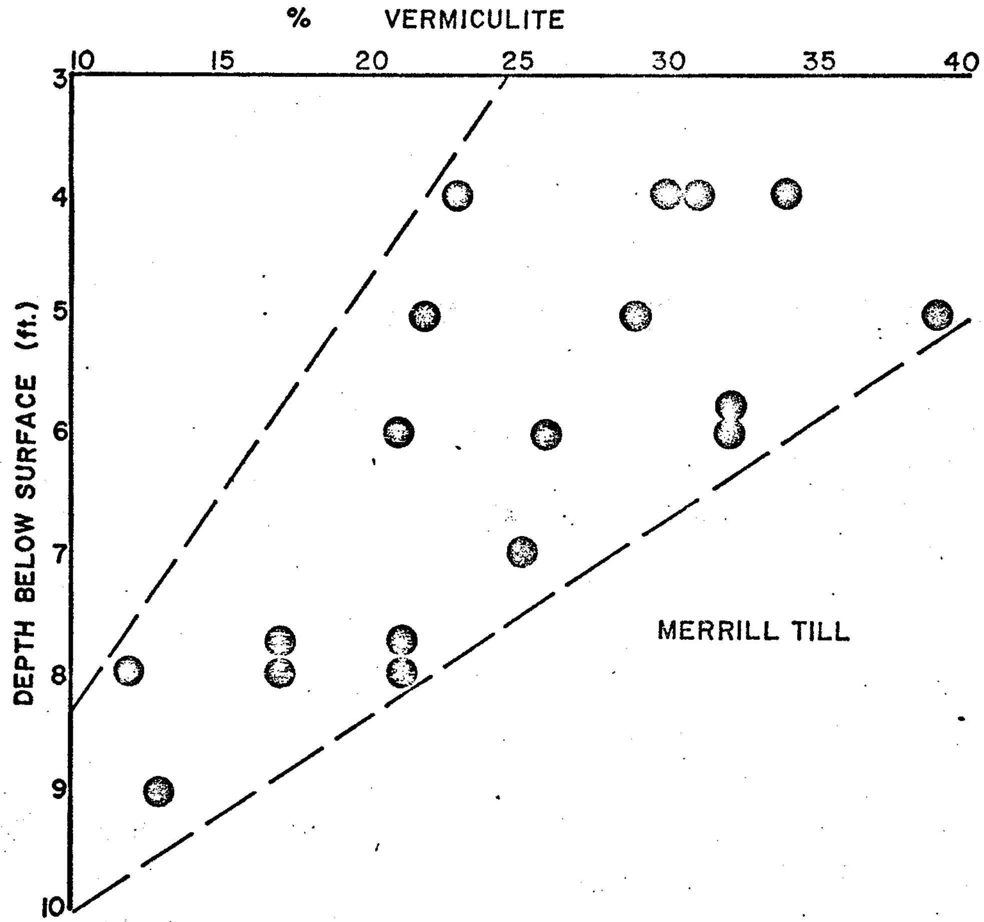

Figure 17C. A plot of weathering product vermiculite vs. sampling depth.

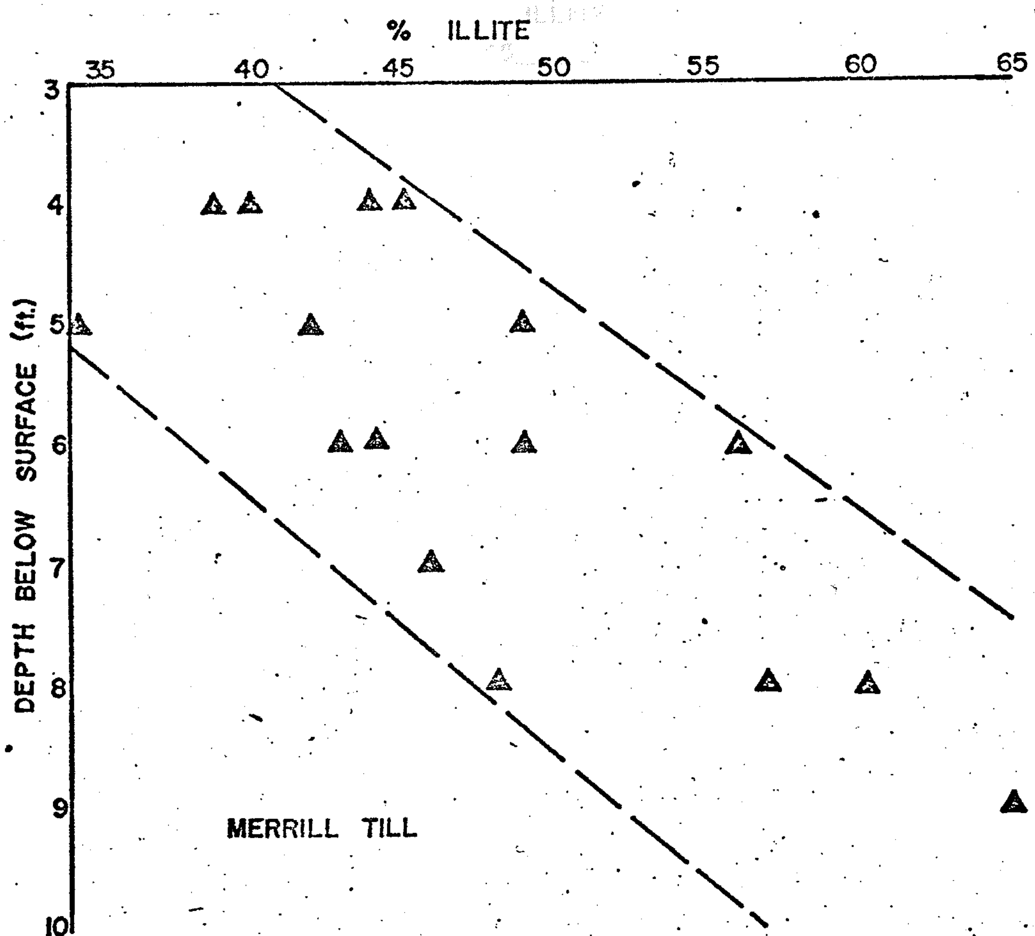

Figure 17D. A plot of parent material illite vs. sampling depth.

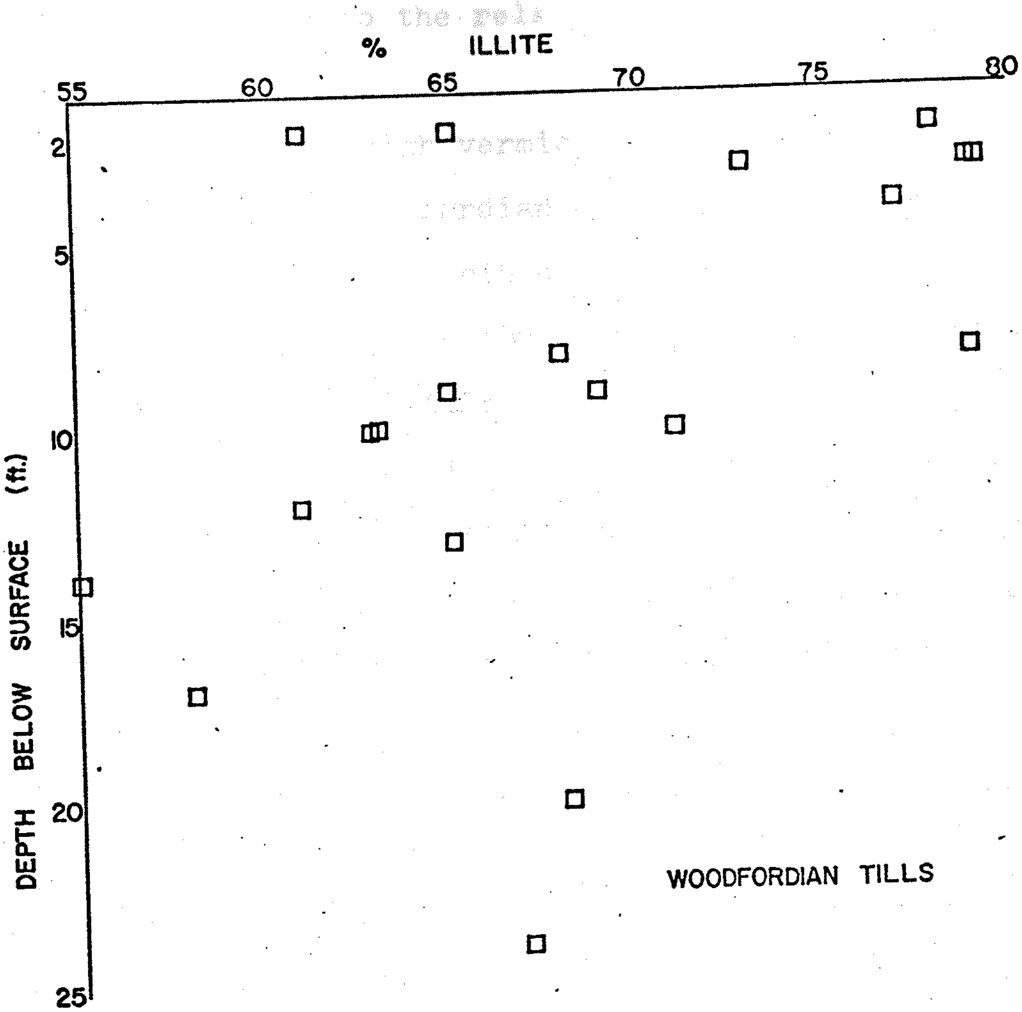

Figure 17E. A plot of parent material illite vs. sampling depth for the Woodfordian drifts.

situ weathering over varying time periods. Since higher vermiculite and smectite values imply longer or more intense weathering histories, it follows that the semi-quantitative clay mineralogy is related to the relative ages of the till units.

The Merrill till has high vermiculite values compared to the values for the late Woodfordian drifts. The values of expandable clays are similar in both units. Frye, et. al., (1969) state that chlorite alteration is very rapid, but that even in late Altonian tills, little illite alteration has occurred. They measure illite alteration by noting the increase in smectite and do not quantify vermiculite. Since vermiculite is an intermediate step, noting its increase is a more sensitive test, allowing for detection of illite alteration in younger tills. The implication is that the Merrill till is significantly older than the late Woodfordian drifts. Black and Rubin (1968) report radiocarbon dates on spruce in the single Border Drift till of St. Croix Co., Wisconsin of 29,000 ± 1,000 years BP (W-747) and 30,650 ± 1,650 years BP. This agrees well with the latest Altonian Capron till of northern Illinois (Frye, et. al., 1969). A late Altonian age would not be incompatable with the degree of weathering of the Merrill till.

The two samples of Wausau till are differentiated from the Merrill till by significantly lower illite values and very high smectite values. This strong decrease in illite and corresponding increase in smectite suggests a much longer period of sub-aerial weathering for the Wausau till than for the Merrill till. An estimation of age is difficult, but there are indications of great age. In Illinois illite alteration is present in the C horizon only in Illinoian tills (Willman, et. al., 1968). Also Black and Rubin (1968) reported that in addition to spruce, the Border Drift till in St. Croix County contained peat from pre-glacial bogs which yielded dates of > 45,000 years BP (W-1788). This suggests that the Wausau till may be older than 45,000 years BP. The outcrops of the unit are mottled and highly weathered (App. A-5) and an outcrop near Hogarty in Marathon County (Fig. 12) shows a deep red-brown, highly weathered till overlain by a deep red, mottled horizon which may represent an inter-glacial or inter-stadial paleosol. It is evident that the Wausau till is much older than the Merrill till, and may be as old as Illinoian or early Altonian in age.

Conclusions

1. The Border Drift of north-central Wisconsin can be separated into two units on the basis of pebble lithologies and semi-quantitative clay mineralogy. The two units are informally termed the Merrill and Wausau drifts (LaBerge, 1971).

2. The Merrill till was deposited by ice moving from the north-northwest as evidenced by till fabrics. Boulder trains provide the best evidence of a westerly source for the ice which deposited the Wausau drift (LaBerge, 1971).

3. The Merrill till is pre-Woodfordian in age and probably correlates with the late Altonian till of St. Croix County, Wisconsin (Black and Rubin, 1968) and the late Altonian Capron till of Illinois and southern Wisconsin (Bleuer, 1971).

4. The Wausau till is older than the Merrill till, but an exact age determination is difficult. It may be as old as early Altonian or Illinoian in age.

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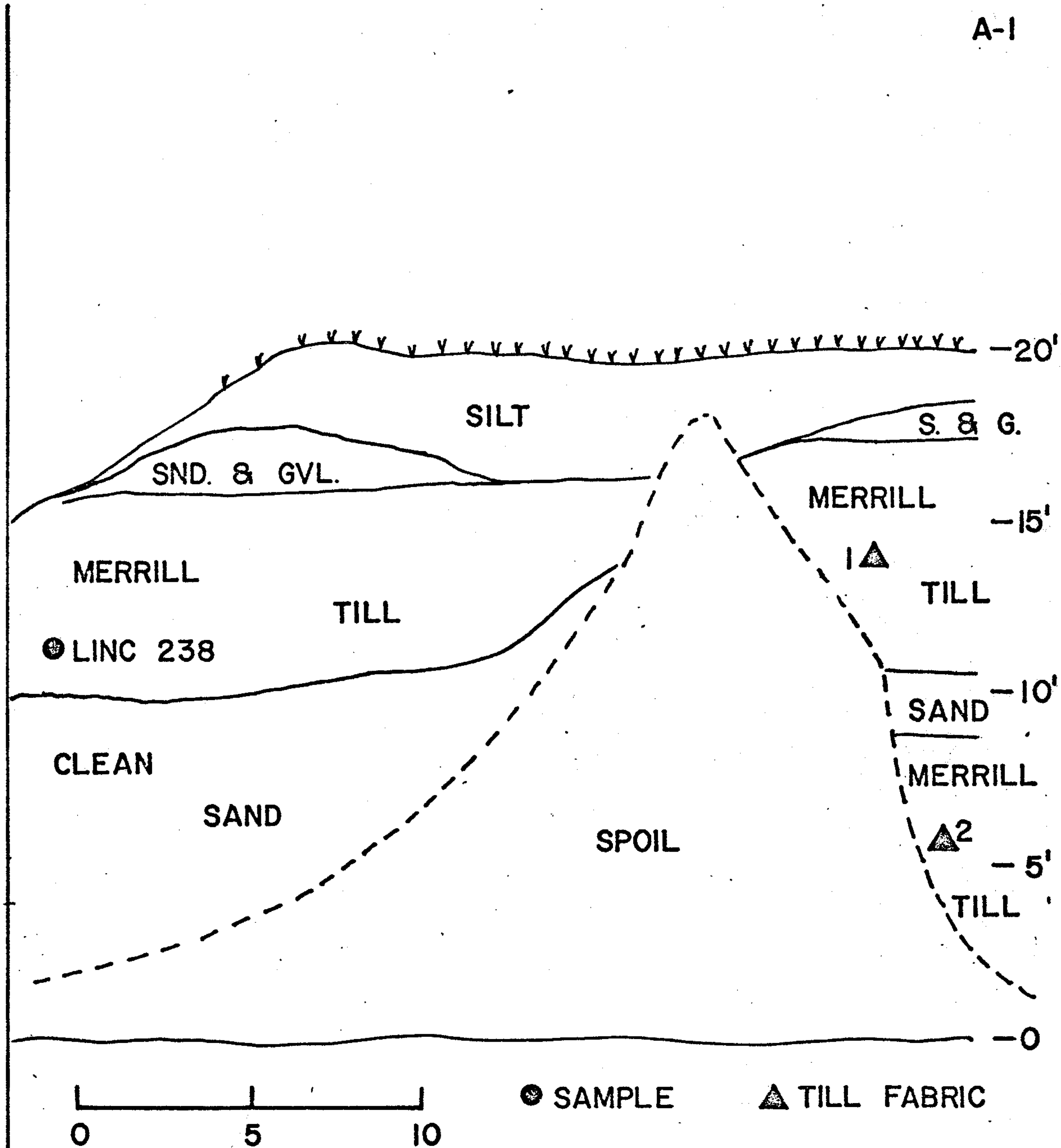
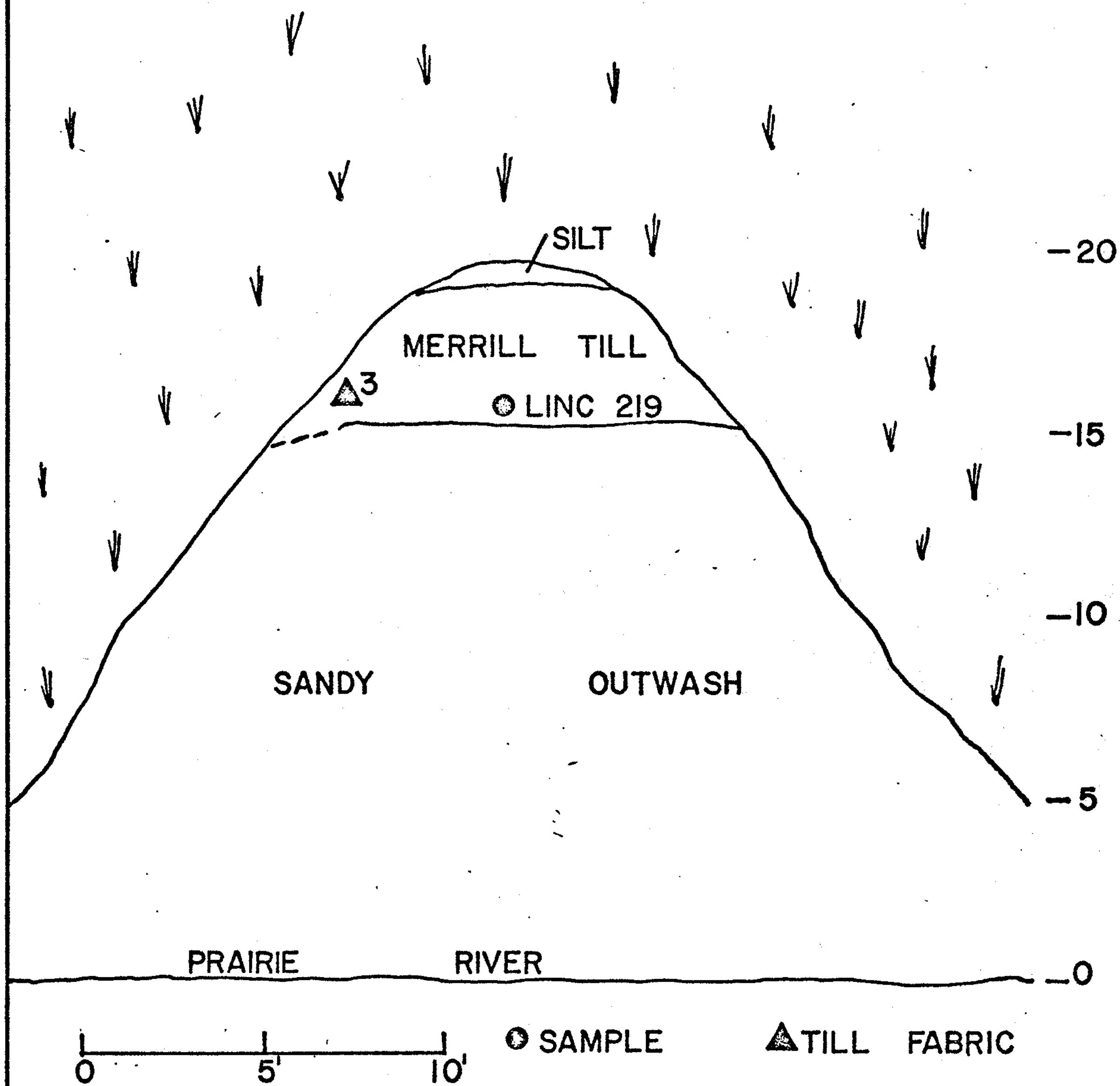
Appendix A. Stratigraphic sections of till fabric sites.



SE I/4 NW I/4 SEC I T3IN R6E GRAVEL PIT

MERRILL I:62,500

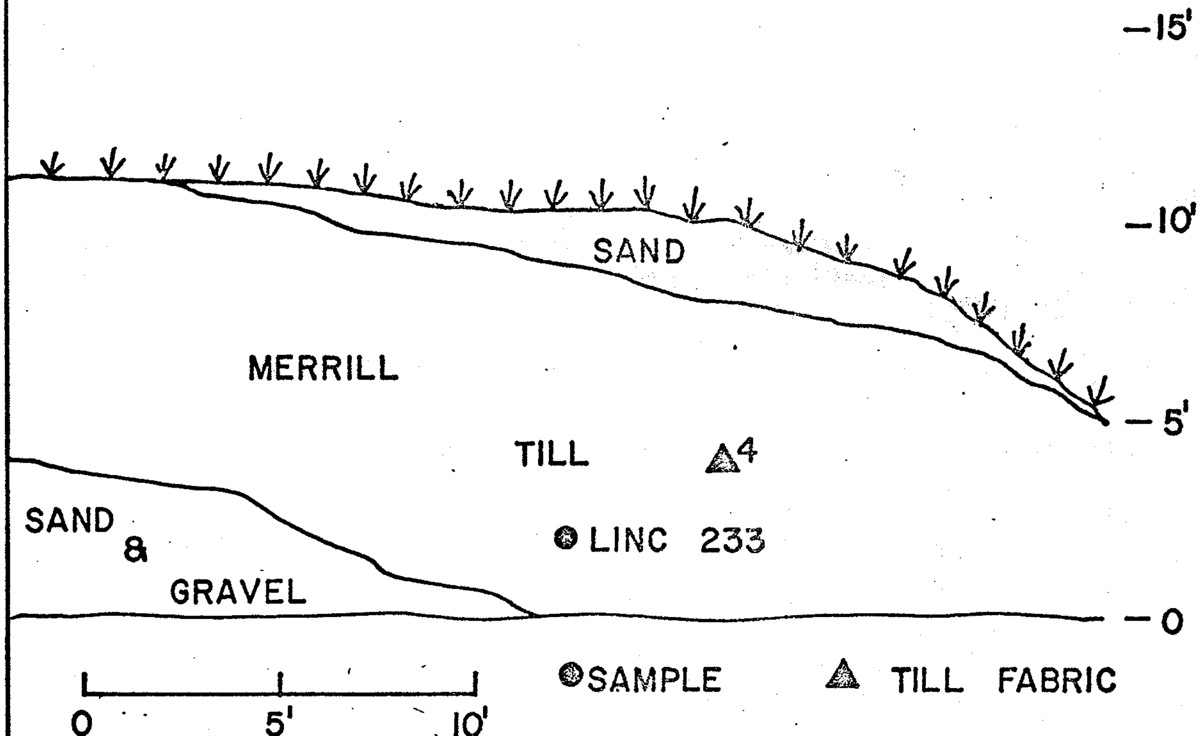
APPENDIX A-2



SE 1/4 SE 1/4 SEC 1 T31N R6E RIVER BANK GULLY

MERRILL 1:62,500

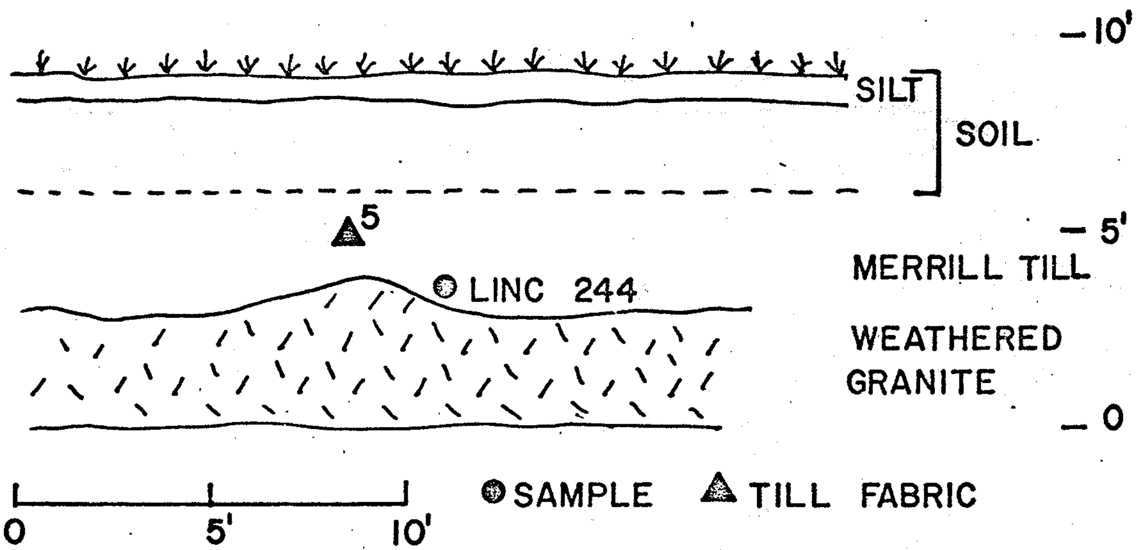
APPENDIX A-3



SE 1/4 SW 1/4 SEC 22 T32N R7E GRAVEL PIT

MERRILL 1:62,500

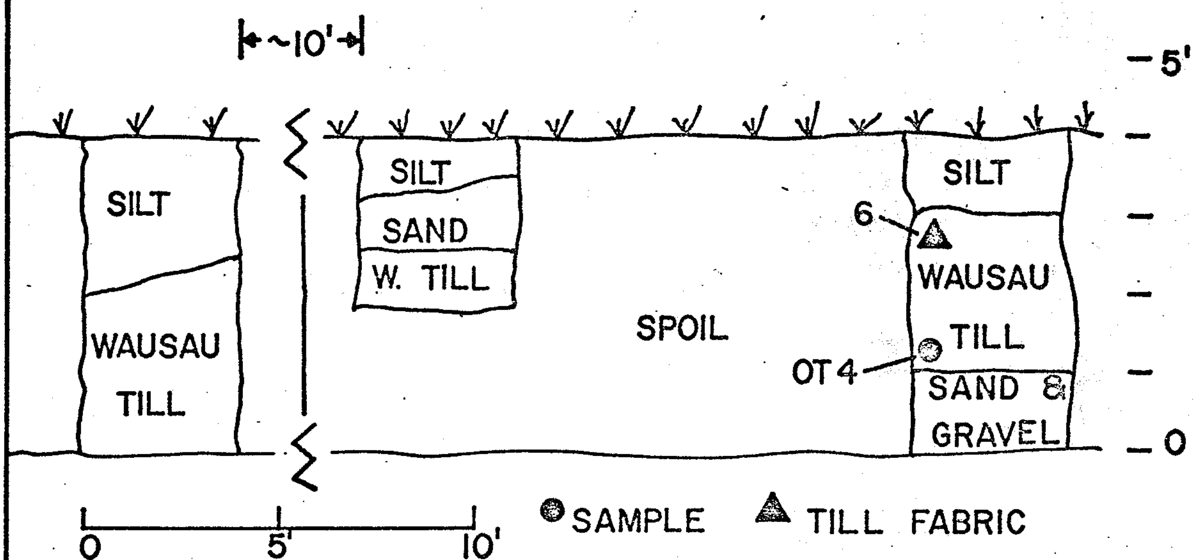
APPENDIX A-4



SW 1/4 SE 1/4 SEC 27 T 31 N R 7 E GRAVEL PIT

MERRILL 1:62,500

APPENDIX A-5



NW 1/4 NE 1/4 SEC I T 32 N R 8 E GRAVEL PIT

PARRISH 1:48,000

Appendix B. Sample locations and data

	sample #	1/4 section	1/4 section	section	township (N)	range (E)	hole #	depth	% sand	% silt	% clay	% mica	% kaolinite-chlorite	% vermiculite	% smectite	amphibole (8.5A)	quartz (3.34/4.27A)	calcite (3.03A)	dolomite (2.88A)	plagioclase (3.19A)	K-feldspar (3.28A)
LNG GRN. BY. LOBE	25	SW	NW	3	31	12	out	4	83	14	3	71	14	3	12	45	210/55	t	20	30	50
	26	SW	SW	31	31	12	"	6	81	14	5	81	12	0	7	--	420/50	20	20	30	60
	31	NW	SE	7	31	14	"	3.5	--	--	--	64	16	0	20	t	230/55	--	t	30	50
	32	SW	NW	13	31	13	"	5	86	11	3	62	13	14	11	--	310/40	t	t	30	55
	34	SW	SE	10	30	11	"	20	82	14	4	66	8	9	18	--	270/40	--	--	55	40
LN LANGLADE LOBE	8		SE	2	35	9	out	3	62	29	9	79	9	3	9	--	230/25	--	30	30	30
	9		SW	25	35	9	"	8	72	22	6	80	20	0	6	30	300/55	--	--	40	25
	10		SW	7	34	10	"	4	72	22	6	78	19	0	4	t	170/20	--	--	20	20
	11		NE	26	33	10	"	10	77	16	7	63	23	0	14	--	230/20	--	--	25	30
	12		SW	34	35	10	"	3	77	17	6	79	17	0	4	t	300/40	--	30	30	40
	13		NE	26	33	10	"	10	78	17	5	71	22	0	7	t	360/20	--	--	20	30
	14		SE	30	36	9	"	4	76	17	7	77	15	0	8	40	290/30	--	--	45	40
	20		SE	26	36	8	"	2	88	11	1	65	9	11	4	--	270/50	--	--	--	--
	21		SW	25	33	10	"	14	80	18	2	54	22	0	24	20	380/35	20	--	30	50
	34		NW	10	35	8	"	2	84	14	2	61	19	0	20	--	270/45	--	--	70	50
LN WISC. VLY. LOBE	1		SE	22	34	8	out	9	80	15	5	65	20	0	15	t	320/30	--	--	30	30
	2		NW	10	33	8	"	8	76	19	5	68	28	0	4	30	260/30	30	--	50	40
	3		SW	7	34	8	"	12	80	15	5	61	24	8	6	20	210/20	t	--	40	20
	4		SE	33	35	8	"	10	80	16	5	63	18	0	9	t	240/25	--	--	60	50
	5		SW	12	34	8	"	9	77	18	5	69	22	0	9	--	210/20	--	--	40	35
	6		NW	7	34	9	"	17	76	20	4	58	21	0	21	t	190/20	--	--	40	30
	7		NW	31	35	9	"	13	80	16	4	65	28	0	8	--	210/20	--	--	35	30
	16		SE	30	35	9	"	20	80	20	0	68	10	8	14	20	240/15	--	--	20	30
	17		SW	29	35	9	"	24	81	18	2	67	18	0	14	--	160/30	--	--	40	50
	19		NW	31	35	9	"	3	84	14	2	73	19	0	7	--	190/30	--	--	32	50
LINC MERRILL	213		NW	6	31	8	out	4	46	48	5	57	5	29	8	--	210/30	--	--	--	20
	215		SE	1	31	6	"	6	70	24	6	--	--	--	--	--	--	--	--	--	--
	219		SE	1	31	6	"	4	62	22	12	39	6	30	24	60	230/40	55	--	90	70
	233		SW	22	32	7	"	6	62	30	8	--	--	--	--	--	--	--	--	--	--
	238		NW	1	31	7	"	6	73	17	10	56	7	21	16	20	220/20	40	--	50	20
	239		SW	28	32	7	7	6	72	12	16	--	--	--	--	--	--	--	--	--	--
	240		SE	35	32	7	8	7	52	33	15	--	--	--	--	--	--	--	--	--	--
	242		SW	10	32	8	11	9	62	26	12	64	8	13	16	40	290/30	60	--	60	36
	244		SE	27	31	7	12	4	57	35	8	40	14	23	23	--	140/--	--	--	--	--
	246		SW	19	31	8	14	6	--	--	--	43	7	32	18	--	310/20	100	--	30	40
	250		NE	2	30	8	17	5	60	30	10	49	14	22	16	--	300/35	40	--	30	t
	253		SW	27	31	8	22	8	--	--	--	48	7	24	21	20	110/--	40	--	t	--

		sample #	1/4 section	1/4 section	section	township (N)	range (E)	hole #	depth	% sand	% silt	% clay	% mica	% kaolinite-chlorite	% vermiculite	% smectite	amphibole (8.5A)	quartz (3.34/4.27A)	calcite (3.03A)	dolomite (2.88A)	plagioclase (3.19A)	K-feldspar (3.28A)
MERRILL	LINC	256		SW	12	31	8	25	4	66	25	9	44	10	34	12	--	320/20	85	--	38	30
		257		SE	29	32	8	27	4	--	--	--	45	8	31	15	30	210/--	70	--	t	20
		259		SE	29	32	8	27	8	61	39	0	65	8	20	7	--	310/--	90	--	50	20
		266		NE	36	33	8	34	8	68	19	13	72	5	17	7	--	430/30	130	--	t	t
		267		NE	26	32	7	35	8	55	32	13	49	7	32	13	--	300/30	60	--	50	20
		269		NE	11	31	7	36	8	42	58	0	60	12	21	7	--	270/35	--	--	--	--
	LANG	208		SW	19	33	9	3	6	64	26	11	--	--	--	--	--	--	--	--	--	--
		213		SW	11	33	9	6	8	--	--	--	58	15	12	15	--	280/50	--	--	--	--
		216		SE	30	32	10	20	7	69	25	26	46	8	25	20	t	170/--	20	20	t	t
		221		SW	17	32	9	26	8	63	37	0	47	16	17	21	--	300/30	--	--	--	--
		222		NW	4	33	9	out	5	66	25	9	42	14	29	14	--	250/40	--	--	--	--
	MAR	201		NW	7	30	9	28	6	--	--	--	44	5	26	24	60	230/30	70	--	58	50
		205		NW	8	30	8	30	5	42	42	16	34	6	39	22	--	220/30	45	--	--	--
WAUSAU	MAR	206		NW	8	30	8	30	8	48	33	19	27	8	31	35	t	140/--	20	--	20	20
	OT	4		NE	1	32	8	out	4	45	37	18	30	5	21	44	--	290/20	--	--	--	--
	HY US	51											21	5	29	44	--	130/--	--	--	--	--

Appendix C

Well Log Data

1. NE NE SEC 7 T33N R9E Langlade County H, 4 miles east of Parrish

0-7'	brown sand and gravel
7-8'	grey sandy clay till
8-13'	wet grey sandy clay till

2. NE SW SEC 17 T33N R9E

0-4'	soil
4-7'	red clay till (Merrill till)

3. NW SW SEC 19 T33N R9E

0-4'	soil
4-7'	red clay till LANG 208 (Merrill till)

4. NW NE SEC 35 T33N R9E

0-10'	sand and gravel
10-12'	coarse sand and gravel
12-24'	red till mixed with lots of water (Merrill till)

5. NE NW SEC 3 T32N R9E ½ mile east of intersection of County J and H

0-2.5'	fill
2.5-4'	grey black clayey soil, 1-3 inch lumps
4-12'	reddish brown very clayey stuff
12-18'	getting gritty, still a lot of clay, but more coarse sand and pebbles
18-20'	change to wetter, slightly sandy light dirt brown clay
20-24'	lighter color, more sand

6. NE SW SEC 11 T33N R9E

0-2'	soil
2-4'	dark grey sandy clay
4-8'	medium brown clayey sand, lumps but mostly sand
8-14'	medium brown sandy clay with pebbles, pebbles not frequent LANG 213 (Merrill till)

7. NW SW SEC 28 T32N R7E

0-3'	soil, clay rich
3-4'	transition to red-brown Merrill till
7.5'	bit bottomed on rock, LINC 239

8. SE SE SEC 35 T32N R7E

0-3.5' soil brown loam 0-1 feet, clay loam 1-3 feet
3-6.5' transition to red-brown Merrill till
9.5' bottomed on rock, LINC 240 7-9.5'

9. SE SE SEC 8 T32N R8E

0-4' clay rich soil
Bottomed four times over 15-20' line at 4-5' on rock. Chips of medium grained Kspar granite came up with soil. Looks like the clay rich soil usually found above the Merrill till.

10. SE SE SEC 20 T33N R8E Russell Township Dump, Townline Rd. north of Gleason

10' clean sand, hit rock, no till

11. SW SW SEC 10 T32N R8E County X, intersection County X and Mosser Rd.

0-7' soil and road fill
7-15' red-brown Merrill till, LINC 242 9-10'
18' bottomed on rock

12. SW SE SEC 27 T31N R7E

3' of soil developed on total of 5.5' of till on top of bedrock regolith. Bedrock is Kspar granite. LINC 244 Merrill till from below soil

13. NW NW SEC 23 T31N R7E

hole drilled thru 2-3' of light brown clay, looks like C horizon on till. Hit bedrock five times, quit.

14. SW SW SEC 19 T31N R8E Rangeline Rd.

0-4' soil
4-7.5' red-brown Merrill till, LINC 246 two bags
I 5-5' II 6-7.5'
7.5' coarse grained Kspar granite

15. SW SE SEC 9 T31N R7E Oak Ridge Rd.

0-2.5' soil
2.5-4' red-brown Merrill till
4-5' grey-green silt with abundant dark grey pebbles
5' bottomed on hard rock, probably bedrock

16. SW SE SEC 8 T31N R8E

0-2' mucky soil
2-4' mucky light brown clay
4-8' wet Merrill till

17. SE NE SEC 2 T30N R8E

0-3' road fill and soil
3-4' transition to Merrill till
4-7.5' red-brown Merrill till, LINC 250D 4-6' possible weathered bedrock in bottom of hole. Bottomed on hard rock.

18. NW NW SEC 26 T32N R8E

0-1' brown, sandy topsoil
1-3' dark grey sandy soil with pebbles
3-6' grey brown mottled sandy clay
6-40' clean sand
40-55' grey green, light brown, dark grey, silty, compact organic rich clay. Some twigs, probably bog.
55-57' sandy Merrill till

19. SW SE SEC 19 T32N R9E

0-4' soil and road fill
4-32' sandy outwash
32-34' red sandy clay
34-35' sand, bottomed on rock

20. SW SE SEC 30 T32N R10E

0-4' road fill, dark grey soil, light brown clayey soil
4-8' red-brown Merrill till, LANG 216D 7-8'
8' bottomed on very hard rock, nothing came up, soil not stoney, i.e., bedrock

21. NE SE SEC 7 T31N R10E glacial lake (?) very flat topography

0-2' brown soil
2-4' dark grey clay
4-5' mucky light brown clay
5-9' light grey mottled sandy clay possibly lake sediments or bog deposit, a few pebbles and granules
9-13' light brown sandy clay
13-18' mucky light brown clay
18-23' dark to light grey clay

22. SW SW SEC 27 T31N R8E

0-2' road fill
2-5' soil
5-12' Merrill till, LINC 253

23. NE NW SEC 30 T31N R9E looks like western edge of large lake bed

0-2' fill
2-5' soil
5-12' red silt grading into red clay silt. LINC 254D
12-15' possible red-brown till LINC 255D
16' rock

24. NW NE SEC 29 T31N R10E

0-5' soil developed on bedrock, possible till influence
5' bedrock, some outcrops in area, granite

25. NE SW SEC 12 T31N R8E

0-3' soil
3-6' Merrill till, LINC 256

26. SE SW SEC 17 T32N R9E

0-5' road fill and soil
5-7.5 brown pebbly till, Merrill till, but not red, LANG 221

27. SE SE SEC 29 T32N R8E

0-4' soil
4-6' good Merrill till, maybe a little more clay, LINC 257 4-6'
6-7' transition zone
7-16' apparently an old soil or regolith, LINC 259D 6-8' first "regolith" on stem
16' bottomed on large immovable object

28. SE NW SEC 7 T30N R9E Trappe River sch

0-2.5' soil
2.5-7' red-brown Merrill till, MAR 201
7' bottom, possible bedrock

29. NW NW SEC 34 T30N R9E northeast of Kalinke

0-2' soil
2-5' grey clay with pebbles and granules, fair amount sand
5-9' weathered regolith on granite. Less clay toward bedrock.
9' Kspar granite

30. NW NW SEC 31 T30N R10E

0-5' soil and regolith on weathered granite (Kspar) no obvious evidence of till influence on soil.

31. NW NW SEC 12 T30N R9E

0-4' soil
4-11' grey, clay rich, micaceous weathered soil
11' bedrock (?)

32. NW NW SEC 8 T30N R8E

0-2.5' road fill
2.5-5' soil
5-7' brown clayey sandy pebbly till MAR 205 (Merrill till)
7-10' MAR 206 (Wausau till)
10-12' silty powder, light brown
12' bottom, bedrock

33. SE SE SEC 13 T33N R7E

0-2' sandy red-brown till
2-20' orange sand
20-42' reddish grey slightly clayey pebbly sand, gets more coarse at base
42' bottom

34. SE NE SEC 36 T33N R8E

0-2' road fill
2-5' soil
5-8' Merrill till, not quite red as usual, LINC 266D 6-8'

35. NE NE SEC 26 T32N R7E

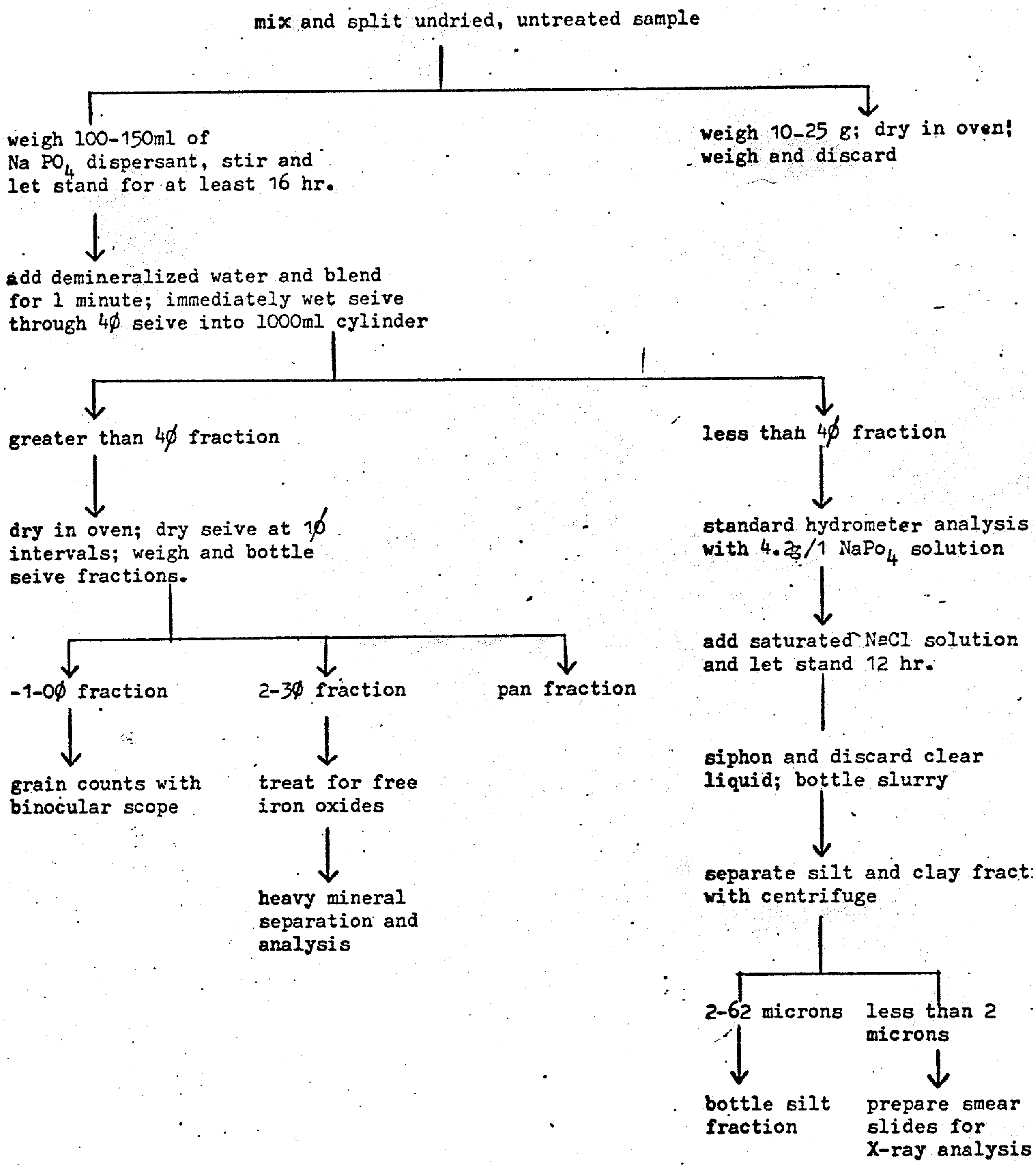
0-5' soil and road fill
5-12' red-brown Merrill till, LINC 267 6-10'
12' bottom, possibly bedrock

36. SW NE SEC 11 T31N R7E

0-6' sandy soil developed on light orange brown sand with pebbles and some clay
6-8' brown sandy clay
8-12' darker brown more clayey, Merrill till with many pebbles, LINC 269D 8-12'
12' weathered white bedrock

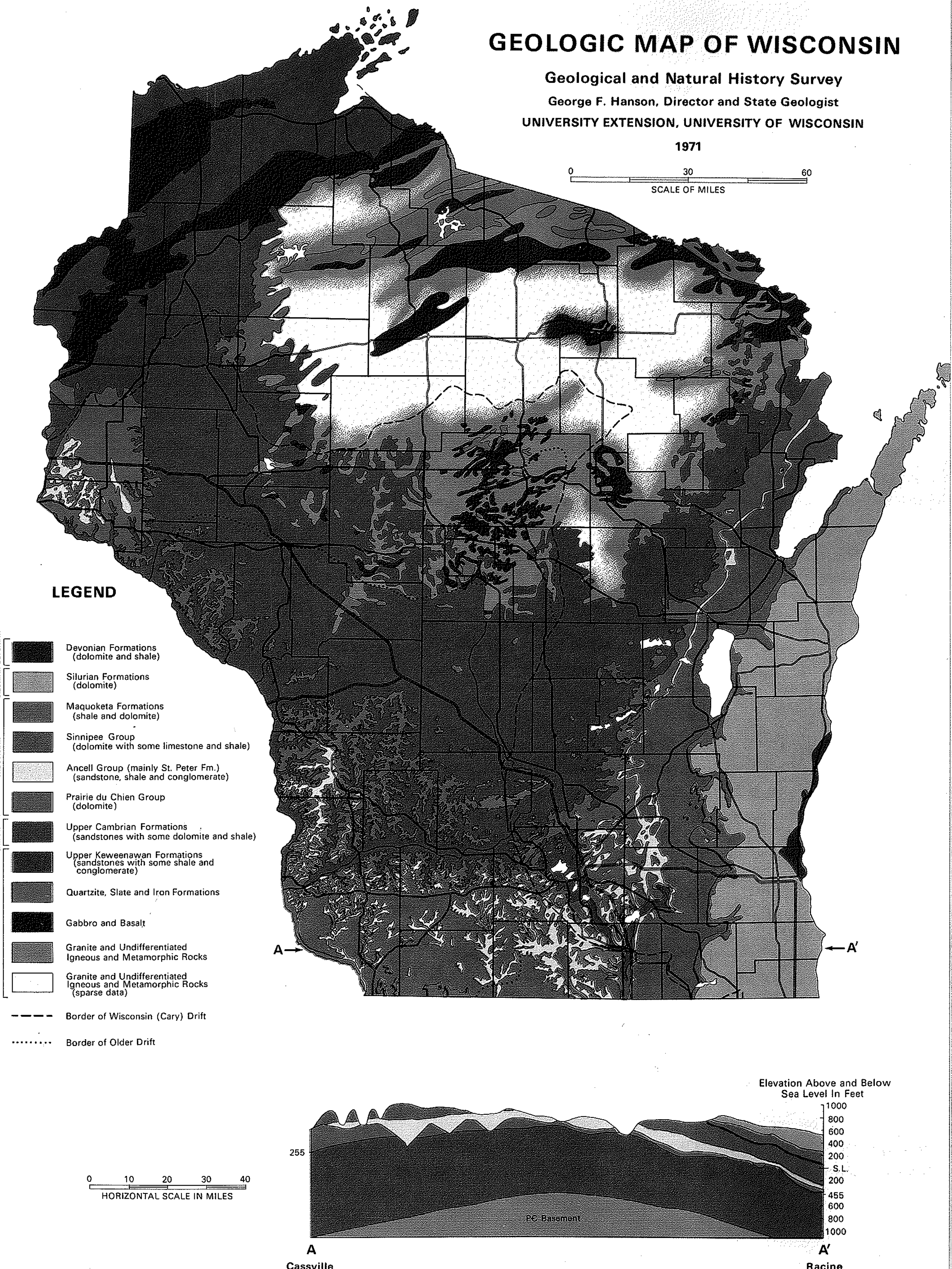
Appendix D

GRAIN SIZE ANALYSIS FLOW CHART

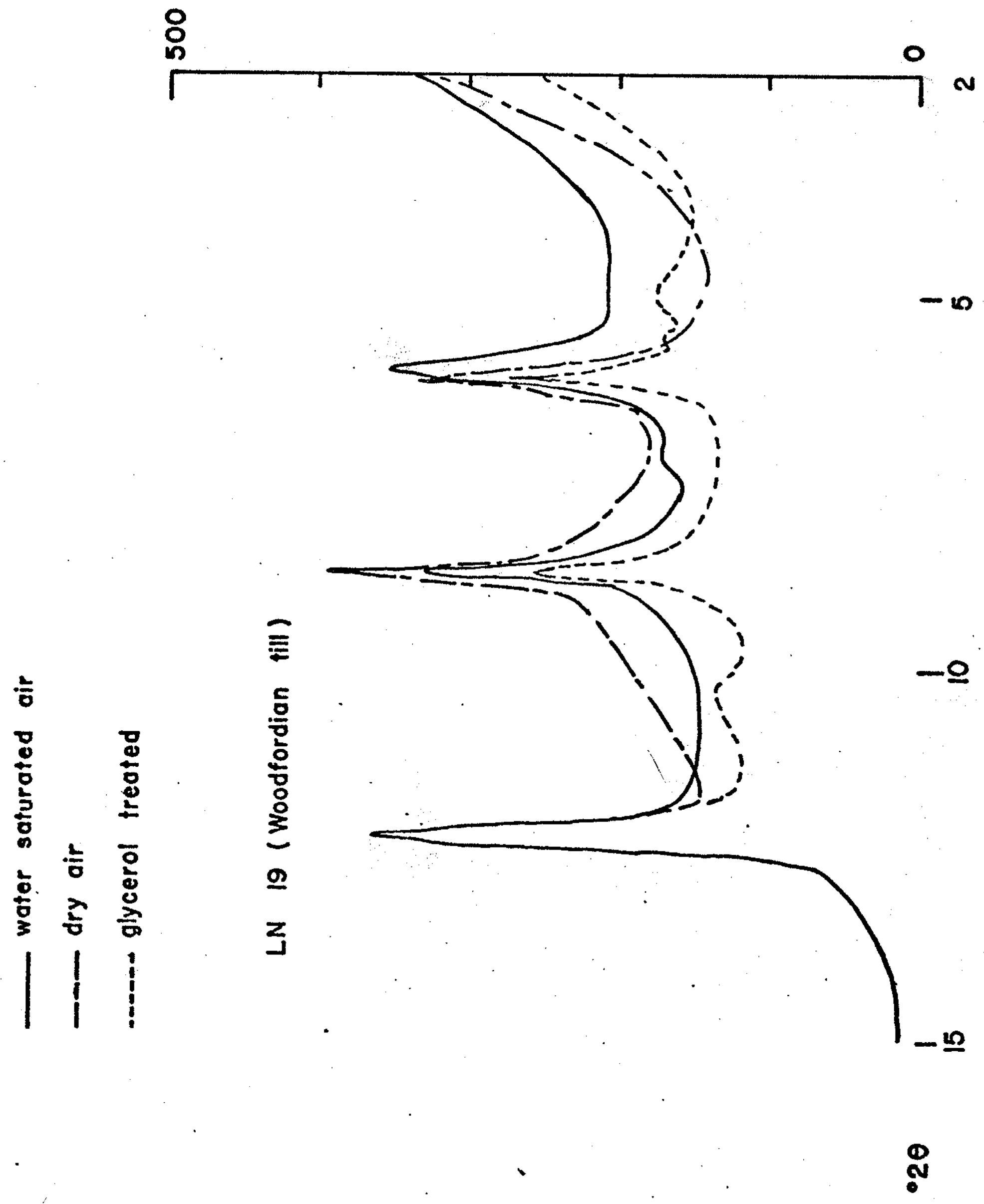


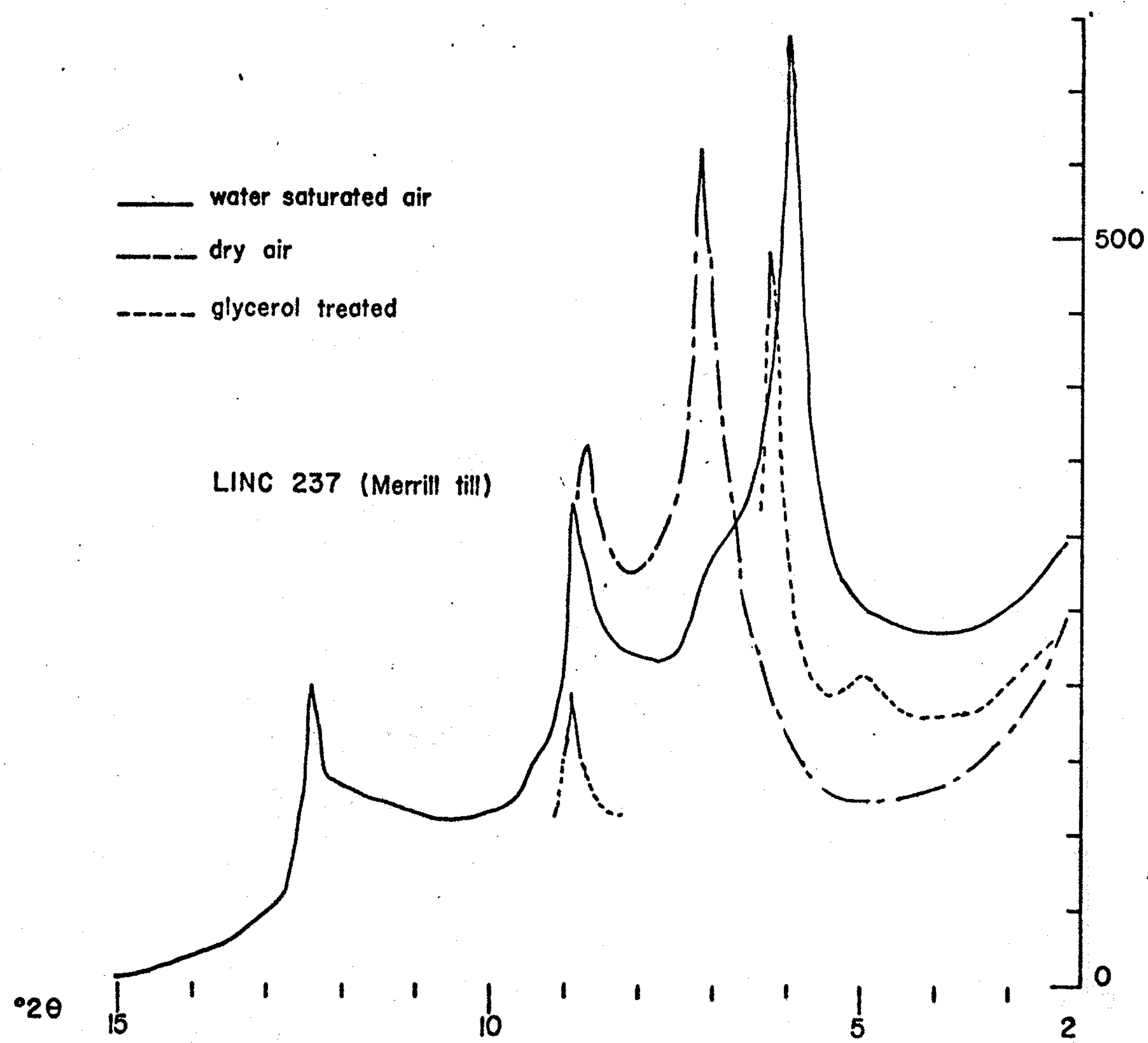
GEOLOGIC MAP OF WISCONSIN

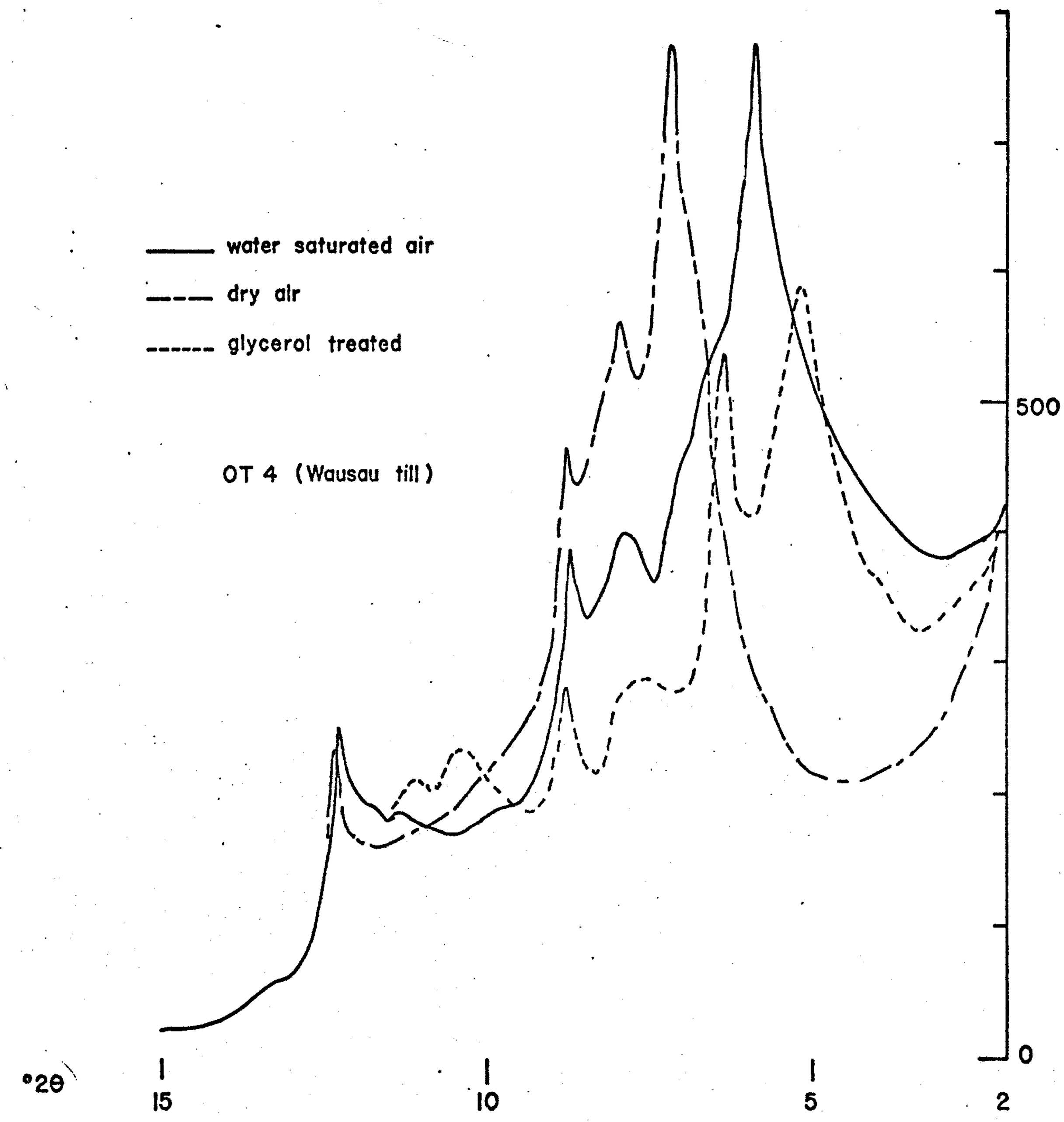
Geological and Natural History Survey
George F. Hanson, Director and State Geologist
UNIVERSITY EXTENSION, UNIVERSITY OF WISCONSIN
1971



Appendix F. X-ray diffractograms of typical samples of Woodfordian, Merrill, and Wausau tills.




water saturated air
dry air
glycerol treated
LINC 237 (Merrill till)
500
0
°2θ
15
10
5
2



water saturated air
dry air
glycerol treated
OT 4 (Wausau till)
500
0
°2θ
15
10
5
2

APPROVED: David M. Mickelson

Carl J. Bowser

Francis D. Hole

DATE: December 19, 1973