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QUATERNARY GEOLOGY OF THE
ITASCA - ST. CROIX MORAINE INTERLOBATE AREA,
NORTH-CENTRAL MINNESOTA

A THESIS

SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL

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BY

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ABSTRACT

During the St. Croix Phase of the Late Wisconsinan Substage, two lobes of the Laurentide Ice Sheet terminated and formed an interlobate junction in Cass County, Minnesota. Coarse textured, yellowish- to reddish-brown supraglacial sediments (Brainerd Till) were deposited as the north-south trending St. Croix Moraine by a southwestward advance of the Brainerd Sublobe of the Rainy Lobe. Brainerd Till is characterized by a high percentage of reddish crystalline rocks derived from a source area to the northeast and also by a low percentage of carbonate, probably derived by incorporation of underlying carbonate-rich till. The terminal position of the Brainerd Sublobe is also marked by a continuous fosse and dump ridge at the head of the westerly grading Oshawa outwash plain. A second outwash plain was formed behind the St. Croix Moraine during retreat of the Rainy Lobe at the end of the Itasca-St. Croix Phase.

A contemporaneous advance of the Wadena Lobe deposited the Lower Red Lake Falls Formation, a light olive brown to gray sandy loam till which contains moderate amounts of carbonate clasts and sparse northeast-source rock types. The bulk of the sediments were deposited as the east-west trending Itasca Moraine. Within that moraine are numerous sets of transverse compressional ridges with a broad curvature to the northeast, reflecting a south-southwesterly course for the Wadena Lobe at its terminus. An advance of that glacier to a position some 25 km south of the Itasca Moraine is indicated by extra-moranic till and pitted outwash. Outwash sediments from the Wadena Lobe dominate the proglacial and interlobate areas. The surfaces of two pitted outwash plains grade south and southeastward from the Itasca Moraine and bury the northern part of the St. Croix Moraine.

Sediment texture in both the Itasca and St. Croix moraines becomes coarser to the southeast across the study area. Carbonate content decreases and northeast-source rock types increase in the same direction. These variations are best explained as the result of incorporation of underlying till during several glaciations of the Wisconsinan Stage prior to and including the Itasca-St. Croix Phase.

The Hewitt Till, deposited by a southwestward advance of the Wadena Lobe during the earlier Hewitt Phase of the Wisconsinan Glaciation, is a compact, dark brown, sandy lodgement till. It is completely buried by outwash sediments close to the Itasca and St. Croix moraines, but gradually emerges to become the dominant surficial deposit as the outwash sediments thin to the southwest. The Hewitt Till surface in the study area is drumlinized, forming the northernmost exposed portion of the Wadena Drumlin Field. Trends of Wadena drumlins show a gradual shift from S 22° W in the eastern part of the study area to S 64° W in the western part. Fabric measurements on drumlins show a strong preferred orientation of elongate stones dipping to the northeast, indicating a southwest advance of the Wadena Lobe during the Hewitt Phase.

Eolian sands form a thin blanket over the Wadena drumlins and outwash sediments in the southeast part of the study area. Barchan dunes developed in a small area where an abundant supply of fine-grained sand and a long northwesterly fetch were present. Eolian activity probably occurred during the mid-Holocene Hypsithermal Interval, approximately 8,000 to 5,000 B. P., when the climate was more arid and prairie vegetation dominated the area.

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INTRODUCTION

General Statement

The Itasca-St. Croix Moraine interlobate area is an important landmark of late Pleistocene glacial activity in northern Minnesota. In this locality, two prominent end moraines merge in a complex of meltwater deposits. The St. Croix Moraine forms a narrow, sharply defined, ice stagnation complex trending northward in the study area. It merges at its northern end with the much broader Itasca Moraine which is oriented east-west. Glaciofluvial sediments dominate the interlobate area between the two moraines, and proglacial outwash sediments form an almost flat plain which extends southward for several tens of kilometers. The northern end of the Wadena Drumlin Field is also found in the study area. The drumlins are buried by the Itasca Moraine to the north and St. Croix Moraine to the east, but gradually emerge to the southwest from beneath the overlying mantle of outwash.

Although the general relationships between the moraines and underlying drumlinized ground moraine have been postulated, and much work on the glacial history and stratigraphy has been done in surrounding areas, no detailed work has been done in the interlobate area where the two moraines coincide. This project was undertaken with the purpose of studying lithologic and geomorphic relationships between the different glacial till units, to better understand late Wisconsinan glacial stratigraphy and history in this key area of northern Minnesota.

Study Area

The study area is located in north-central Minnesota, and includes portions of Hubbard, Cass and Wadena counties (Figure 1). Sampling and mapping were concentrated in a core area encompassed by the Crystal Lake, Hackensack, Oshawa and Backus quadrangle maps (U. S. Geological Survey, 7.5 minute series), covering an area of approximately 525 km^2 (205 mi^2). Reconnaissance mapping, consisting primarily of aerial photography interpretation and limited sampling, was carried out in the quadrangles surrounding the core area, as indicated in Figure 1.

Previous Work

Early interpretations of the glacial deposits in north-central Minnesota were part of statewide studies undertaken by the first Minnesota state geologist, N. H. Winchell, and his colleagues, Warren Upham, J. E. Todd and U. S. Grant. Between 1872 and 1895 they mapped the surficial geology of Minnesota on a county by county basis. A total of twelve moraine systems were identified which were summarized on a single map by H. E. Wright, Jr. (1962), shown in Figure 2. These were interpreted as having been deposited by one or both of two major ice lobes: the Lake Superior Lobe and the Minnesota Lobe. The Lake Superior Lobe (now called the Superior Lobe) was thought to have advanced southwest out of the Lake Superior Basin, whereas the Minnesota Lobe (now called the Des Moines Lobe) moved towards the southeast from the Winnipeg Lowlands.

Upham (Winchell et al., 1899; Chapter 3) recognized two belts of terminal moraine in Cass County. He named the east-west moraine, which lay south of Leech Lake, the Itasca Moraine. It was part of the tenth in

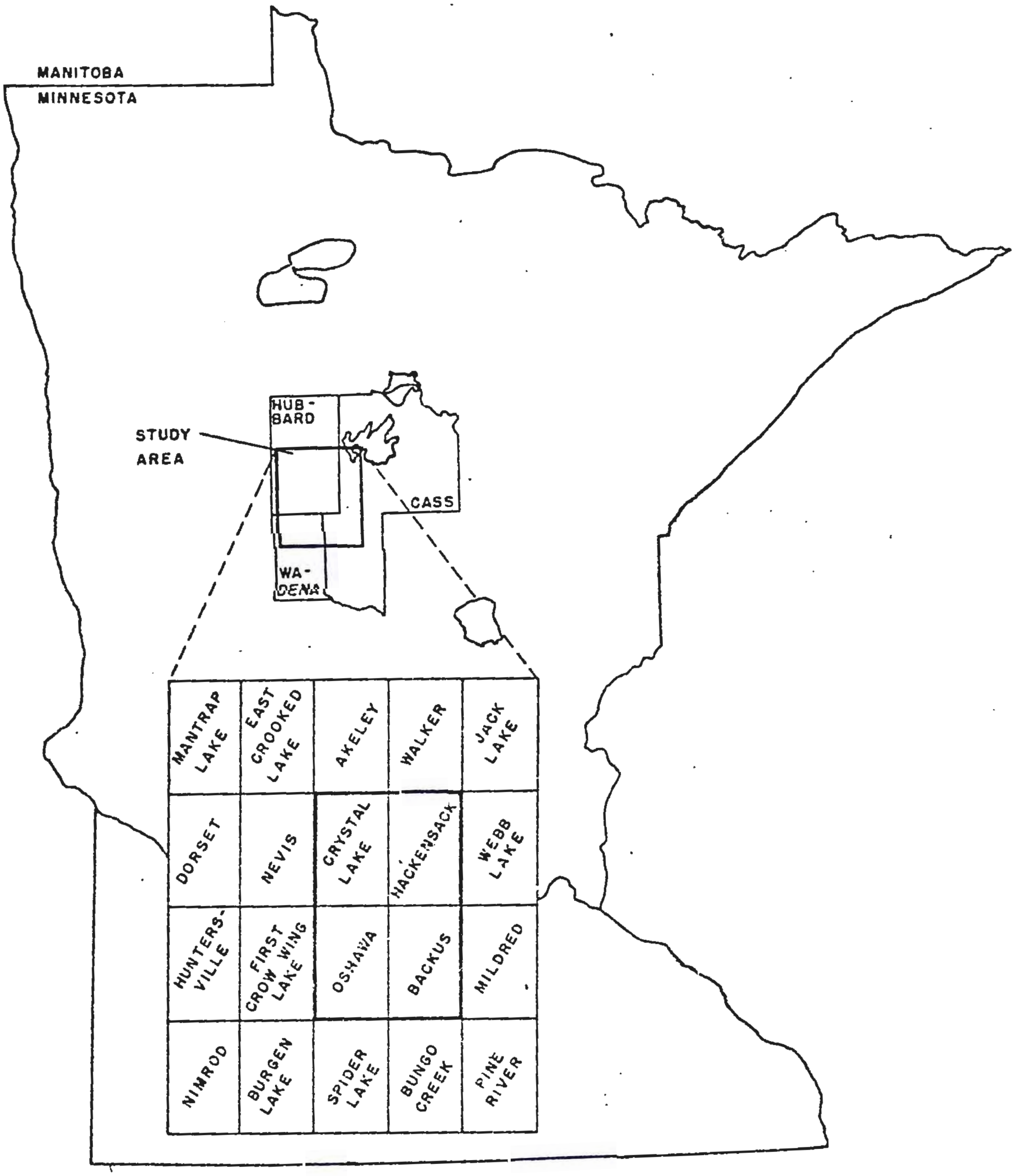


Figure 1. Index map of study area.

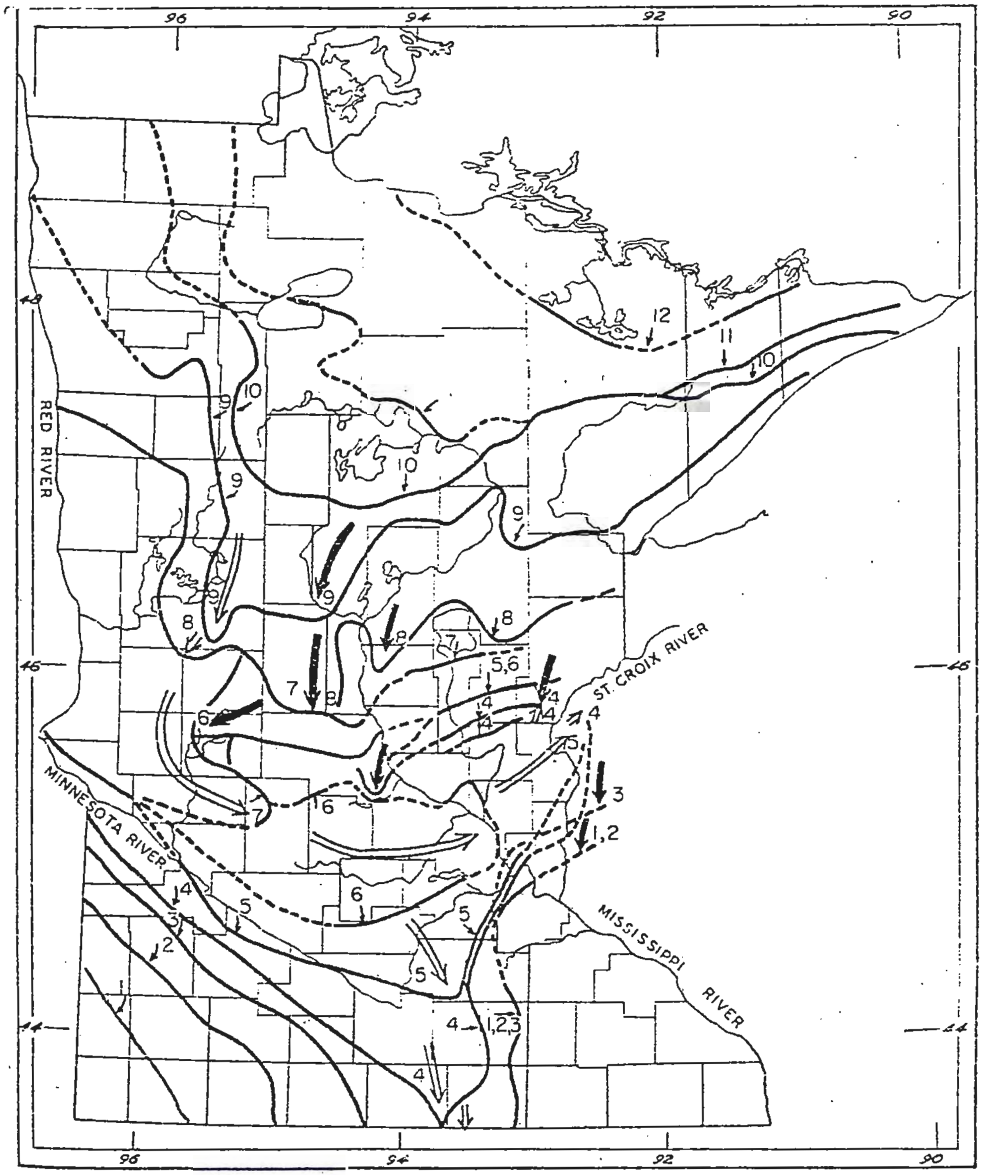


Figure 1. Sequence of retreatal moraines of Wisconsin stage in Minnesota according to Upham. Large black arrows show flow direction of eastern ice mass at different moraine stages; large open arrows refer to western ice. Compiled and simplified from Upham (1881; 1896; Wright, 1920) and from separate county maps in Winchell and Upham (1888). The moraines were also known by the following names: 1st, Altamont; 2d, Gary; 3d, Antelope; 4th, Kiester; 5th, Elysian; 6th, Waconia; 7th, Dovre; 8th, Fergus Falls; 9th, Leaf Hills; 10th, Itasca; 11th, Mesabi; 12th, Vermilion.

Figure 2. Late Pleistocene moraines mapped by Winchell and Upham (from, Wright, 1962)

a sequence of retreatal moraine systems envisioned by Winchell and Upham (Figure 2). The other terminal moraine in Cass County, part of the ninth moraine system, was named the Leaf Hills Moraine. Upham also briefly described the abundant ice-block depressions and glaciofluvial deposits surrounding the moraines in Cass and Hubbard counties.

Frank Leverett of the U. S. Geological Survey, with the assistance of Frederick Sardeson, remapped the entire state during the early 1900's. His final report and statewide surficial geology map (Leverett and Sardson, 1932) contain the interpretations of glacial geology still used in many areas of the state. They made very little mention of Winchell and Upham's previous work, however, and introduced a new set of nomenclature to describe the glacial history of Minnesota. The Lake Superior Lobe became the Patrician Ice Sheet, with a small Superior Lobe advancing from the Labradorean Ice Sheet; the Minnesota Lobe became the Des Moines Lobe of the Keewatin Ice Sheet.

In the Itasca-St. Croix moraine interlobate area, Leverett renamed the Leaf Hills Moraine of Upham. Under the new terminology, it became the northern end of the St. Croix morainic system, composed of "young red drift" of the Keewatin Ice Sheet. Leverett also recognized the northeast-southwest trending hills (later named the Wadena Drumlin Field) in Wadena and Todd counties, but he interpreted them as being deposited by an offshoot of ice which moved northeastward from the main Kewatin Ice Sheet which lay to the southwest. Except for his interpretation of the drumlin field, Leverett's work stands as the accepted interpretation of the surficial geology in much of the study area.

Leverett recognized three major subdivisions of the Wisconsinan Glaciation in Minnesota, and used the modifiers "Early", "Middle" and "Late" to refer to subages of the Wisconsinan Age. Thus, the Altamont-

Gary Moraine (later renamed the Alexandria Moraine) was Early Wisconsinan in age, the St. Croix and Itasca moraines were deposited during the Middle Wisconsinan, and the extensive southward advance of the Des Moines Lobe which deposited the Bemis Moraine was Late Wisconsinan in age. During the following decades, a different terminology, using geographical names, was developed for subdividing the Wisconsinan Glaciation. In place of Early, Middle and Late, the Wisconsinan was subdivided into Iowan, Tazewell, Cary, Mankato and Valders (Wright, 1962; 1972).

Subsequent investigations have revealed problems in correlating Wisconsinan substages in the midwestern part of the continent. Most recently, a system of naming individual phases of glacial activity in Minnesota has been developed by Wright and Ruhe (1965). Under their system, the phase of glaciation that formed the Alexandria Moraine was named the Hewitt Phase of the Wadena Lobe, and the St. Croix Moraine was formed during the St. Croix Phase of the Rainy/Superior lobes. This system of designating separate phases of glacial activity will be followed in this report.

A detailed study of the Wadena Drumlin Field was done by Wright (1962). With the aid of large scale topographic maps, aerial photographs and field studies of the orientation of long stones within the drumlins, he showed that the glacier which formed the Wadena drumlins was moving towards the southeast, not towards the northeast as Leverett believed.

Wright's contributions to the understanding of the glacial geology of Minnesota have been numerous and significant (e.g., Wright, 1972; 1976; Wright and Ruhe, 1965; Wright et al., 1969). Within central Minnesota, closer to the study area, he has completed several other important studies relating to Quaternary geology (Wright, 1955; 1956; 1962; Arneman and Wright, 1959).

Other recent works pertinent to this study include Schneider's (1961) study of the Randall region, which lies south of the Itasca-St. Croix moraine interlobate area in Morrison and Todd counties; Winter, Cotter and Young's (1973) study of drift lithologies and stratigraphy overlying the Mesabi Iron Range in northeastern Minnesota; and Teller and Fenton's (1979) summary of Late Wisconsinan glacial stratigraphy in southern Manitoba. Regional stratigraphic correlations were made for northwestern Minnesota, North Dakota and southern Manitoba by Moran et al. (1976), and a recent summary of Wisconsinan Stage glacial history in Minnesota was written by Matsch and Schneider (in preparation).

Immediately to the north and west of the interlobate area, several graduate theses were recently completed under the direction of Lee Clayton and Stephen Moran at the University of North Dakota (Harris, 1975; Sackreiter, 1975; Anderson, 1976; Perkins, 1977). The work by Sackreiter and Harris was aided by the drilling of several deep auger holes through the surficial sediments to obtain a three-dimensional view of the glacial stratigraphy.

Field Methods

Most of the field work was done from May 31 to July 5, 1979. A preliminary reconnaissance trip was made in early May, 1979, and final field checks were made in late October, 1979, and early May, 1980.

Surficial geology was studied primarily at road cuts. These were present throughout most of the study area along the extensive network of primary and secondary roads which crisscross the area. Unstable bank slopes adjacent to the many lakes in the area and gravel pits were also examined. Field mapping was done initially on U. S. Geological Survey quadrangle maps (scale 1:24,000) and later transferred to a base map at a scale of 1 in. = 2 mi. (1:126,720), using State of Minnesota county highway maps.

Two hundred and seventy samples were taken from a total of 287 sites. Many of the samples were multiple, taken either systematically (e.g. at 50 cm intervals down a vertical face of a gravel pit), or to sample differing sediment types at one location (e.g., samples from both calcareous and overlying non-calcareous (weathered) drift.

Sample sites were excavated to at least two meters depth below surface wherever possible, because of a weathering problem which obscured field identification of the major till types in the area. Briefly stated, the process of soil formation has altered Itasca Moraine material, originally gray to light olive brown (2.5Y 5/4) in color and calcareous, such that it resembles drift from the St. Croix Moraine: non-calcareous, yellowish-brown (10YR 5/4), and often sandy and loose in texture. Oxidation and carbonate weathering horizons (depth of leaching of carbonate fragments) are commonly about 1.5 to 1.7 m below the surface. Appendix A contains detailed descriptions of soil profiles developed on the major tills present in the study area.

Auger cores were taken in a grid pattern from the outwash plain in the southwest part of the study area. Utilization of north-south and east-west roads made it possible to achieve approximately one mile spacing between samples. Grain size and lithologic compositional changes with respect to provenance of the outwash sediment were then studied. Outwash sediment samples and unpublished data from the outwash plains fronting the Itasca and St. Croix moraines were also studied at the U. S. Geological Survey Water Resources Division field office in Grand Rapids, Minnesota. The USGS outwash samples were collected during a study of the Pineland Sands surficial aquifer (Helgesen, 1977), which comprises most of the Park Rapids and Oshawa outwash plains in the study area.

Approximately 50 pebble samples were collected in the field by sieving sediment through a wire screen with 6.4 mm (0.25 in) openings. Stones greater than 64 mm in size were discarded. Relative abundance of different lithologies was later determined in the lab. This more objective method of "pebble counts" was felt to be necessary in determining the extent of mixing of sediment, if any, that had occurred between the Wadena and Rainy lobes.

Fabric analyses (measurement of the orientation of elongate stones with a length:width ratio of at least 1.5:1) were made at several localities. Paleocurrent direction in glaciofluvial sediments was measured at locations where current indicators such as ripplemarks, cross-bedding and attitude of bed contacts showed a persistent direction.

Aerial photographs were used in addition to field work to help delineate mapping unit boundaries on the basis of geomorphology. A complete set of 1:90,000 scale aerial photos taken in 1969 by the Minnesota State Planning Agency (SPA) was used for regional correlations. For more detailed study, 1:20,000 scale Agricultural Stabilization and Conservation Service (ASCS) aerial photos were used. These were flown in 1939 and were available in stereo coverage for parts of the mapping area.

Bemidji (1978) and Brainerd (1969) Minnesota Soil Atlas maps (scale 1:250,000) were examined for general correlations of soil types to surficial geology. In addition, larger scale county soils maps were obtained from area Soil Conservation Service offices in Park Rapids (Hubbard County) and Walker (Cass County).

Laboratory Methods

Grain size distributions were determined for 83 samples. All samples were analyzed by sieving through eight-inch diameter U. S. Standard sieves; the silt plus clay fraction was determined by pipette analysis if it made up more than approximately five percent of the total sample. Standard methods of sediment analysis as described in Royce (1970) were followed. Grain size histograms, cumulative frequency graphs and sorting statistics (mean, sorting, skewness and kurtosis) were plotted and calculated by computer. Results of grain size analyses are listed in Appendix B.

Wentworth (1922) clast size boundaries were used in this study, and equations published by Folk and Ward (1957) were used to calculate sorting statistics (Table 1).

The 1 to 2 mm sand fraction obtained from size analysis was used for constituent particle analysis on 35 samples. Sample splits of between 200 and 400 sand grains were identified by rock type and later grouped into the following major categories:

1) Eastern Indicators

a) Felsite; red to purple colored, vesicular and amygdaloidal basalt and rhyolite (derived primarily from the North Shore Volcanic Group), and red phaneritic granophyre (derived from the Duluth Complex)

b) Gabbro and diabase (Duluth Complex)

c) Red to pink sandstone and siltstone (Fond du Lac and Hinckly formations)

d) Iron formation (primarily Mesabi, Gunflint and Cuyuna fms.)

e) Red agate (North Shore Volcanic Group)

2) Northwest Indicators
    a) Carbonate (Winnipeg Lowlands)
    b) Buff to white chert (Winnipeg Lowlands)

3) Crystalline (igneous and metamorphic)
    a) Phaneritic, felsic ingeous (Canadian Shield, widespread)
    b) Schist and gneiss (Canadian Shield, widespread)

4) Mafics
    a) Basalt (mostly North Shore Volcanic Group)
    b) Greenstone (Canadian shield, widespread distribution)

5) Shale

a) Yellow to white siltstones and shales, some fossiliferous, some non-marine (widespread across North Dakota, northwest and north-central Minnesota (Coleraine Fm.)

b) light green, siliceous marine shale (North and South Dakota, Pierre Fm.)

TABLE 1. GRAIN SIZE PARAMETERS AND SORTING EQUATIONS[1]

I. CLAST SIZE BOUNDARIES, DIAMETERS

	phi Units	millimeters
Boulder	less than -8	greater than 256
Cobble	-6 to -8	64 to 256
Pebble	-2 to -6	4 to 64
Granule	-1 to -2	2 to 4
Sand	+4 to -1	.063 to 2
Silt	+8 to +4	.004 to .063
Clay	greater than -8	less than .004

II. SORTING EQUATIONS

Graphic Mean: $$Mz = \frac{\text{Ø}16 + \text{Ø}50 + \text{Ø}84}{3}$$

Inclusive graphic standard deviation: $$\sigma_1 = \frac{\text{Ø}84 - \text{Ø}16}{4} + \frac{\text{Ø}95 - \text{Ø}5}{6.6}$$

Inclusive graphic skewness: $$Sk_1 = \frac{\text{Ø}16 + \text{Ø}84 - 2\text{Ø}50}{2(\text{Ø}84 - \text{Ø}16)} + \frac{\text{Ø}5 + \text{Ø}95 - 2\text{Ø}50}{2(\text{Ø}95 - \text{Ø}5)}$$

Graphic kurtosis: $$Kg = \frac{\text{Ø}95 - \text{Ø}5}{2.44(\text{Ø}75 - \text{Ø}25)}$$

All statistics are calculated from points on a standard cumulative frequency curve. "Ø" refers to the grain size at a given percentile value (e.g., Ø16 corresponds to the grain size at which 16 percent of a given sample, by weight, is coarser-grained).

[1] From Folk and Ward, 1957.

Lithologic composition of the glacial sediment based on the 1-2 mm sand fraction could be compared with data from other glacial studies (e.g., Sackreiter, 1975; Perkins, 1977). However, some workers (e.g., Wright, 1962; Winters et al., 1973) have relied upon pebble counts to characterize the different rock types present in the drift. Because of this dichotomy in methods, lithologic composition was also determined for 49 pebble samples (6-64 mm size fraction). Results of sand and pebble counts are listed in Appendix C.

Pebble counts and 1-2 mm sand counts from the same sample do not yield equivalent results. Figure 3 shows the results of grain counts made at single phi intervals down to +4 phi (0.063 mm) on two samples. The fine sand fractions are dominated by monomineralic quartz, feldspar and mica grains, which are produced primarily by crushing or incorporation of sand derived from coarse grained igneous and metamorphic rocks during glacial transport. Finer-grained rocks, such as felsite and limestone, tend to be reduced in size by abrasion, which yields silt-sized particles (Dreimanis and Vagners, 1971).

Analysis of the pebble fraction gives the most detailed information concerning provenance of the glacial sediments, because more rock types are represented in significant amounts, and are more easily identified. Because of these factors, pebble counts were preferred over sand counts for use in interpreting glacial movements in the study area.

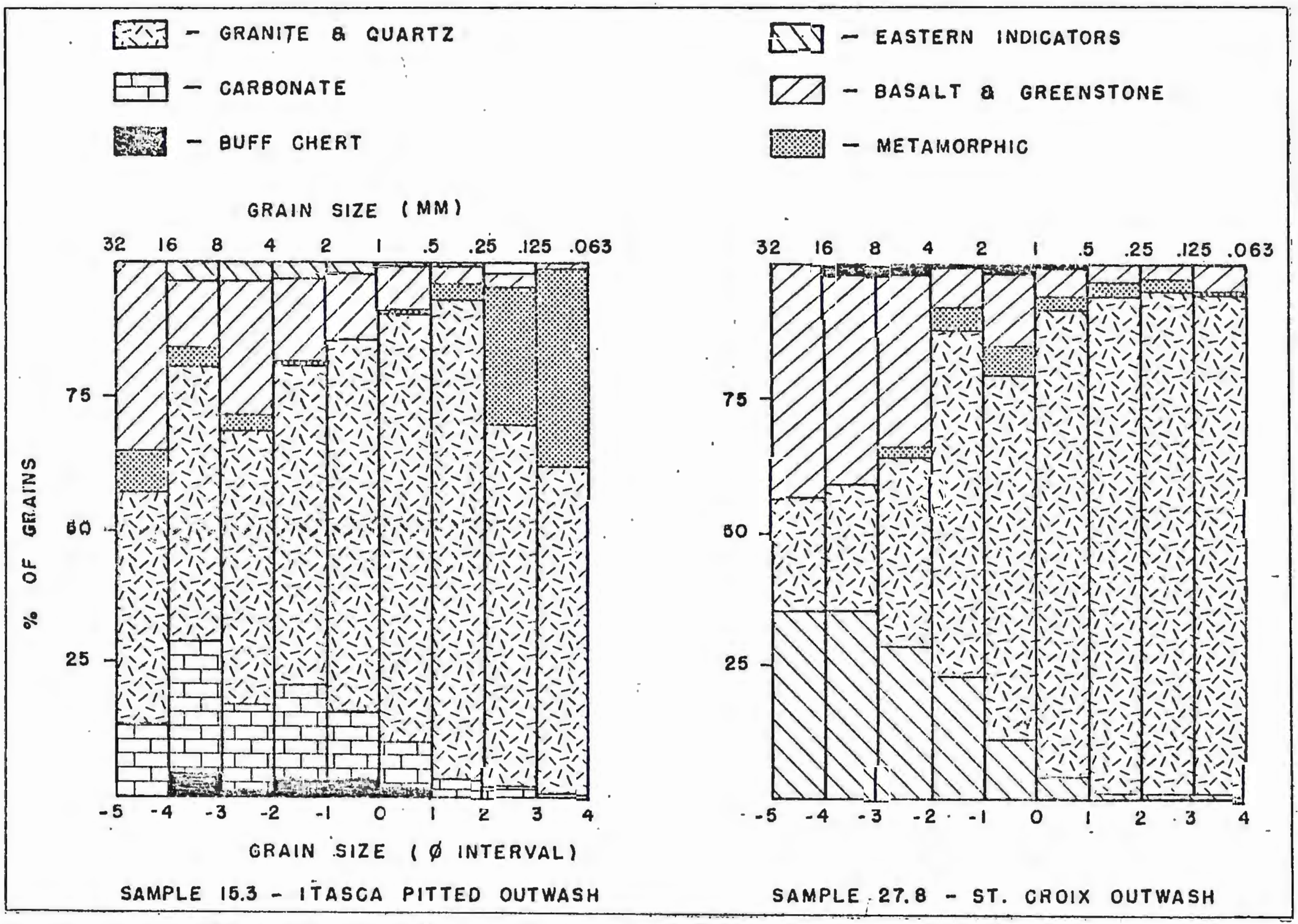


Figure 3. Lithologies of glacial drift as a function of grain size

REGIONAL GEOLOGY

Bedrock Lithology

A variety of bedrock lithologies in Minnesota, North Dakota and Canada contributed several distinctive rock types to the glacial tills of north-central Minnesota. These have been helpful in defining the flow paths and the sequence of the different ice lobes which were active in northern Minnesota during the Wisconsinan Glaciation.

Early Precambrian rocks (labeled "crystalline rocks" in Figure 4) form the bedrock surface across much of northern Minnesota. They can be divided into two major groups. The first group consists of volcanic and sedimentary (mostly graywacke) rocks metamorphosed to the greenschist facies. They are the "greenstones" of the Canadian Shield. Granitic and granodioritic rocks, mostly unmetamorphosed, are the other major type of Canadian Shield rocks. Surface exposures are common in northeastern and extreme north-central Minnesota, and adjoining parts of southern Canada, but they are mostly buried below glacial drift in northwestern Minnesota.

Middle and Upper Precambrian rocks cover much of northeastern and central Minnesota. Argillites, siltstones and graywackes, often deformed and metamorphosed to the amphobolite facies, were deposited in the Animikie basin. They are underlain by a thin bed of quartzite and distinctive intercalated iron-chert-slate beds of iron formation.

During Late Precambrian time, basalts, andesites and rhyolites of the North Shore Volcanic Group were extruded along the Keweenawan rift

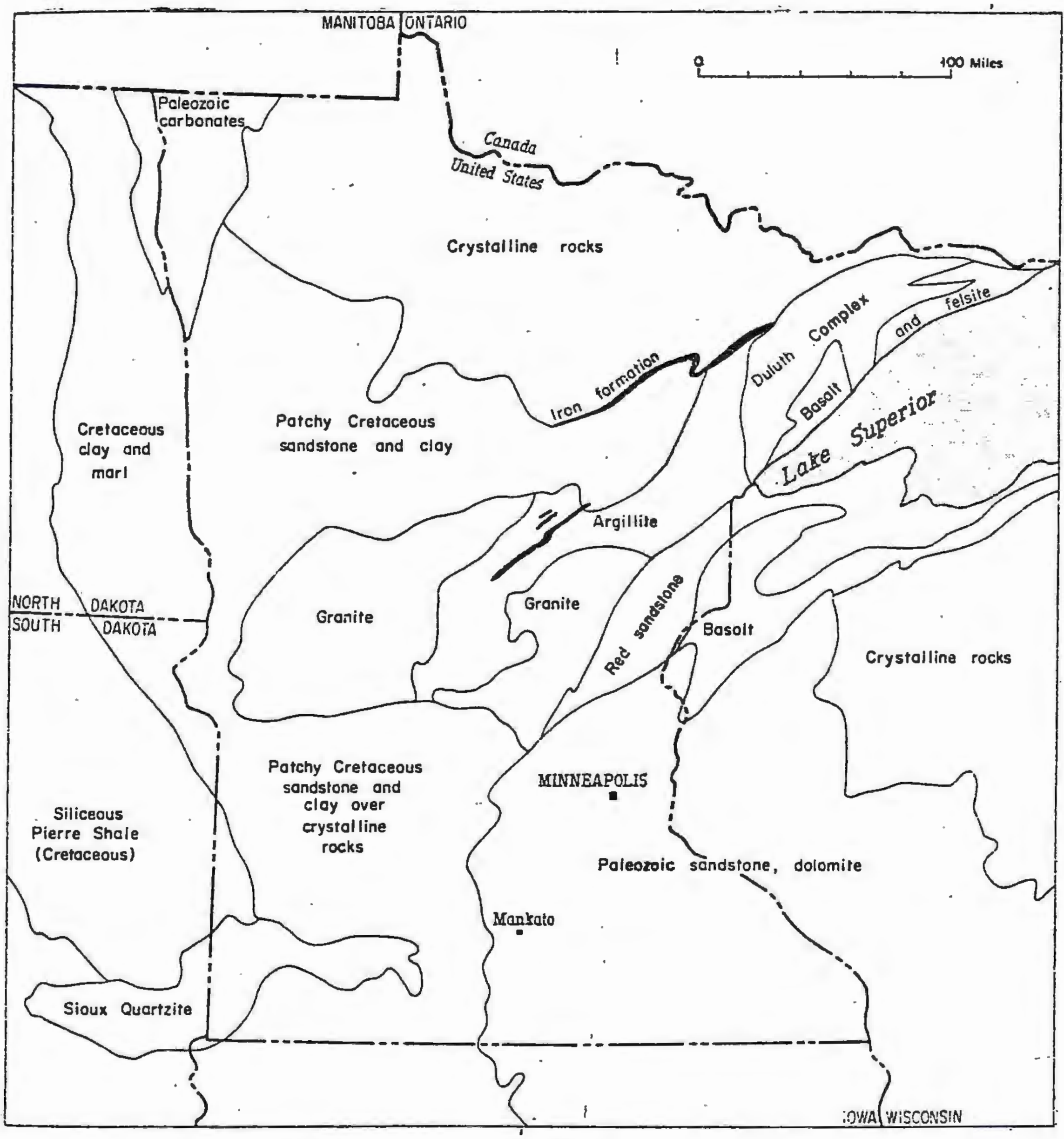


Figure 4. Generalized bedrock geology of Minnesota and parts of adjoining states (from, Wright, 1972, p. 519).

system in northeastern Minnesota. Locally, sedimentary beds were developed on the surface of flows, and were subsequently buried by later flows. These were later intruded by gabbroic, troctolitic and diabasic rocks, most of which have been assigned to the Duluth Complex. Sandstones, commonly arkosic, were subsequently deposited in the Lake Superior basin. These lie to the southeast of the North Shore Volcanic Group and the metasedimentary rocks of the Animikie basin.

Limestone, dolomite, and associated shale and sandstone beds were deposited in extreme northwestern Minnesota and northeastern North Dakota and extend northwestward into Canada. They are mostly Ordovician in age. No other major source of carbonate rocks exists to the north, except for limestone beds in the Hudson Bay area of Canada, 1000 km northeast of the study area.

Many of the Precambrian and Paleozoic rocks in western and north-central Minnesota are overlain by a thin veneer of predominantly marine sedimentary rocks deposited during Late Cretaceous time. The rocks consist mostly of white to tan fossiliferous shales in the west, grading to non-marine shales, sandstones and iron formation conglomerates in the east.

Bedrock Topography

Differences in resistance to erosion of the many rock types were important in determining the direction of ice movement across Minnesota. Several distinct lowlands in the bedrock surface of Minnesota, as shown in Figure 5, apparently channeled the flow of ice. The Superior Lowland, oriented northeast-southwest, is formed in Upper Precambrian sedimentary rocks. It very likely determined the southwesterly direction of flow of the Superior ice lobe. The North Shore Highland or the Giant's Range (a northeast striking granite-cored ridge) may have caused the separation of ice lobes in northeastern Minnesota.

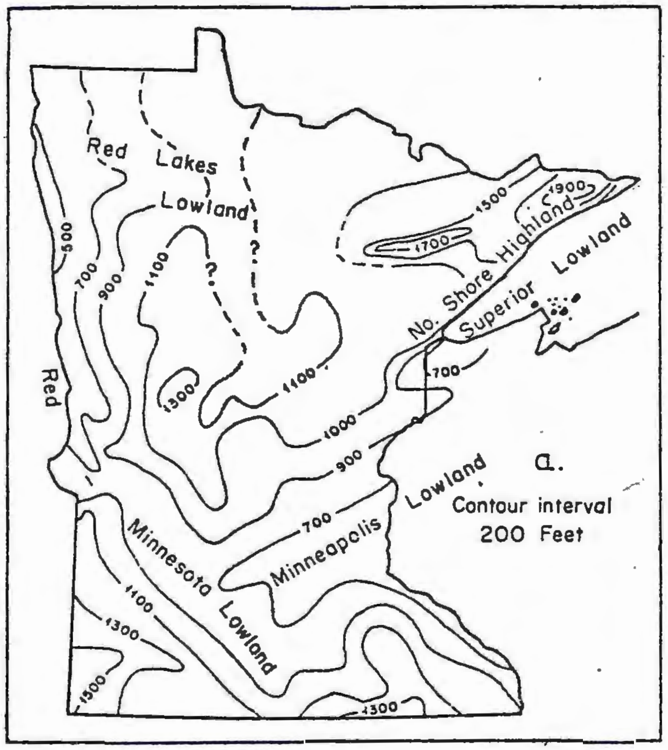


Figure 5. Contour map of the bedrock surface in Minnesota (From Wright, 1972, p. 520).

Similarly, on the western side of the state, the Red River and Minnesota lowlands dictated the southerly flow of the Des Moines Lobe. The Minneapolis Lowland probably caused the northeasterly diversion of the Grantsburg Sublobe, an offshoot of the Des Moines Lobe in Late Wisconsinan time.

Quaternary Geology

Pre-Wisconsinan Glaciations

Deposits of early Pleistocene glaciations are buried or absent throughout most of Minnesota. In the midwestern United States the southern limit of the early advances of the Laurentide Ice Sheet reached as far as Nebraska, Kansas, Missouri and Illinois. Until very recently, four major stages of glaciation were recognized in North America, the Wisconsinan, Illinoian, Kansan and Nebraskan (from youngest to oldest). These were separated by warmer interglacial periods marked by extensive soil and gumbotil development. Age of the beginning of Pleistocene glaciation was estimated at approximately two million years B. P. (Matsch, 1976).

Recent detailed work on pre-Wisconsinan glacial deposits in Iowa has shown some serious errors in previously accepted stratigraphic and time correlations. . Deep core drilling has revealed as many as three distinct tills below the type Nebraskan (Hallberg, unpublished manuscript). The Pearlette ash, widely used as a time-stratigraphic marker, is now known to be at least four distince ash layers, ranging in age from 0.6 to 2.0 million years B. P. Until a more satisfactory rock- and time-stratigraphic framework is developed, Hallberg (1980) suggests that the terms Kansan and Nebraskan should be replaced by the term Pre-Illinoian.

Wisconsinan Glaciation

The most recent period of major glaciation was the Wisconsinan Stage, which began approximately 70,000 B. P. (Wright, 1972). Nearly all of the surficial deposits of glacial drift throughout the Dakotas, Minnesota and

Wisconsin were deposited during the Wisconsinan Stage. The record of Wisconsinan glaciation in Minnesota is complex; several major phases of glacial activity have been delineated by Wright (1972), and four distinct ice lobes are now envisioned. All were active at different times during the Wisconinan, and resulted in the deposition of one or more of the various tills, moraines, drumlin fields, glaciofluvial and glaciolacustrine deposits that dominate the Minnesota landscape. Figure 6 is a composite of the different phases of ice movements during the Wisconsinan Age as interpreted by Wright (1972).

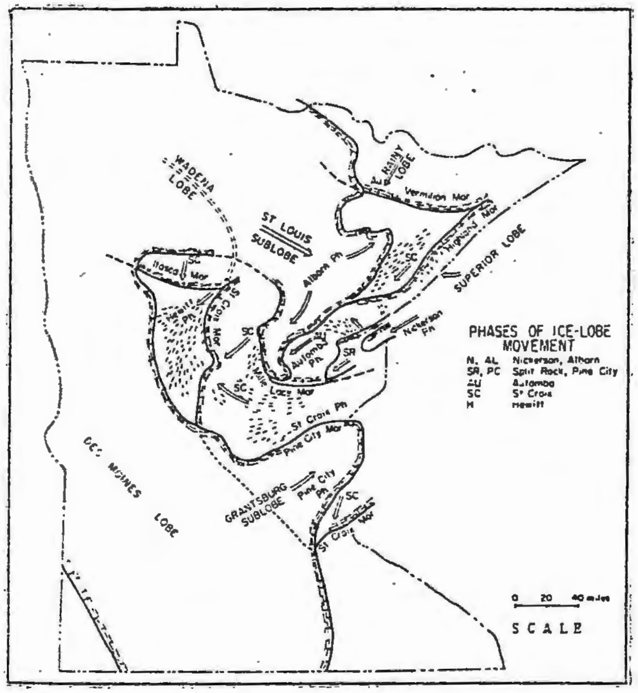


Figure 6. Composite map showing main phases of Wisconsin glaciation in Minnesota. Short dashes show drumlin fields (from, Wright, 1972, p. 525).

The earliest phase of the Wisconsinan Glaciation may be represented by an unnamed, limestone-bearing, shale-poor till located below the Hawk

Creek Till (described below) in southwestern Minnesota. Matsch (1972) attributes this till to an ice advance from the north and northwest. This would correspond to an advance of the Wadena Lobe, picking up carbonate clasts from the Winnipeg lowlands in southern Manitoba, but bypassing the Cretaceous shale bedrock in eastern North Dakota. The same advance may have deposited the weakly calcareous basal till in northeastern Minnesota (Winter, 1971) and the Unit 1 till in northwestern Minnesota (Sackreiter, 1975), which was found by drilling near the study area (Table 2).

The next oldest known till of possible Wisconsinan age is also exposed in southwestern Minnesota in the Minnesota River Valley. Named the Hawk Creek Till by Matsch (1972), it is a reddish-colored sandy till which contains pebbles of a northeastern provenance. It was probably deposited by an early advance of the Superior Lobe. Wright (1972) suggests that it may be correlative with the Hampton Moraine in east-central Minnesota. It may also correlate with the Unit 2 and Unit A tills described by Sackreiter (1975) and Perkins (1977). Clayton and Moran (1981) consider Unit 2 to have been deposited during the Early Wisconsinan, prior to 50,000 B. P.

The next major period of Wisconsinan Glaciation was the Hewitt Phase, marked by a major advance of the Wadena Lobe. According to Wright (1972), it moved in a southeasterly direction, crossing the carbonate province of the Winnipeg lowlands. There it incorporated abundant carbonate fragments characteristic of the drift deposited by it. In northern Minnesota the course of the Wadena Lobe was diverted towards the southwest by a concurrent advance of ice, presumably the Rainy Lobe, from the northeast. The Wadena Lobe advanced at least 45 km southwest of the Minnesota River Valley where it deposited the Granite Falls Till (Matsch, 1972), but no end moraine can be found to document its final position.

TABLE 2. CORRELATION OF LATE PLEISTOCENE SEDIMENTS

GLACIAL PHASE (Wright, 1972)	SOUTHWEST MN (Matsch, 1972)	NORTH-CENTRAL MN (Wright, 1962)	SOUTHEAST MN (Savina et al., 1979)	SOUTHERN MANITOBA (Teller and Fenton, 1979)	NORTHEAST MN (Winter, 1973)	NORTHWEST MN (Sackreiter, 1975)	WEST-CENTRAL MN (Perkins, 1977)	NORTH-CENTRAL MN (Norton, this paper)
Bemis and Alborn phases of the Des Moines Lobe and St. Louis Sublobe 12-14,000 B. P. (Wright, 1972)	New Ulm Till (43-30-27) ssc (30-25-45) xcs (MN River Valley)	np[1]	Des Moines Lobe Till (78-20-2)[2]xcs	Roseau Fm. (33-44-23) ssc (62% carb, 1-2mm)	red clayey till (89-3-8)[3]xcs brown silty till (78-6-16)[3]xcs	Upper Unit of the Red Lake Falls Fm. (35-41-24) ssc (51-34-13) xcs	Dunvilla Fm. (36-39-25) ssc[5] (41-24-35) xcs[6]	np
ST. CROIX PHASE 20,000 B. P. (Wright, 1972)	np	Formation of St. Croix and Itasca moraines and associated outwash plains.	St. Croix Till (81-19-0)[2]xcs	Senkiw Fm. (60-29-11) ssc (42% carb, 1-2mm) Whiteshell Fm. (68-26-6) ssc (5% carb, 4-16mm)	bouldery till (100-0-0)[3]xcs	Lower Unit of the Red Lake Falls Fm. (44-36-30) ssc (57-37-5) xcs	New York Mills Fm. (50-31-17) ssc (71-27-2) xcs	Lower Red Lake Falls Till (66-21-13) ssc (89-11-0) xcs Brainerd Till (79-13-8) ssc (100-0-0) xcs (leached)
HEWITT PHASE 20-28,000 B. P. (Clayton and Moran, 1981) 30-60,000 B. P. (Wright, 1972)	Deposition of Alexandria Moraine, Granite Falls Till (42-36-22) ssc (45-50-5) xcs	Hewitt Till (63-27-10) ssc	yellow calcareous till	?	bouldery till?	Marcoux Fm. (54-33-13) ssc (78-19-5) xcs	Sebeka Fm. (61-26-13) ssc (80-20-0) xcs	Hewitt Till (74-13-13) ssc (100-0-0) xcs (leached?)
HAWK CREEK PHASE Early or pre-Wisconsinan (Moran et, al., 1976, Matsch, 1972)	Hawk Creek Till (55-22-23) ssc (80-20-0) xcs	nr?	Hampton Drift (81-19-0)[2]xcs	nr[4]	np?	unnamed Unit 2 (37-34-29) ssc (69-28-3) xcs	unnamed Unit A (58-31-11) ssc (79-22-0) xcs (one sample)	nr
Southeastward advance of ice across western Minnesota pre-Wisconsinan (Clayton and Moran, 1981)	shale-free, gray clacareous clay loam till	nr?	np?	nr	Basal till (97-3-0)[3]xcs	unnamed Unit 1 (17-46-36) ssc (61-39-1) xcs	nr	nr

[1] not present. [2] pebble counts (2-8 cm diameter). [3] pebble counts (greater than 2 mm). [4] not reached.

[5] ssc - percent sand-silt-clay. [6] xcs - percent crystalline-carbonate-shale rock types (1-2 mm size fraction except where otherwise noted).

Harris (1974) and Perkins (1977) correlate the Granite Falls Till with the lower unit of the Red Lake Falls Fm. and the New York Mills Fm.; they also correlate the Hawk Creek Till with the Marcoux and Sebeka formations. Difficulties with these correlations are discussed in the text on pages 26-28.

A major standstill of the Wadena Lobe occurred 65 km northeast of the Minnesota River, where it built the large Alexandria Moraine. The Wadena Drumlin Field was also formed by the Wadena Lobe during the Hewitt Phase. Located northeast (up-glacier) of the Alexandria Moraine, it is a fan-shaped field of some 1200 drumlins which spread to the southwest. Savina, Jacobson and Rodgers (1979), tentatively correlate the Hewitt Till with a yellow calcareous till which overlies Hampton Drift in Dakota County. The Hewitt Till may also be equivalent to the lower part of the bouldery till in northeastern Minnesota (Winter, 1971) and the Senkiw and Whiteshell formations in southeastern Manitoba, which have a strong northeast-southwest till fabric (Teller and Fenton, 1979).

Organic silt on top of Hewitt Till has been dated at greater than 40,000 B. P. (Wright, 1972), which would make it Early Wisconsinan in age. A younger age for the Hewitt Phase is postulated by other workers, however, Clayton and Moran (1981) rejected the ^{14}C date because of the possibility of contamination by lignite or another source of "old carbon" which would artificially increase the ^{14}C age of the sediment. They tentatively placed the Hewitt Till in their Phase D of Wisconsinan Glaciation, which reached a maximum about 20,000 B. P. Matsch and Schneider (in preparation) also consider the till to be younger than Early Wisconsinan, based on weathering characteristics.

The Itasca-St. Croix Phase is named after the two major moraines built during the next phase of glacial activity. The Wadena, Rainy and Superior lobes each left records of their advances during this phase. The Rainy and Superior lobes flowed in a southwesterly direction and merged to form the prominent St. Croix Moraine, which can be traced for 450 km through Minnesota and Wisconsin. Drumlin fields were formed by both lobes. The Superior Lobe formed the Brainerd and Pierz drumlin fields in central Minnesota, northeast of the St. Croix Moraine; the Rainy Lobe constructed the Toimi Drumlin Field in northeastern Minnesota.

The Wadena Lobe readvanced during the Itasca-St. Croix Phase to form the broad east-west trending Itasca Moraine which merges with the northern end of the St. Croix Moraine. Both moraines overlie the Wadena Drumlin Field. The St. Croix Phase may have reached a maximum prior to 20,500 B. P., based on several radiocarbon dates on lake sediments (Wright, 1972).

There followed a general deglaciation of northern Minnesota. The Superior Lobe then advanced again out of the Lake Superior Basin. It deposited the Mille Lacs and Highland moraines and formed the Automba Drumlin Field, for which this phase of glacial activity is named. The Rainy Lobe readvanced to a position just south of the Canadian border in northeastern Minnesota. There it deposited the Vermilion Moraine which forms an interlobate junction at its eastern end with the Highland Moraine.

The most recent phase of glaciation was marked by extensive development of the Des Moines Lobe. It advanced southward along the Red River and Minnesota lowlands, then flowed northeastward along the Minneapolis Lowland as the Grantsburg Sublobe. Thickening of the ice eventually permitted a major expansion of the Des Moines Lobe southward over a low divide in southern Minnesota (see Figure 5). It reached its maximum southern extent near Des Moines about 14,000 B. P. (Ruhe, 1969). Sediments deposited by the Des Moines Lobe are characterized by fragments of Cretaceous marine siliceous shale. They bury, but do not obscur completely, the St. Croix and Alexandria moraines through much of southwestern Minnesota.

Another major extension of the Des Moines Lobe, the St. Louis Sublobe, moved eastward across northern Minnesota, almost to Lake Superior. Till deposited by the St. Louis Sublobe forms the surface drift across most of northern Minnesota. It buries the northern part of the Itasca Moraine and obscures the northern extension (if there was one) of the St. Croix Moraine in north-central Minnesota.

The Superior Lobe made several minor advances during the Bemis and Alborn phases, but the Wadena and Rainy lobes apparently were not active in Minnesota. There is no evidence of ice advances from the north during these phases, the presence of which would have prevented the eastward flow of the St. Louis Sublobe.

Many pro-glacial lakes were formed as the glaciers melted. Glacial Lake Duluth developed in the Lake Superior Basin. Glacial lakes Aitkin and Upham formed in front of the St. Louis Sublobe, and similarly, Glacial Lake Grantsburg formed northeast of the Grantsburg Sublobe, for which it is named. Lake Agassiz occupied the Red River Lowland and most of northwestern Minnesota. It formed approximately 12,500 B. P., and finally drained about 9300 B. P. (Clayton and Moran, 1981). Successive lowerings of its lake level in Minnesota are marked by distinct beach ridges.

Post-glacial Landforms

Final retreat of ice from Minnesota occurred about 11,500 B. P. Based mostly on lake sediment pollen studies, it appears that the climate continued to warm, reaching a peak of maximum warmth and dryness about 7000 B. P. (Wright and Watts, 1969). From about 8000 to 5000 B. P., active dune fields were present in northern Minnesota (Grigal et al., 1976).

A subsequent cooling trend resulted in climatic conditions favorable to the formation of peat bogs and fens. Vast areas of peat developed in the poorly drained lake bed of Glacial Lake Agassiz. Smaller but significant accumulations of peat developed on other glacial lake beds and in many depressions present in the deglaciated landscape. Peat is most abundant in northern Minnesota, but is present throughout the state.

Alternative Glacial History

An alternate interpretation of Wisconsinan Stage glacial history in Minnesota is offered by researchers from the University of North Dakota (Anderson, 1976; Harris, 1975; Perkins, 1977; Sackreiter, 1975). Subsurface data were obtained by them from several drill holes within the Bemidji and Grand Forks quadrangles (U. S. Geological Survey maps, scale 1:250,000). Sackreiter (1975) and Harris (1975) correlated subsurface and surface tills with surficial units elsewhere in Minnesota and North Dakota.

The lowermost two tills, present in only a few drill holes, Unit 1 and Unit 2, were attributed to ice advances from the Winnipeg lowlands because of their calcareous-rich, shale-poor lithologies. Sackreiter (1975) correlates Unit 1 with the Granite Falls Till in southwestern Minnesota and deposition of the sediment (but not the formation of drumlins) of the Wadena Drumlin Field.

Stratigraphically above Unit 2 is the Marcoux Formation. It is also calcareous, although less so than Unit 1 and Unit 2, and is shale-poor. According to Sackreiter's model, it was deposited by a glacier advancing from northeastern Minnesota. The glacier eroded Unit 2 to form the Wadena drumlins and subsequently deposited a sand blanket on top of the drumlins. This model is a major departure from the premise that the drumlins are depositional (Wright, 1962). An extensive study of the Wadena Drumlin Field (Wright, 1962) disclosed no capping till, and showed a strong development of till fabric aligned parallel to the drumlin axes. Accordingly, Wright concluded that the drumlins must have been deposited by the Hewitt Phase advance of the Wadena Lobe and not subglacially molded or "eroded" in an underlying till as proposed by Sackreiter.

Sackreiter does not give any explanation for the presence of carbonate pebbles present in the Marcoux Formation. According to his model, the glacier which deposited that till would not have crossed over any carbonate bedrock as it moved across the Precambrian terrain of northeastern Minnesota, Perkins (1977), however, does mention the possibility of incorporation of limestone and dolomite from an underlying till as the glacier advanced southwestward across central Minnesota, over the previously deposited calcareous-rich Unit 1 and Unit 2 tills.

The St. Hilaire Formation (high in carbonate and shale fragments) is the next younger till in their sequence. Sackreiter correlates this formation with a "lower part of the New Ulm Till", but there seems to be no evidence in southwestern Minnesota for splitting the New Ulm Till into two members, separated by the lower unit of the Red Lake Falls Formation (Matsch, personal communication).

The lower unit of the Red Lake Falls Formation (calcareous and shale-poor) is thought to have been deposited by an advance of ice from the northeast, which formed the Itasca Moraine (Sackreiter, 1975). The same glacier is supposed to have formed the St. Croix Moraine, but no mention is made of the junction between the two moraines.

The most recent ice advance in the area is correlated with the Late Wisconsinan advance of the Des Moines Lobe and St. Louis Sublobe. Sediment deposited by the glacier was named the upper unit of the Red Lake Falls Formation (calcareous and shale-bearing) by Sackreiter. He ascribes the Tazewell Drift of Ruhe (1969) to this advance, and gives it an approximate date of 22,000 B. P. That date does not correspond with other workers much more recent dates for the Des Moines Lobe maximum.

QUATERNARY SEDIMENTS

Introduction

Several geologic units have been distinguished in the study area. They are identified primarily on the basis of lithology, including texture and lithic composition, sedimentary structures, stratigraphic position and morphology. Not all of these features are useful as distinguishing features at any one location. The deposits range in age from early Wisconsinan through Holocene. All are exposed at the surface except for the oldest unit which is capped by a sand blanket of variable thickness. No paleosols were observed in the study area, nor was any datable material found from which absolute ages could be determined.

Hewitt Till

General

The Hewitt Till (Wright, 1965) is the oldest unit exposed in the area. It is a lodgement till, deposited by the southwesterly moving Wadena Lobe, which also deposited the massive Alexandria Moraine in southwestern Minnesota (Wright, 1962). It advanced during the Hewitt Phase of the Early Wisconsinan or pre-Wisconsinan Stage. The deposit has not been dated precisely, but Wright (1972) estimates the till to be 30,000 to 60,000 years old, based partly on a ^{14}C date of greater than 40,000 B.P. from organic silts which overlie the Hewitt Till.

In the southwest part of the study area, the Hewitt Till is covered by a thin layer of fine to medium sand, probably of eolian origin. The till is presumed to be present throughout the study area, buried beneath younger glacial deposits.

Geomorphology

The Hewitt Till surface is drumlinized in the study area. These drumlins make up the northernmost exposed portion of the geomorphic region named the Wadena Drumlin Field by Wright (1962), who studied the drumlins in detail to the south of the exposures described herein. Many northeast-southwest trending drumlins can be seen in the southwestern part of the study area. Toward the northeast, however, they become progressively more deeply buried by outwash sediments. Their surface expression is completely obliterated close to the heads of the overlying outwash plains.

The presence of drumlin forms is clearly expressed topographically even where they are partially buried beneath outwash sands. Outlines of 97 drumlins were determined from topographic maps. They show a gradual shift from S 22° W in the eastern part of the drumlin field, to S 64° W in the western part; the overall average is S 41° W (Table 3). Orientations of the drumlins suggest formation by a glacier moving from the northeast and spreading laterally to the south and west as it advanced.

Average length of the drumlins is about 1.9 km and average width is about 0.5 km (Table 3). The average length:width ratio is 3.3:1. Most drumlins rise 6 to 9 m above the surrounding outwash plain; maximum height measured is 20 m. It should be emphasized that the dimensions of the original drumlin forms have been modified by the subsequent deposition of outwash sediments in intervening swales, and to a lesser degree by eolian sediments which partially cover the drumlins.

TABLE 3. SUMMARY OF DRUMLIN SHAPES AND ORIENTATIONS

Drumlin Measurement	Mean	Range
Length[1]	1,880 m	370-7620 m
Width[1]	540 m	180-1220 m
$\frac{\text{Length}}{\text{Width}}$	3.3	1.5-6.5
Height[2]	8 m	2-20 m
Azimuth	221°	202°-244°

[1] Figures may be inaccurate in some cases because of an obscuring sand cover.

[2] Height above surrounding outwash, including sand cap on the top of the drumlin, if present.

Till fabric was measured in two drumlins in the study area. The results are shown in Figure 7. The till in both drumlins has a preferred orientation of elongated stones (length:width ratio at least 1.5:1) a northeast-southwest direction and a northeast plunge of the stones. Stone orientation in lodgement till has been shown to be helpful in determining direction of ice movement in other areas (Holmes, 1951; Harrison, 1957; Evenson, 1971). In the Wadena Drumlin Field, drumlins have been shown to have strong stone orientations which generally parallel drumlin axes (Wright, 1962). Wright also reported a preferred northeast plunge of oriented stones in Wadena drumlins. He interpreted the imbrication to be caused by alignment of stones along shear planes and flow lines near the base of the glacier

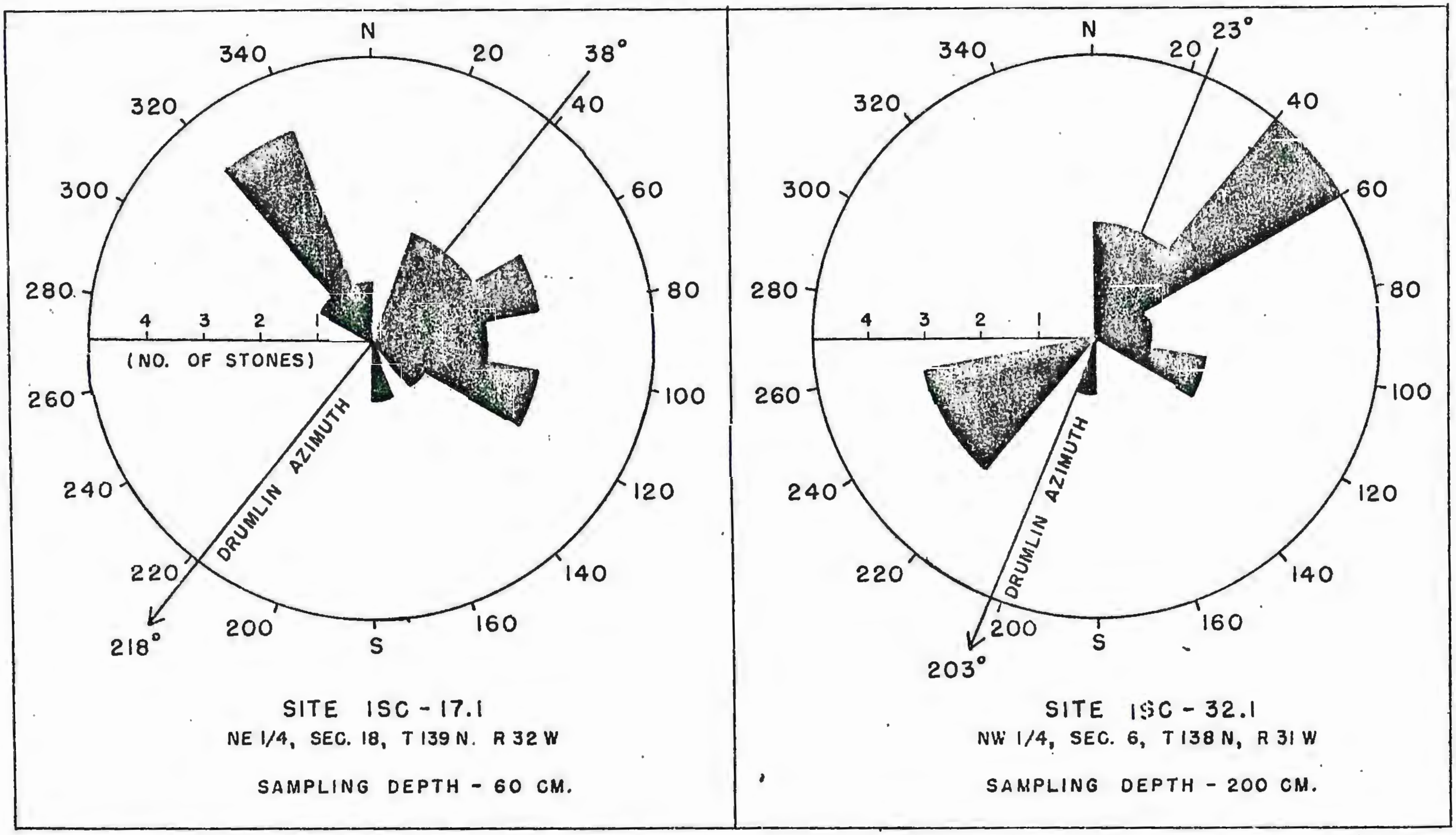


Figure 7. Fabric analyses in the Wadena Drumlin Field

which dip upglacier. Fabric development in the drumlins examined in this study support Wright's interpretation of a southwestward advance of the glacier which formed them.

In both drumlins examined in this study, the azimuth of the drumlin feature as measured from topographic maps is about 30° more northerly than the average stone orientation. The reason for this divergence is not known, but may be a result of shear stresses which were produced as ice flowed around the drumlin form. The resulting strain on the drumlinized sediment would be oblique to the overall direction of ice flow (Muller, 1974). Wright (1962) also found that fabric development near the surface of Wadena drumlins often did not parallel the drumlin axis. He offered no firm explanation for the divergence, but suggested that it might be due to soil-forming processes.

The question of whether drumlins are depositional or erosional in origin has long been debated. Wright (1957; 1962) considered the Wadena drumlins to be depositional because of the close relationship between stone orientation and drumlin axis, and because he could find no evidence of more than one till in any of the drumlins.

Other studies indicate that drumlins may be formed by erosion of pre-existing drift. Clayton and Moran (1974) concluded from field studies in North Dakota that erosion is dominant and that the core of most drumlins is composed of highly permeable or slightly compressible sediment deposited during a previous glaciation. A study of the Waukesha Drumlin Field, formed by the Lake Michigan Lobe in eastern Wisconsin, demonstrates that erosion played a major part in drumlin formation there (Whittecar and Mickelson, 1979). Many of the drumlins are formed of undisturbed layers of sand and gravel outwash deposits which are truncated at the edges of the drumlins. The top and sides of the drumlins are covered with a layer of till, the observed thickness of which ranges form 3 to 30 m. Deformation of the core of some of the Waukesha drumlins suggests that material was being squeezed up into the drumlins, perhaps as glacial erosion was shaping the surface of the drumlins. Whittecar and Mickelson conclude that drumlins form by a combination of erosional and constructional forces, a conclusion also reached by Muller (1974).

The exposures in Wadena drumlins in the Itasca-St. Croix moraine interlobate area are relatively shallow. They did not penetrate more than one till, nor were fluvial deposits encountered below the surface till. Therefore, conclusions regarding the mechanism of formation of the drumlins are beyond the scope of this study.

Weathering Characteristics and Physical Properties

The Hewitt Till was examined at four locations (see Appendices B and C for locations and detailed results of analyses). The soil profile for one of them (ISC-32.1) is described in detail in Appendix A. The soil at this locality was developed on a Wadena drumlin covered by a thin layer of sand. The site was a 2.5 m deep trench located in a field presently under cultivation. Color of the upper part of the soil profile is dark brown (Munsell Index Color 10YR 3/3) near the surface in the sandy A1 horizon, gradually lightening to yellowish brown (10YR 5/4) in the B3 horizon. Below the strongly oxidized zone the till is noncalcareous and brown (10YR 4/3). It is extremely compact and difficult to dig, with a platy structure below the solum. It has a bulk density of 2.6 g/cm^3, the highest of the tills tested in the study area (see Appendix A for method of bulk density determination).

The depth of the top of the C horizon was determined to be 1.7 m at site ISC-32.1. From there to the base of the exposed section at 2.5 m depth, the till is noncalcareous and unoxidized. Some sand grains have a coating of gray clay. It may be that carbonate clasts are actually present in the parent material, but have been leached to a depth of more than 2.5 m. If so, then what has been described as the C horizon may be similar to Leighton and MacClintock's (1930) soil horizon zone 3 which consists of leached till which is otherwise very little altered. The gray clay coating present in this zone suggests that chemical weathering is or has been active at least to 2.5 m. This possibility is supported by the findings of Wright (1962). He stated that depth of leaching is inversely related to carbonate content in the original (unweathered) till. He further found that drumlins in the northeastern part of the Wadena Drumlin Field contain relatively few carbonate clasts and are leached of carbonate to depths of 8 to 14 feet (2.4 to 4.3 m).

Grain size distribution of the till matrix (sand-silt-clay fractions) is shown in Figure 8. All samples were taken from as great a depth as possible, but it may be that none were of unleached parent material. If so, grain size distributions may have been altered by soil-forming processes. The samples contained an average of 11% granules and larger clasts. The till is very stony, and boulders greater than two meters in diameter were noted. The sediment is very poorly to extremely poorly sorted and is finely skewed (Table 4).

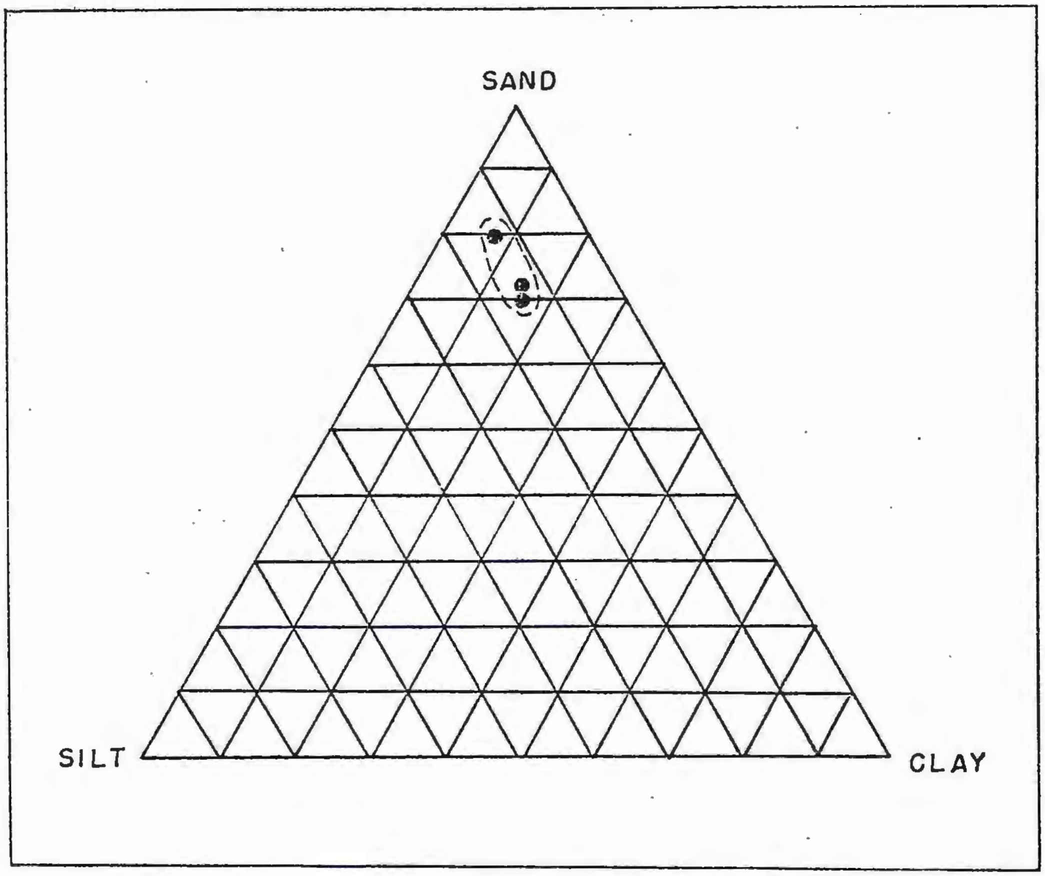


Figure 8. Sand-silt-clay content of Hewitt Till (3 samples.)

Lithologic Composition

A high percentage of eastern indicator stones (28%) is present in the pebble fraction of the easternmost samples (ISC-32.1 and ISC-27.10b). Almost equal amounts of coarsely crystalline (36%) and aphanitic mafic rock types (33%) are contained in those samples. A sample from a drumlin further west (ISC-17.1f) contains only 12% eastern indicator stones and a much higher percentage of crystalline rocks (56%). Average lithologic makeup of four till samples is given in Tables 5 and 6.

TABLE 4. SUMMARY OF GRAIN SIZE PARAMETERS OF GLACIAL TILL UNITS

	% greater than 2 mm[1]	MATRIX[2]			MEAN DIAMETER M_z (phi)	SORTING σ_1	SKEWNESS Sk_1	KURTOSIS K_g
		% SAND	% SILT	% CLAY				
Hewitt Till (n = 3)	11	74	13	13	2.55	3.62	+.28	1.75
	(6.4)[3]	(5.3)	(1.0)	(4.4)	(.83)	(.74)	(.17)	(.29)
Brainerd Till								
Flowtill (n = 10)	13	79	13	8	1.87	3.05	+.15	1.71
	(5.2)	(8.9)	(5.1)	(4.6)	(.92)	(.66)	(.22)	(.26)
Glaciofluvial (n = 7)	19	86	10	4	1.10	2.52	+.04	1.37
	(15.2)	(7.8)	(5.6)	(3.9)	(1.2)	(.60)	(.25)	(.40)
Ground moraine (n = 1)	18	80	17	3	1.39	2.94	-.03	1.46
Lower Red Lake Falls Till								
Flowtill (n = 13)	9	66	21	13	3.06	3.30	+.21	1.47
	(5.6)	(19.9)	(10.3)	(12.3)	(1.71)	(.56)	(.19)	(.38)
Glaciofluvial (n = 3)	14	94	4	2	.71	1.73	-.10	1.25
	(7.6)	(3.5)	(3.0)	(.6)	(.46)	(.66)	(.09)	(.11)

[1] includes all size fractions larger than sand: granules, pebbles, cobbles and boulders

[2] recalculated to 100%

[3] (standard deviation)

TABLE 5. SUMMARY OF DRIFT LITHOLOGIES
PEBBLE FRACTION (6 - 64 mm) IN PERCENT

	Drift Unit	N[1]	Eastern Ind.	Carbonate	Chert	Crystalline	Mafics	Shale	Other
Eastern Source	Brainerd Till (leached)	11	29 (8.3)[2]	0 (0)	2 (.92)	32 (7.5)	34 (6.0)	<1 (.79)	<1 (.79)
	Brainerd Till (unleached)	3	21 (4.5)	6 (6.4)	2 (.6)	36 (5.7)	35 (2.5)	<1 (.17)	<1 (.58)
	Oshawa Outwash Plain (leached)	4	25 (6.9)	0 (0)	2 (.5)	31 (2.9)	42 (5.0)	0 (0)	1 (.82)
	Pine River Outwash Plain (leached)	1	21 -	0 -	3 -	39 -	37 -	0 -	0 -
	Pine River Outwash Plain (unleached	2	20 -	7 -	1 -	34 -	37 -	0 -	<1 -
Western Source	Lower Red Lake Falls Till (leached)	2	12 -	0 -	1 -	49 -	36 -	1 -	0 -
	Lower Red Lake Falls Till (unleached)	8	11 (3.3)	16 (5.7)	3 (.8)	39 (4.8)	30 (4.7)	0 (0)	<1 (1.6)
	Park Rapids Outwash Plain (leached)	1	19 -	0 -	2 -	43 -	35 -	0 -	0 -
	Park Rapids Outwash Plain (unleached)	7	5 (2.8)	15 (4.8)	3 (1.9)	42 (7.7)	34 (7.9)	<1 (1.9)	<1 (.22)
	Hackensack Outwash Plain (leached)	1	7 -	0 -	2 -	48 -	42 -	0 -	1 -
	Hackensack Outwash Plain (unleached)	6	13 (9.5)	13 (7.7)	3 (1.8)	40 (5.1)	31 (3.5)	0 (0)	0 (0)
	Hewitt Till (leached?)	3	23 (9.7)	0 (0)	3 (2.6)	42 (12.1)	32 (8.3)	0 (0)	<1 (.6)

[1] Number of samples [2] Standard deviation (in parentheses)

TABLE 6. SUMMARY OF DRIFT LITHOLOGIES
SAND FRACTION (1 - 2 mm) IN PERCENT

	Drift Unit	N[1]	Eastern Ind.	Carbonate	Chert	Granitic	Mafics	Shale	Other
Eastern Source	Brainerd Till (leached)	6	11 (3.8)[2]	0 (0)	2 (1.2)	73 (7.3)	13 (3.6)	0 (0)	<1 (.6)
	Oshawa Outwash Plain (leached)	2	10 -	0 -	1 -	75 -	13 -	0 -	0 -
	Pine River Outwash Plain (leached)	3	6 (2.0)	0 (0)	2 (.6)	79 (4.4)	13 (2.5)	0 (0)	0 (0)
	Pine River Outwash Plain (unleached)	1	10 -	5 -	4 -	71 -	12 -	0 -	0 -
Western Source	Lower Red Lake Falls Till (leached)	3	4 (2.1)	0 (0)	2 (.6)	81 (.6)	13 (2.0)	0 (0)	0 (0)
	Lower Red Lake Falls Till (unleached)	4	4 (1.3)	9 (3.3)	2 (.8)	72 (4.1)	13 (3.7)	0 (0)	<1 (.6)
	Park Rapids Outwash Plain (leached)	3	4 (2.0)	0 (0)	1 (0)	77 (3.2)	18 (5.9)	0 (0)	<1 (.3)
	Park Rapids Outwash Plain (unleached)	4	3 (1.4)	10 (5.0)	3 (.5)	69 (5.5)	15 (3.3)	0 (0)	<1 (.2)
	Hackensack Outwash Plain (leached)	2	5 -	0 -	2 -	80 -	13 -	0 -	<1 -
	Hackensack Outwash Plain (unleached)	3	9 (2.6)	3 (4.0)	2 (.6)	71 (7.8)	16 (2.3)	0 (0)	<1 (.5)
	Hewitt Till (leached)	1	8 -	0 -	1 -	80 -	11 -	0 -	1 -

[1] Number of samples

[2] Standard deviation (in parentheses)

Brainerd Till

General

Glacial sediments were deposited on top of the Hewitt Till in the eastern part of the study area. They were transported by the Rainy Lobe, which advanced from the northeast during the St. Croix Phase of glaciation. The St. Croix Phase sediments were probably deposited near the end of the Middle Wisconsinan Stage. Based largely on ^{14}C dates from basal lake sediments, the Rainy Lobe is thought to have reached its maximum at least 20,500 B. P. (Wright, 1972). The Rainy Lobe stalled near the center of the study area, where it built the St. Croix end moraine and the proglacial Oshawa outwash plain.

Brown, stone-rich, noncalcareous and sandstone-poor sediments are characteristic of sediments deposited by the Brainerd Sublobe of the Rainy Lobe. They were named the Brainerd Till by Schneider (1961), who studied them in the St. Croix Moraine about 75 km south of the Itasca-St. Croix moraine interlobate area. Because of their close similarities in texture, color and lithologic composition, and their lateral geomorphic continuity (both are part of the St. Croix Moraine), the name Brainerd Till is herein extended to include sediments deposited by the Rainy Lobe in the interlobate area during the St. Croix Phase.

Geomorphic features, sedimentary structures and lithologic composition are the most important criteria for distinguishing the Brainerd Till from other sediments in the study area.

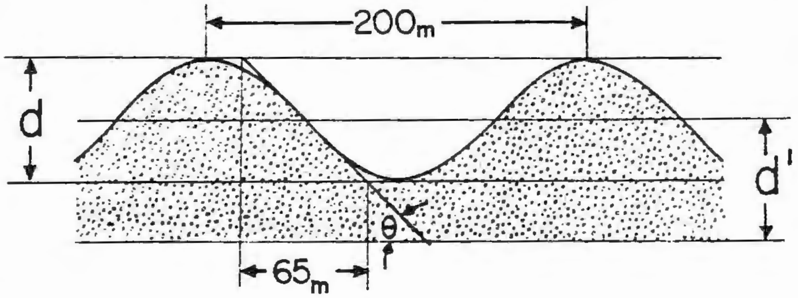
Geomorphology

The terminal position of the westward advance of the Rainy Lobe is well demarcated in the south-central part of the study area. A thick sequence of supraglacial sediments was deposited there, forming a prominent belt of hummocky knob and kettle topography named the St. Croix Moraine by Leverett and Sardeson (1932). The moraine is oriented north-south in the study area, and is buried at its northern end by outwash sediments. Two other hummocky areas of similar origin are separated by outwash deposits from the northern end of the St. Croix Moraine (Plate I).

The St. Croix Moraine rises a maximum of 70 m above the Wadena Drumlin Field which lies to the west. It attains an average elevation of 425 m in the south, rising to 430 m in the north. Sections B-B' and C-C', Plate II, demonstrate the geomorphic variations between the St. Croix Moraine, associated outwash deposits, and the Wadena Drumlin Field. The topographic surface behind, to the east of the moraine, is about 30 m lower than the surface of the outwash plains deposited in front of the St. Croix Moraine. Even allowing for the thickness of the outwash sediments, the surface east of the moraine is still at least 25 m lower than the surface west of it. This may have been the "quarrying zone" described by Clayton and Moran (1974), which is a zone of intensified erosion of the sub-glacial surface in a narrow band immediately up-ice from the frozen toe of the glacier. The width of the St. Croix Moraine ranges from 4.8 to 7 km.

Local relief of the moraine is rugged. Most of the land surface is in slope, with very few flat upland surfaces. Circular depressions, conical hills and randomly oriented elongate ridges are very common. Maximum local relief is 43 m and maximum slope angle of the hillsides is

24°. According to Clayton and Moran (1974), the thickness of supraglacial material is approximately equal to local relief expressed in meters and to the maximum slope angle expressed in degrees (Figure 9).



Relationship between local relief *(d)* and average thickness of glacial sediment *(d')*, which are about equal, the average distance between hummocks (200 m), the average horizontal distance (65 m) between the intersection of the tangent to the slope and the elevation of the top and bottom of the hummock, and the maximum slope (θ): $65 \tan \theta = d$, where θ is almost the same as d if θ is measured in degrees and d is measured in meters.

Figure 9. Estimation of thickness of supraglacial sediments (from, Clayton and Moran, 1974).

If those relations hold true for the St. Croix Moraine, then the thickness of supraglacial sediment in this area is approximately 24 to 43 m. Since the angle of slope is limited by the angle of repose of the material composing the hill, local relief would appear to be a fairly reliable indicator of supraglacial thickness. Therefore, 43 m of supraglacial sediment appears to be a more accurate estimate of true maximum thickness.

Interconnected drainageways (streams) are virtually absent within the St. Croix Moraine. Lakes and marshes are abundant, however. In one square-mile area in the southern part of the moraine in the study area, for example, there are 42 bodies of surface water either partly or wholly within the section (section 30, T 137 N, R 31 W).

A large esker can be traced for 2.6 km to the eastern margin of the St. Croix Moraine. There it becomes confluent with a large outwash fan.

It is located in sections 30 and 31, T 138 N, R 31 W and section 25, T 138N, R 32 W. No other recognizeable eskers were noted in the St. Croix Moraine.

Glaciolacustrine deposits are much more limited in extent than flowtill and glaciofluvial sediments. One such deposit is located in section 5, T 138 N, R 31 W, and covers an area of about 1.3 km^2. It was probably formed as an ice-walled lake, since its surface forms a plateau 15 m above the surrounding land surface. Sediments in the lake plain are generally massive, loose, medium sand. Very few stones larger than small pebbles are encountered at the surface. Soil development is poor, with an A-B horizon only 10 cm thick. No other lake sediments were discovered in the St. Croix Moraine; other supraglacial lake sediments probably were deposited but later redeposited as underlying ice melted.

Weathering Characteristics

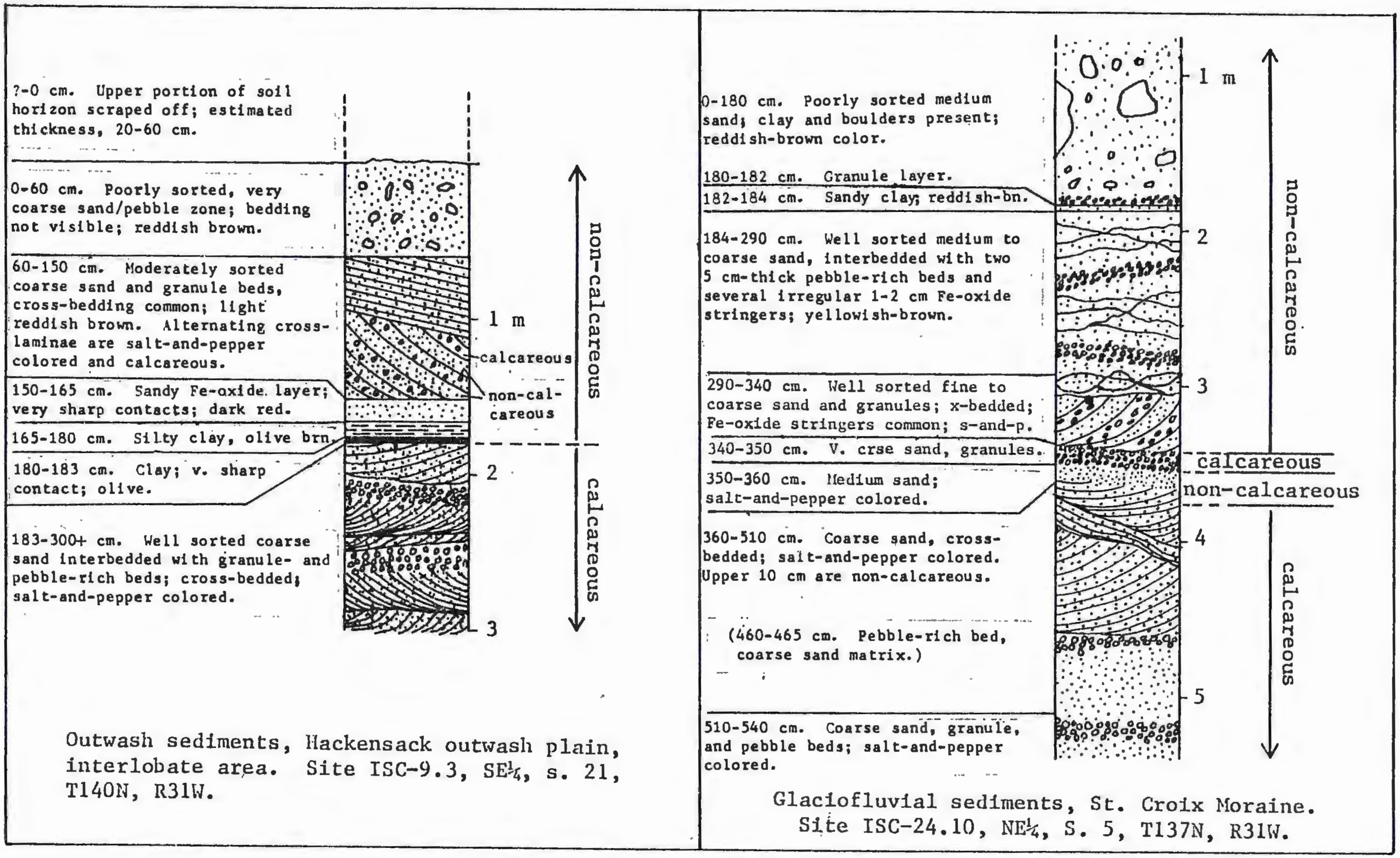
Sediments found within the St. Croix Moraine are characteristically reddish in color. Munsell Index colors of unoxidized flowtills are usually yellowish brown (10YR 5/4) to dark yellowish brown (10YR 4/4). Material in the oxidized zone is usually yellowish brown (10YR 5/4) to dark brown 7.5YR 4/4), depending on local conditions. Flowtills are usually coarse-grained, loose and non-plastic in texture.

The soil profile of a St. Croix Moraine flowtill in the southern part of the study area is described in appendix A. Soil development at this 2.0 m roadcut (site ISC-32.3) is typical of flowtills in the St. Croix Moraine, even though its texture is coarser than most other flowtills studied in the moraine. Color is dark brown (10YR 4/4) in the A1 horizon, becoming yellowish brown (10YR 5/4) to dark brown (10YR 4/4) in the lower part of the soil profile. Except for the clay-rich A11 and B2t horizons, the soil is coarse-textured, non-sticky, non-plastic and friable. Bulk density is 2.1 g/cm^3. Pebbles make up 5 to 10% of the soil. Iron-stained quartz grains are present throughout the exposed profile, but are uncommon below 1 m.

The soil at site ISC-32.3 is noncalcareous and slightly acid throughout the exposed profile. Till of the Rainy Lobe has been thought to be noncalcareous. This is probably due to the relatively great depth of leaching of the carbonate fragments. Dreimanis (1969) cautions that leaching of carbonates may alter a till significantly. He states that permeable tills which originally contained small amounts of carbonate may become entirely leached of carbonate, giving the erroneous impression that the original till was noncalcareous.

Carbonate clasts, when found in the study area, are almost always leached to a depth of 1.7 m, rarely to depths of up to 4.3 m. Wright (1962) found a similar weathering pattern in the Hewitt Till in the Wadena Drumlin Field. He suggested that depth of leaching was inversely related to original carbonate content. The southern part of the drumlin field has a high carbonate plus chert pebble fraction (45%) and a depth of leaching of 1 to 3 feet (0.3 to 0.9 m). Further north, including the southern part of the Itasca-St. Croix moraine study area, depths of leaching were 8 to 14 feet (2.4 to 4.3 m) and carbonate plus chert averaged only 8%

The present study indicates similar percentages of carbonate plus chert to Wright's northern sector, and depths to carbonate are also the same. Another factor may be important in the St. Croix area, however. All occurrences of unleached material were found in very permeable fluvial sediments. In the less permeable flowtills, the base of the leached horizon was never reached. Also, in several locations, a layer of



Outwash sediments, Hackensack outwash plain, interlobate area. Site ISC-9.3, SE¼, s. 21, T140N, R31W.

Glaciofluvial sediments, St. Croix Moraine. Site ISC-24.10, NE¼, S. 5, T137N, R31W.

Figure 10. Differential chemical weathering of carbonates.

relatively coarse sediment containing carbonate fragments was "perched" a short distance above the actual leached horizon (Figure 10). Underlying it was always a layer of leached, finer-grained material. These observations suggest that less permeable and finer-grained material is more rapidly leached of carbonate. This may be because it has a higher surface area to volume ratio, which would make it more chemically reactive. Also, coarser layers may tend to be excessively drained and therefore would be subject to chemical weathering for less time.

Physical Properties

Deposits found within the St. Croix Moraine can be grouped into three major categories, based primarily on sedimentary structures and secondarily by grain size distribution. They are; 1) flowtill, 2) glaciofluvial (including eskers), and 3) glaciolacustrine deposits. All were deposited during downwasting of debris-laden glacial ice at its terminus, and except for eskers, were deposited supraglacially.

In the St. Croix Moraine, flowtill and glaciofluvial deposits together make up almost all of the observed supraglacial sediments. Field characteristics, especially degree of sorting (amounts of boulders and/or clay) and sedimentary structures (presence of bedding, graded bedding, cross-bedding), were used to distinguish between the two types of deposits. Several deposits were examined which are intermediate in character between the two categories, but these are relatively minor in abundance. Sharp contacts between flowtills and fluvial deposits were often observed in the field.

Flowtill and glaciofluvial deposits were mapped as one unit in the St. Croix Moraine. Because of the limited lateral extent of individual deposits and complex interfingering relationships, it was not possible to delineate many entire bodies. Neither do they have consistently differing geomorphic forms by which to distinguish them on aerial photographs or topographic maps. Flowtills appear to be the more abundant surficial deposit in the interior of the moraine. Near the eastern edge of the moraine, however, flowtills show some of the characteristics of glaciofluvial deposits. They gradually become noticeably sandier, looser-textured and better sorted. Local relief also becomes less pronounced and the topography somewhat more subdued (see Plate II, cross-sections B-B' and C-C').

Flowtills, also called sediment flows, have been described and categorized by Boulton (1976) and Lawson (1979) from studies of active glaciers. They typically form by the mass wasting of unstable debris which accumulates on the surface of a melting glacier. As underlying ice melts, englacial and supraglacial sediments flow, slump or spall, depending on the water content of the sediments, slope conditions and texture of the sediment. Sediment flows are usually redeposited many times before meltout is completed. Lawson estimated that 95% of the sediment released by the Matanuska Glacier at its terminus was reworked several times in the space of two years. The resulting deposits, lumped under the general term flowtill (or sediment flow), have the following characteristics: They are usually massive, with local depletion or enrichment of fines due to an increase in water content, often at the top or near the base of a flow. Texture is usually compact and fabric is either absent, with many vertical clasts, or shows a bimodal distribution, parallel and transverse to the sediment flow direction. Areal extent of individual deposits is fairly restricted, usually less than 2000 m^2. Sediment flows are most commonly 0.5 to 2.5 m in thickness, rarely thicker than 3.5 m. Contacts between different flowtills are often sharp and non-erosional in nature, but may be indistinguishable between flows of similar types. Silty to sandy moderately sorted lenses, deposited by local meltwater sheet and rill flows, commonly occur interbedded with sediment flows (Lawson, 1979).

In contrast to flowtills, glaciofluvial deposits commonly show excellent sedimentary fluvial structures such as graded bedding, cross-bedding and scour-and-fill channels. Clast-supported pebble and gravel beds can be found, as well as massive sand deposits. Even though the fluvial nature of the sediments may be readily apparent in the field, commonly only a relatively poor degree of sorting was accomplished before final deposition. This is not surprising, considering that meltwater deposits are only transported limited distances in a supraglaical environment.

Sediments within the St. Croix Moraine are very sandy (Figure 11). All but one of the 17 samples analyzed from the moraine contained at least 73% sand in the matrix (less than 2 mm portion of the sample). Overall average is 82% sand, 12% silt and 6% clay. The amount of sand tends to increase towards the south, away from the interlobate junction with the Itasca Moraine (Figure 12). The matrix of the St. Croix Moraine flowtills is, on the average, less sandy than the matrix of glaciofluvial deposits (Table 4). Flowtills also have smaller mean grain size (including granules and larger size fractions, $\bar{M}_z$ = 1.87 phi). Other statistical parameters reflect the more poorly sorted, more finely skewed and more leptokurtic nature of the flowtills.

Kemmis, Hallberg and Lutenegger (1981) found that supraglacial sediments deposited by the Late Wisconsinan Des Moines Lobe in Iowa varied greatly in texture. This is to be expected, considering the abundance

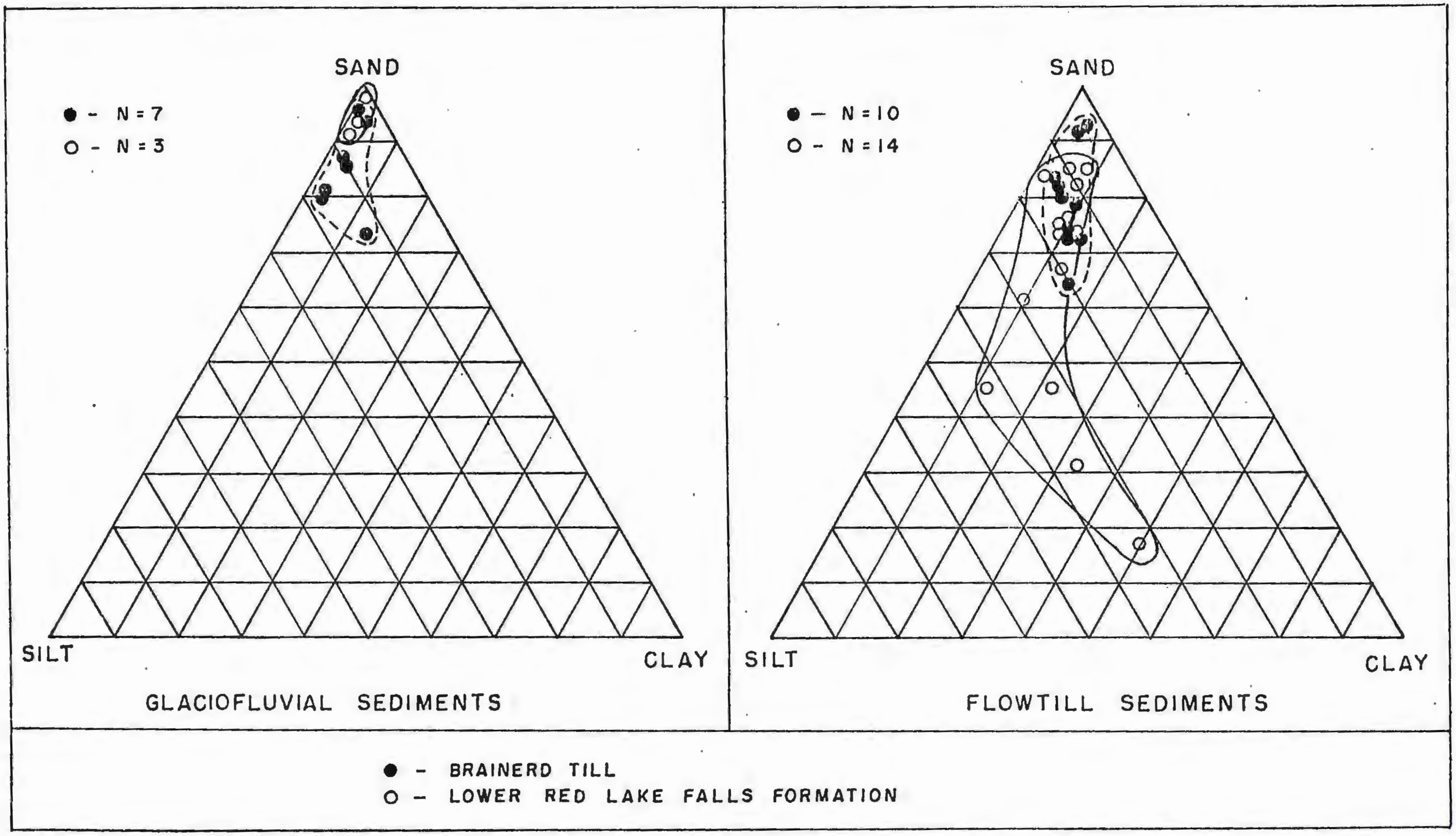


Figure 11. Sand-silt-clay content of Brainerd and Lower Red Lake Falls supraglacial sediments

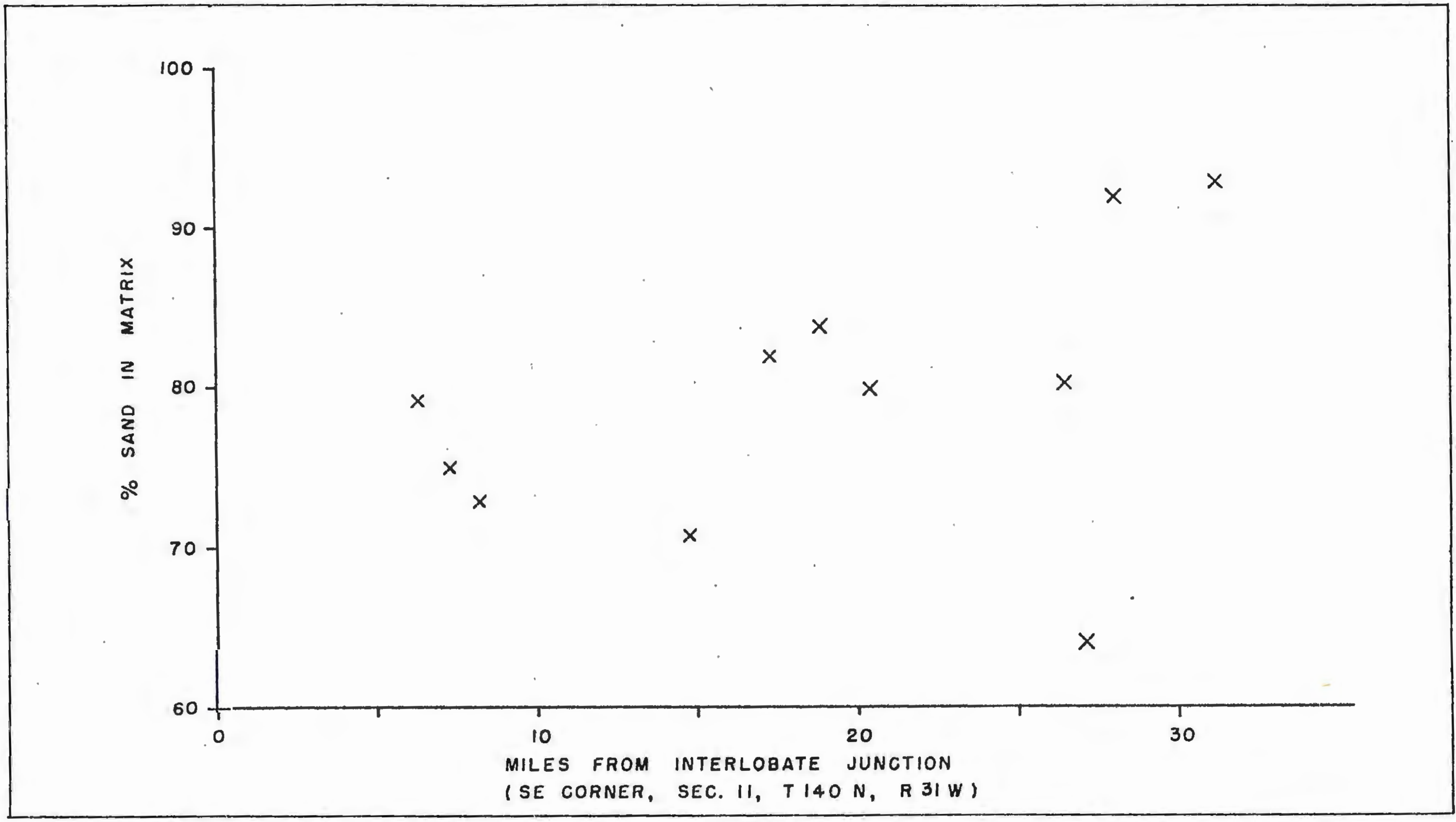


Figure 12. Lateral variation in Brainerd Till flowtills

of meltwater at the supraglacial surface during ablation of an ice sheet, and the many different environments of deposition which were present.

Kemmis et al. (1981) also noted that the average grain size distribution of supraglacial flowtills in the Des Moines Lobe is very close to that of the underlying basal till, which has a very much more restricted range of sizes. This also may be true for Brainerd Till in the study area. Only one occurrence of what may be lodgement till was sampled and its texture is close to the average texture of 10 flowtill samples from the St. Croix Moraine.

St. Croix Moraine supraglacial flowtills are more restricted in their size distribution than those described by Kemmis et al. More sampling would probably increase the range of sediment textures, but a more important factor may have involved the original texture of the glacial sediment. The texture of Rainy Lobe drift has been described as boulder- and cobble-rich till in a sandy matrix in northeastern Minnesota (Winter et al., 1973). As has already been mentioned, a coarse texture is also characteristic of most sediments in the St. Croix Moraine. There was probably a paucity of silt and clay sized particles in the original ice-transported debris, and therefore one would expect relatively few deposits to contain high percentages of those smaller size fractions.

Lithologic Composition

The reddish-brown color of Brainerd Till in the study area is due in large part to a high percentage of reddish-colored rocks which come from northeastern Minnesota, primarily in the Lake Superior region. The most common of these are reddish and purplish volcanic rocks, red granophyre, iron formation, red agate, and red sandstone. These, together with diorite and gabbro from the Duluth Complex make up the "eastern indicators" category shown in Tables 5 and 6. Eastern indicator stones comprise an average of 27% of the pebbles and 11% of the coarse sand fraction of the sediments within the St. Croix Moraine in the study area. Limestone and/or dolomite clasts were found in only two of the 20 samples analyzed, and in only a few other localities which were examined in the field but not analyzed. They average 6% of the pebble fraction in those samples where they are present. Buff chert, also presumed to be derived from the same carbonate bedrock source in the Winnipeg lowlands to the northwest, is found in nearly all samples in uniformly low amounts (usually 1 to 3%). A small amount of light colored chert is obiquitous in glacial sediments in all areas of Minnesota (Arneman and Wright, 1959). This is true even in northeastern Minnesota, where there is very little likelihood that the glacial drift was transported directly from the Winnipeg lowlands. Therefore the presence of buff chert as a "northwest source" indicator should be used with caution.

Granitic and foliated metamorphic rocks make up roughly one-third of the pebble fraction (73% of the coarse sand fraction). Aphanitic mafic rock types also make up one-third of the pebble fraction, but only 13% of the coarse sand fraction. Shale is absent in most samples and comprises a maximum of only 2% where it is present. It is probably derived from the Cretaceous Coleraine Formation which forms a thin, patchy cover over the Precambrian bedrock surface on the south flank of the Mesabi Iron Range in northeastern Minnesota.

There is a systematic variation in the percentages of limestone and eastern indicator rocks throughout the study area. The pattern is described in more detail in the following chapter. Briefly, the percentage of eastern indicator rocks decreases and the percentage of carbonates increases towards the interlobate junction between the Itasca and St. Croix moraine systems. This coincides with a change in flowtill texture as noted earlier.

Lower Red Lake Falls Till

General

Gray calcareous glacial sediments occur in the northern part of the study area. They were deposited at the terminus of the Wadena Lobe during the Middle Wisconsinan St. Croix Phase of glaciation (Wright, 1972). The Itasca Moraine and associated outwash plains deposited by that glacier make up the majority of surficial sediments in the study area. The eastern edge of the Wadena Lobe was confluent with the Rainy Lobe which concurrently advanced to build the St. Croix Moraine. A complex area of primarily glaciofluvial sediments characterizes the interlobate area between the two moraines.

Sackreiter (1975) named the sediments in the Itasca Moraine the lower unit of the Red Lake Falls Formation. In this discussion, these sediments will be referred to as the Lower Red Lake Falls Formation.

Geomorphology

In contrast to the Rainy Lobe, the Wadena Lobe did not build a hummocky, high relief moraine at its terminus. Instead, there is a surface of relatively low relief from 6 to 19 km wide, characterized by the presence of flowtills (or possibly basal till) and glaciofluvial deposits which are mostly covered by outwash sediments. The southern limit of this "extra-moranic till" is marked by an abrupt decrease in the number of boulders seen at the surface. North of the terminus, large boulders (greater than 1 m in length) are commonly seen along roads and piled in fields. South of the terminus there is an almost complete absence of boulders. West of R 32 W (about 5 km east of the town of Nevis), the outermost limit of Lower Red Lake Falls Till is buried by a thick layer of outwash sediments. Boulder abundance has also been used in North Dakota as a useful tool in marking the terminal position of an ice advance (Clayton, 1980, p. 55).

The Wadena Lobe may actually have advanced slightly further south than the surface occurrence of boulders and diamictons would indicate. This is suggested by a band of pitted outwash which extends 13 km further south from the limit of surface boulders. The pitted outwash depressions in this area are restricted to northeast-southwest trending inter-drumlin swales in the underlying Hewitt Till, and end abruptly south of the Shell River (see section on Park Rapids outwash plain for more detailed descriptions). The restricted extent of buried ice and its location fronting the extra-morainic till suggest a brief advance of the Wadena Lobe over that area. For some reason the underlying drumlinized surface was not destroyed by the ice advance, perhaps because the ice was advancing over frozen ground at the toe of the glacier. If so, then the quarrying zone of the glacier may still have been further up ice. Other examples of preservation of sub-ice topography have been mapped in North Dakota (Clayton et al., 1980; p. 40-44) and described in Minnesota (Wright, 1964).

The Wadena Lobe retreated northward a short distance from its terminus before stabilizing and building the Itasca Moraine. Samples of glacial drift from the extra-morainic till area south of the Itasca Moraine are similar in texture and lithology to drift within the moraine and will be grouped with those sediments in the following discussion.

The Itasca Moraine trends approximately east-west through the study area, and is somewhat irregular in outline at its southern margin. It rises to a maximum elevation in the study area of 552 m, considerably higher than the St. Croix Moraine (491 m). It also rises higher above its surrounding outwash, which is at an elevation of approximately 460 m. The moraine is about 11 km broad from north to south. To the north it is covered by outwash and till derived from the St. Louis Sublobe of the Des Moines Lobe during a later advance of ice from the west.

Maximum local relief is 70 m and the maximum slope angle measured is 27°. Both figures are higher than those for the St. Croix Moraine and suggest a greater thickness of supraglacial debris. Plate II, cross sections A-A' and D-D', show some of the relief within the Itasca Moraine. Circular depressions and hills are common and lakes and marshes are abundant. Circular ridges were not noted.

Much of the topography in the Itasca Moraine is composed of semi-parallel ridges which can be traced for up to 3.2 km (Figure 13). They are curvilinear in outline and occur in groups with a spacing between crests ranging from 170 to 690 meters. These have been called thrust ridges or transverse compressional ridges (Sackreiter, 1975; Clayton et al., 1980). They are considered to be the result of shearing at the base of the glacier near its terminus. Bands of sediment are concentrated along shear planes oriented at right angles to the direction of ice flow. The largest group of ridges in the Itasca Moraine are broadly concave to the northeast, suggesting that ice movement came from a direction of about N 20° E to 30° E

Ridges are common elsewhere in the Itasca Moraine, as shown in Figure 13. They occur in groups and singly, but do not have the northeast orientation noted above. These have been identified as ice contact

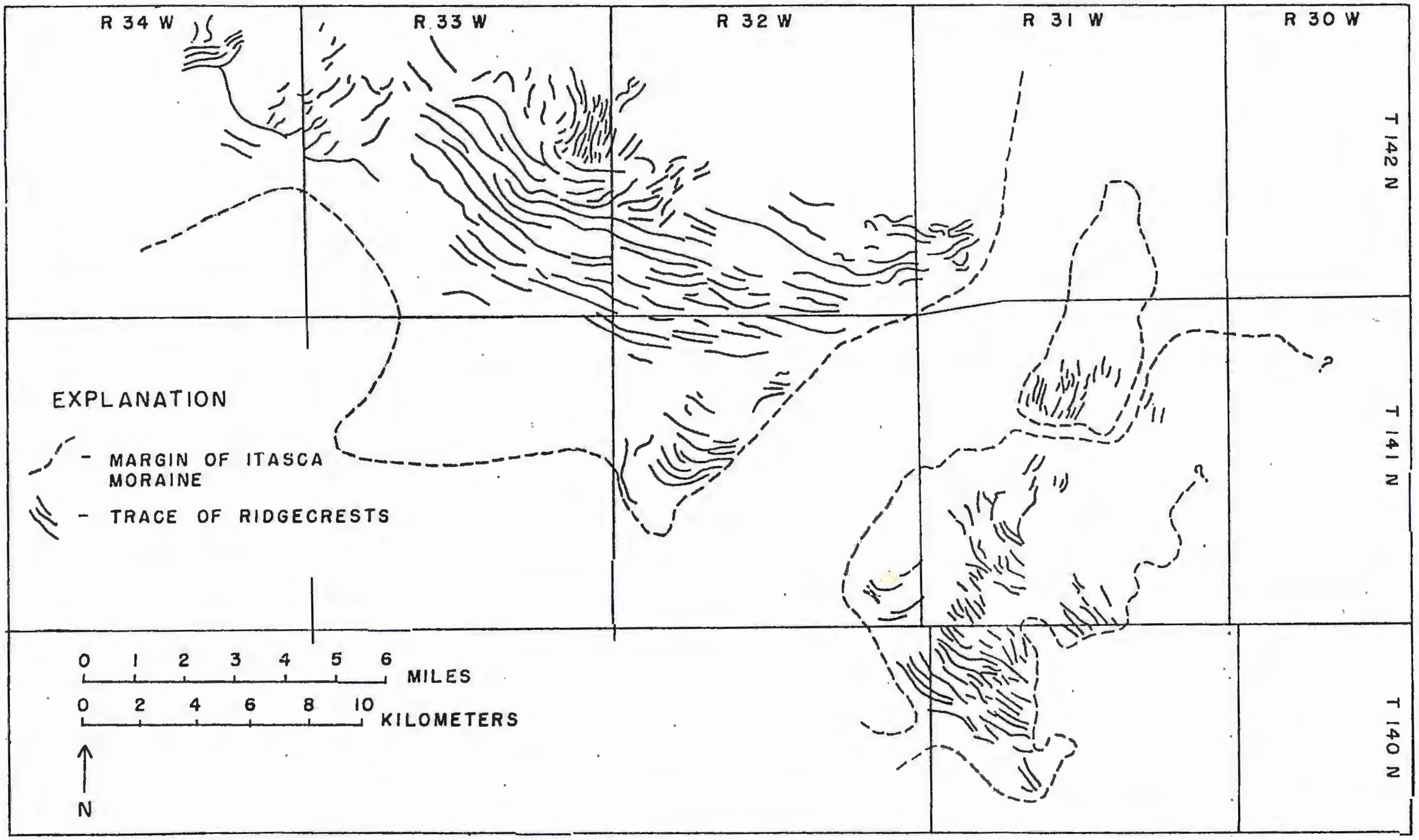


Figure 13. Ridge development in the Itasca Moraine

ridges by Sackreiter (1975) who attributed them to mass wasting of supraglacial debris, unrelated to the direction of ice movement. It appears more likely that they also are transverse compressional ridges, reflecting localized movement of the glacier from directions other than northeast. Lateral compressional forces caused by the merging of the Wadena and Rainy ice lobes may have caused diversion of ice flow, resulting in thrust ridges oriented obliquely to the major direction of glacier movement.

Eskers and glaciolacustrine deposits are present but not abundant in the study area. A large esker is located at the head of the Park Rapids outwash plain in sections 4, 9 and 10, T 140 N, R 32 W. It can be traced southward for 3 km and rises over 18 km above the surrounding terrain. At its terminus it fans abruptly and trends east-west.

A large, interconnected, ice-walled lake plain, about 1.7 km^2 in area, is located in sections 22 and 23, T 141 N, R 31 W. It has steep ice contact slopes and rises over 30 m above the surrounding land surface. No other lake plains or eskers were found in the study area.

Weathering Characteristics

Color of the Lower Red Lake Falls Fm. varies depending on the amount of clay present and whether or not the sediment has been oxidized and/or leached. Unoxidized and unleached flowtill deposits with a high clay content are usually light olive brown (2.5Y 5/4). Sandy fluvial deposits (unoxidized and unleached), however, have a distinctive "salt and pepper" appearance. This is due to the dominantly bimodal color distribution of light-colored granitic and carbonate fragments and dark basalt and greenstone fragments. The scarcity of reddish eastern indicator rocks (rarely more than 2% of the pebble fraction) heightens the black and white color contrast of this sediment. It is very difficult to determine Munsell colors for these unleached sediments.

Oxidized and leached sediments are yellowish- to reddish-brown (10YR 5/4 to 10YR 6/3). Superficially, they resemble noncalcareous Rainy Lobe drift, owing to iron staining of the grains.

A detailed soil profile is described from a 2.5 m flowtill exposure at site ISC-33.1 in the Itasca Moraine (see Appendix A for complete description). The A soil horizon is dark brown (10YR 3/3) to brown (10YR 4/3), becoming yellowish brown (10YR 5/4) and mottled dark brown (7.5YR 4/4) in the B horizon. Below the leached zone at 175 cm, color of the parent material is light olive brown (2.5Y 5/4). Texture is a sandy loam, slightly sticky and plastic in the leached portion of the soil profile, and nonplastic and platy below the solum. Pebble content increases from 5% above 85 cm to 20% below that depth. Soil pH is acid above the leached zone and slightly basic below. Bulk density of the parent material is 1.76 g/cm^3.

Physical Properties

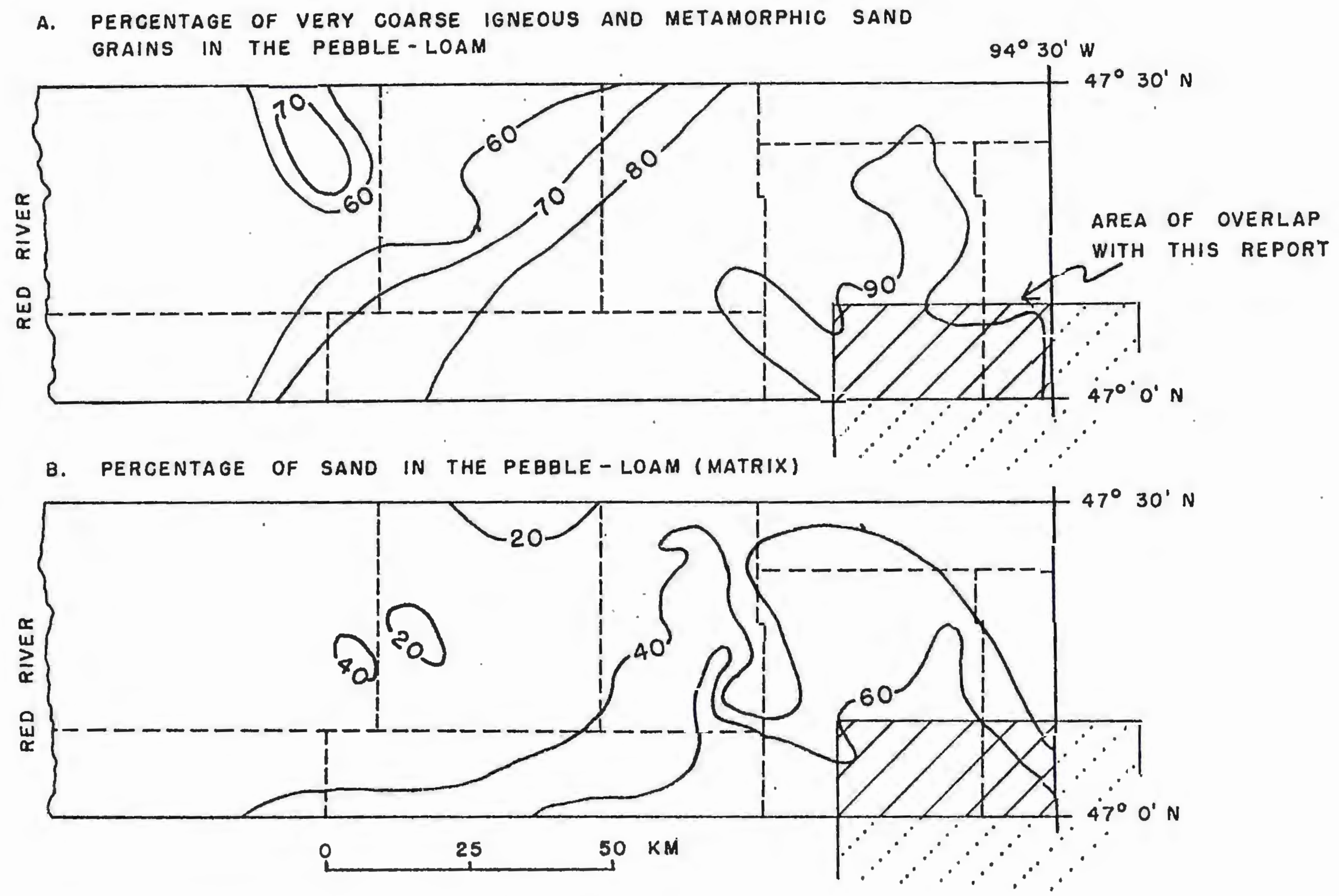
Flowtills and fluvial deposits make up the bulk of the sediments in the Itasca Moraine. Flowtills are noticeably finer-grained then in the St. Croix Moraine. Analysis of 13 samples shows an average of 66% sand, 21% silt, and 13% clay in the till matrix (Table 4). Mean grain size is 3.06 phi. Sediments are slightly more poorly sorted and finely skewed than those of the St. Croix Moraine. The range of grain size distributions is great; as little as 16% sand is found in the matrix. The silty and clayey nature of the flowtills is readily apparent in the field and can often be used as an identifying characteristic. However, as Figure 11 shows, there is considerable overlap between Itasca and St. Croix moraine flowtills. Grain size alone should be used with caution as a distinguishing characteristic between the two tills.

Sackreiter (1975) studied sediments in the Itasca Moraine in detail. He found an average matrix distribution of 45% sand, 39% silt and 16% clay for the lower unit of the Red Lake Falls Fm., which makes up the Itasca Moraine. He also found a systematic coarsening of texture from west to east. His data (Figure 14b) show a greater than 60% sand fraction in the area of the Itasca Moraine, which agrees closely with average matrix texture determined in this study (66% sand).

Three glaciofluvial deposits from the Itasca Moraine were also analyzed for sorting characteristics. The results are shown in Table 4. They are moderately sorted, moderately to well rounded sands and gravels, with an average grain size of coarse sand (0.71 phi). They are coarsely skewed and have a moderately peaked (leptokurtic) size distribution. Matrix grain size distribution is 94% sand, 4% silt, and 2% clay. These sediments are similar in appearance to glaciofluvial sediments in the St. Croix Moraine. However, the negative skewness values, better sorting and a coarser matrix all suggest more extensive fluvial activity in the Itasca Moraine, resulting in a better sorted sediment. More sediments need to be analyzed to confirm this, however.

Lithologic Composition

Carbonate content of the pebble fraction, shown in Table 5, averages 16%, ranging from 5 to 24%. Buff chert, thought to be derived from the same bedrock source, averages 3%. In the coarse sand fraction (Table 6), carbonates average 9%. This is in close agreement with Sackreiter's findings of less than 10% carbonate in the Itasca Moraine portion of his


A. PERCENTAGE OF VERY COARSE IGNEOUS AND METAMORPHIC SAND GRAINS IN THE PEBBLE-LOAM

B. PERCENTAGE OF SAND IN THE PEBBLE-LOAM (MATRIX)

Figure 14. Lithologic and grain size variations in the lower unit of the Red Lake Falls Formation (from, Sackreiter, 1975).

study area (Figure 14a).

Eastern indicator stones average 11% of the pebble fraction and 4% of the coarse sand fraction in the Lower Red Lake Falls Fm. In the pebble fraction, granitic and metamorphic rocks are more common than in the Brainerd Till, and aphanitic mafic rock types are less common. A lateral variation was noticed in the amounts of carbonates and eastern indicators; carbonates increased and eastern indicators decreased in a westerly direction. The significance of this shift will be discussed more fully in the following chapter.

Proglacial Outwash Deposits

Outwash sediments form over 75% of the surficial deposits in the study area. They were laid down by meltwater streams flowing from the Rainy and Wadena ice lobes as they stabilized and then retreated from their respective termini at the end of the St. Croix Phase. Although much of the original outwash plain surfaces have been destroyed by meltout of underlying ice, at least four distinct surfaces can be traced (Plate III). The earliest deposited outwash plains lie immediately in front of the Itasca and St. Croix moraines. Meltwater and sediments were derived from the Wadena and Rainy lobes as they stabilized and concurrently deposited the moraines. Retreatal positions of the ice margins were recorded by deposition of two more outwash plains, one of which was deposited behind the St. Croix Moraine by the Rainy Lobe. The other outwash plain was deposited by the Wadena Lobe across the former interlobate margin between the ice sheets after the Rainy Lobe had retreated from the area completely.

Oshawa Outwash Plain

Geomorphology

The outwash plain deposited by the Rainy Lobe in front of the St. Croix Moraine is here named after the town of Oshawa, which is located on its surface in section 32, T 139 N, R 31 W. The Oshawa outwash plain surface is one of low relief. Apparently little or no ice was present underneath the sediments when they were deposited, since there is not a pitted surface which would have resulted from buried ice meltout. Outwash sediments bury the earlier formed Wadena drumlins for only a short distance from the head of the outwash plain. In the southern part of the study area, Oshawa outwash sediments are restricted to low areas between drumlins, but the westerly slope of the outwash plain is still discernable.

The Oshawa plain pinches out at its northern end. There it becomes intermingled with meltwater features of the interlobate area and is partially buried by the larger Park Rapids outwash plain. It widens southward to approximately 11 km as influence from the Park Rapids outwash sediments lessens. A single large fan was deposited at the mouth of the esker described in the previous section on the St. Croix Moraine (sections 30 and 31, T 138 N, R 31 W). A later stage of the same meltwater stream eroded a meandering channel into the surface of the fan, perhaps due to a decrease in sediment load and an increase in discharge as clean ice at the toe of the glacier melted. The channel is located in sections 21, 22, 23 and 26, T 138 N, R 32 W.

An interesting feature of the Oshawa plain is the abrupt ridge at its proximal margin which runs almost continuously along the length of the plain, parallel to the St. Croix Moraine. The ridge is asymmetric in cross section, being steeper on the moraine-facing, eastern side. A broad low area, or fosse, lies between the ridge and the moraine. Scott (1921) defined a fosse as "A long narrow depression that is sometimes found between a moraine and an outwash plain. It is a remnant of ground moraine upon which the ice stood when the outwash was being formed."

Formation of the fosse and ridge at the head of the outwash plain are probably both linked to the presence of a zone of stagnant ice at the toe of the glacier (Figure 15a). In southern New England, where outwash plains are common, no outwash plain heads have been found that show effects of contact with actively moving ice (Koteff, 1974). Melting of debris-poor stagnant ice at the toe of a glacier results in a trough bordered by thicker accumulations of outwash sediments and supraglacial and englacial morainic sediments (Figure 15b).

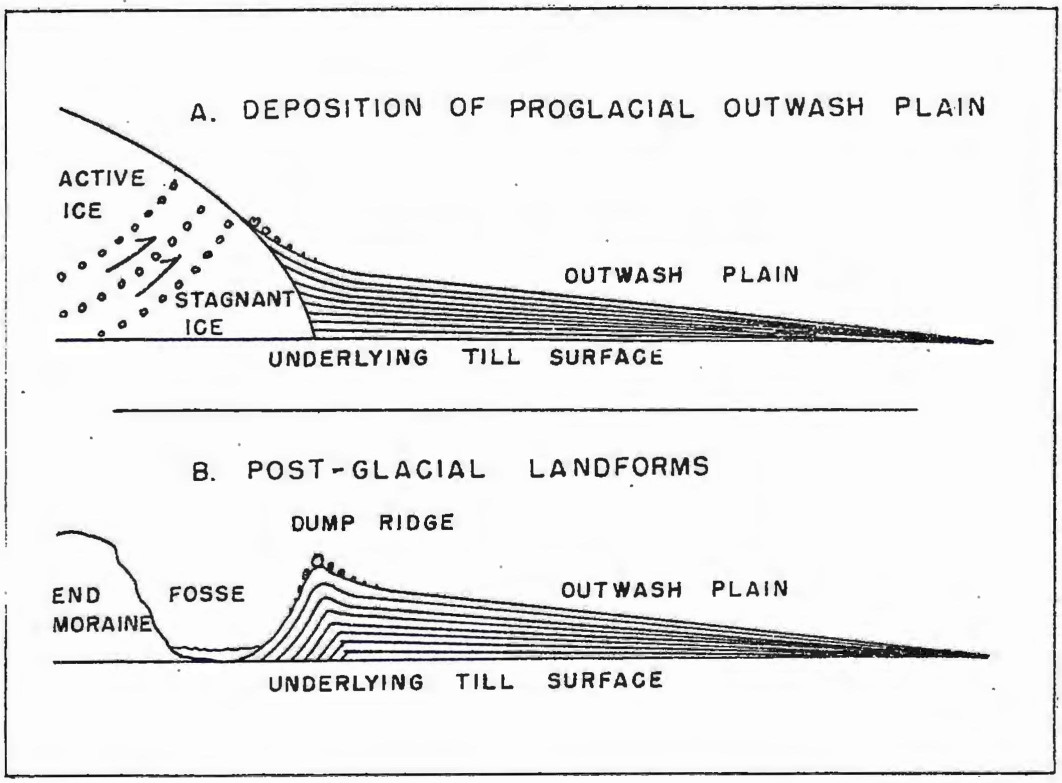


Figure 15. Development of outwash plain ice-contact landforms.

The possibility that the ridge represents a "push moraine" formed by a brief readvance of the Rainy Lobe is not likely. Field examination of the ridge revealed it to be composed of undisturbed layers of coarse sand and gravel interlayered with pebble- and cobble-rich beds (Figure 16). Very large boulders (up to 2 m in length) are common along the top of the ridge. Clast size decreases rapidly to the west, down the slope of the outwash plain.

Figure 16. Oshawa dump ridge sediments.
(shovel is 70 cm long)

The ridge is a large version of what Pettyjohn (1967) called a "dump ridge", which he described for the Missouri Coteau in North Dokata. He attributed their formation to the "dumping of coarse outwash sediments at the margin of stagnant ice, which meltwater streams lacked the competency to remove. The Oshawa dump ridge has an average width of 150 m and a height of 10 to 20 m, somewhat larger than those described by Pettyjohn. Beyond the dump ridge, slope of the outwash plain decreases rapidly westward (Plate II, cross-sections B-B' and C-C'). Slopes of the more distal portions of the outwash plain are very low, approaching .001.

Physical Properties

Massive to poorly stratified sand makes up the great majority of Oshawa outwash plain surface and near surface (less than two meters) sediments. Typically the sand is loose, moderately to poorly rounded and sorted and noncalcareous. Reddish-brown (10YR 4/4) to yellowish-brown (10YR 5/4 near the surface, the sediment lightens to a light yellowish-brown (2.5Y 6/4) at depths below 1.0 to 1.5 m. A dark red oxidized layer was occasionally encountered, usually between a depth of 1.2 and 1.5 m.

Boulders (clast size greater than 25.6 cm) and cobbles (6.4 to 25.6 cm clast size) are uncommon constituents of the outwash sediments at distances greater than 1 km from the dump ridge crest, except for very rare boulders which were found throughout the outwash plains in the study area. As determined by roadside observations, the limit of the cobble zone is 4 km from the head of the outwash plain; the pebble zone (4 mm to 6.4 cm clast size) extends to 5 km. Beyond 5 km, sand and granules are the only constituents of the outwash (Plate III).

Size analysis of several outwash sediment samples shows a rapid decrease in grain size with increasing distance away from the source (Figure 17). Mean grain size falls below 1.5 phi (0.35 mm) beyond 200 m from the head of the Oshawa outwash plain. Although the sample size is

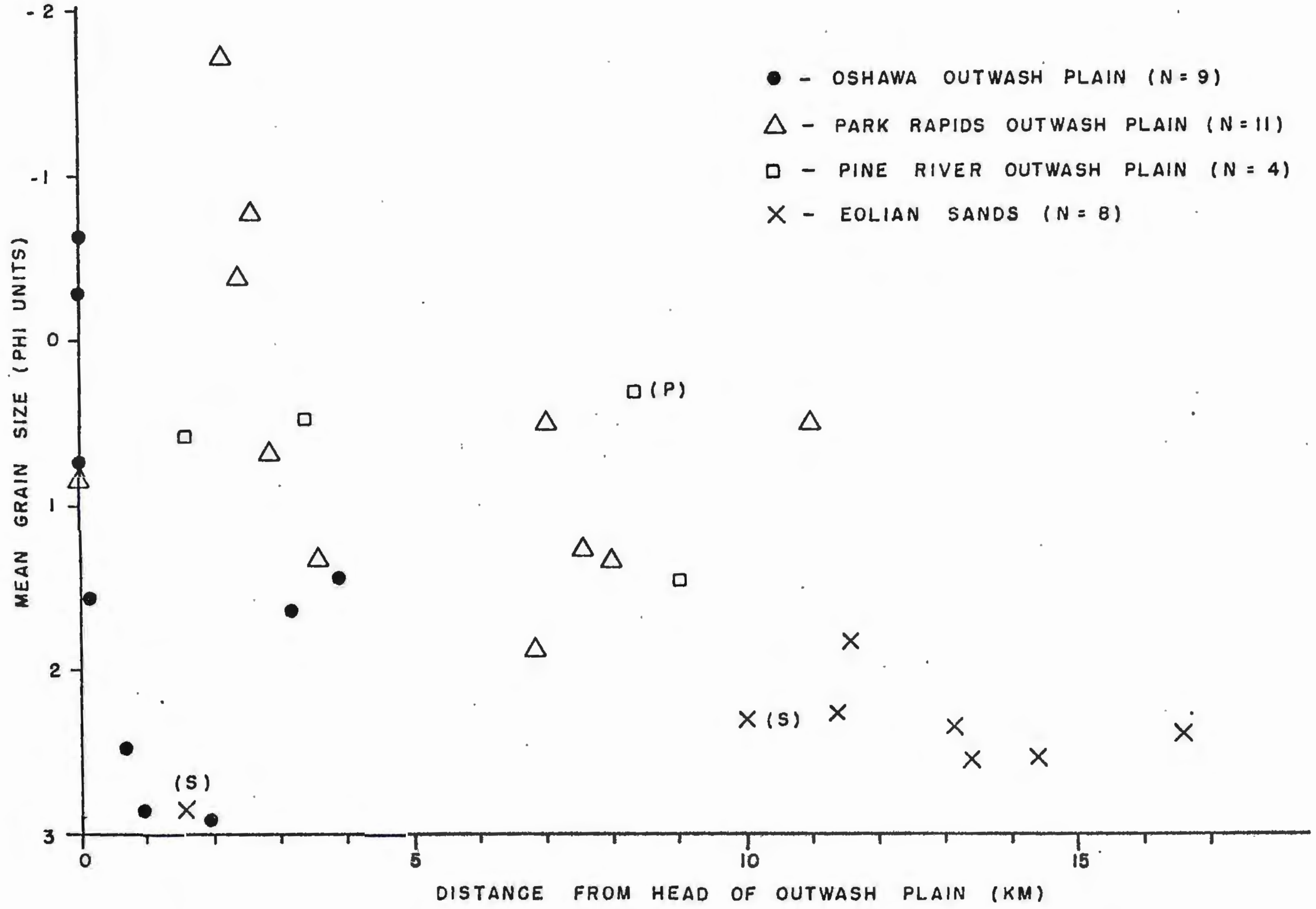


Figure 17. Mean grain size vs. distance from head of the outwash plain
(S) - sample was taken from A-B soil horizon
(P) - sample was taken from a gravel bed

small, it appears that for this area, 3.0 phi (0.125 mm) is the lower limit of mean grain size for near surface outwash stream sediments. Rapid decrease in grain size of Oshawa outwash plain sediments may be due to post-glacial eolian activity, by which fine-grained sand was transported from the Park Rapids outwash plain southeastward towards the Oshawa plain where it became intermingled with those sediments.

Most samples are very poorly sorted (Table 7). Dump ridge sediments tend to have a nearly symmetrical, normally peaked distribution, while more distal sediments have a finely skewed and very peaked distribution.

Lithologic Composition

Oshawa sediments are characterized by a relatively high percentage of eastern indicator stones. The percentage of eastern indicators ranges from 19 to 34% in the pebble fraction, and 9 to 11% in the sand fraction. These amounts are slightly lower than those found for samples taken from the St. Croix Moraine (24 to 42% and 8 to 16% for the pebble and sand fractions, respectively). Carbonate fragments were not found near the surface in the Oshawa plain, but sand samples collected at greater depths for the Pineland Sands aquifer study (Helgesen, 1977) do contain carbonate. The samples examined are mostly located south of the study area, in townships 135 N and 136 N and ranges 32 W and 33 W. There, at depths between 6 and 11 m, carbonate content ranged from 7 to 11% of the 1-2 mm sand fraction.

The possibility exists that these deeper sediments were derived from the Wadena Lobe, and were later buried by outwash sediments from the Rainy Lobe. This could explain their calcareous nature. However, one sample, located in the study area, (sample no. 75MIN67, NW¼ s. 29, T 137 N,

TABLE 7. GRAIN SIZE DISTRIBUTION OF
OUTWASH PLAIN SEDIMENTS

	MATRIX			MEAN DIAMETER Mz (phi)	SORTING σ_1	SKEWNESS Sk_1	KURTOSIS Kg
	% SAND	% SILT	% CLAY				
Oshawa Outwash Dump Ridge (n = 4; 3 used for statistics)	86 (5.3)[1]	8 (4.0)	6 (1.5)	-.05 (.71)	2.96 (.39)	-.06 (.09)	.90 (.22)
Oshawa Outwash Sand Plain (n = 5)	82 (9.9)	11 (6.4)	7 (4.5)	2.26 (.68)	2.56 (.92)	+.17 (.23)	1.62 (.27)
Pine River Outwash Plain (n = 6; 5 used for statistics)	96 (5.6)	2 (2.8)	2 (2.9)	.75 (.44)	1.66 (.86)	-.23 (.14)	1.44 (.44)
Park Rapids Outwash Plain (n = 11; 9 used for statistics)	99.5 (0.7)	0.5 (0.5)	0 (0.3)	.71 (.86)	1.32 (.36)	-.19 (.11)	1.18 (.29)
Hackensack Pitted Outwash Plain (n = 9; 8 used for statistics)	77 (36.4)	16 (26.2)	7 (13.4)	1.55 (3.3)	1.89 (.78)	.22 (.32)	1.00 (.29)
Eolian Sands (n = 8; 6 used for statistics)	98 (1.2)	1.5 (.84)	.5 (.52)	2.33 (.27)	.90 (.16)	-.04 (.10)	1.16 (.12)

[1] standard deviation

R 32 W), did contain a small amount of carbonate (less than one percent) at a depth of only 1.2 m. The presence of carbonate clasts in the Oshawa outwash plain is probably due to their incorporation from underlying calcareous glacial sediments by the Rainy Lobe as it advanced.

Buff chert is present in fairly uniformly low amounts, usually comprising 1 to 3% of a sample. Shale was not present in any of the samples counted. Igneous and metamorphic rock fragments average 31% of the pebble fraction and 75% of the sand fraction (Tables 5 and 6). Dark-colored aphanitic rocks make up 42% and 13% of those fractions.

Park Rapids Outwash Plain

Geomorphology

The Park Rapids outwash plain was described briefly by Leverett and Sardeson (1932) and also by Wright (1962), who named it. The plain extends for 60 km along its northern boundary. Perkins (1977) described the western portion of the outwash plain, which he called the sand and gravel facies of the New York Mills Formation. Thickness of the outwash sediments, mapped by Helgesen (1977), varies from 10 to 40 m along the northern edge of the Pineland Sands surficial aquifer. It thins southward to less than 8 m in the southern part of the Itasca-St. Croix moraine study area.

Most of the outwash plain grades southward from the front of the Itasca Moraine. At its eastern end, however, it slopes southwesterly, radiating outward from the interlobate junction between the Wadena and Rainy ice lobes. Deposition may have been concurrent with the Oshawa plain, but more sediments were eventually deposited in the Park Rapids plain. It stands at a higher elevation, contains a greater volume of sediments, and pinches out the Oshawa plain in the interlobate area where the two outwash plains merge.

The head of the outwash plain in the interlobate area rises 25 m above a poorly drained lowland surface immediately north and east of it. This low area is probably a fosse, similar to the one which occurs between the Oshawa outwash plain and the St. Croix Moraine. This fosse is wider and more discontinuous, but does separate morainic from outwash sediments.

The surface of the Park Rapids plain grades southeastward at an average slope of .003 near the northeastern corner of the outwash plain. The gradient decreases to only .0006 (0.6 m per kilometer) in the southwestern corner of the study area in the Nimrod map quadrangle (USGS, scale 1:24,000). The outwash plain is over 40 km long from the head of the outwash to the Nimrod quadrangle, and it can probably be traced even further southward.

A large meltwater channel is eroded into the surface of the alluvial fan in the northeast corner of the outwash plain. It is 0.2 to 0.5 km wide and 10 to 20 m deep in most places. Many small lakes, mostly unconnected, lie in the former bed of this meltwater channel. It can be traced for 17 km from its beginning in section 30, T 140 N, R 31 W southwestward to the confluence of the Crow Wing and Shell rivers.

Further west, in ranges 33 W and 34 W, the outwash plain slopes southward from the front of the Itasca Moraine. It is discernable as far downslope as the large single fan to the east, with which it eventually merges. It extends further northward, however. Rather than having an isolated plateau at its head, it continues upslope to the Itasca Moraine. Dump ridges and fosses are locally present along the head of the Park Rapids plain, but are not as well developed as the ones associated with the Oshawa plain.

A tunnel valley may have existed beneath the Wadena Lobe in the study area (Plate I). Helgesen (1977) mapped a zone of water-saturated sand and gravel approximately 40 m thick at the northern edge of the Pineland Sands surficial aquifer. This southwestward trending zone is not expressed topographically, so it must represent a large valley at least 1.2 km wide which was probably eroded into the Hewitt Till underneath the Wadena Lobe before it retreated and stabilized at the Itasca Moraine. The tunnel valley extends further to the northeast, underlying the lakes which front the Itasca Moraine and lead to Leech Lake. Sackreiter (1975) also considers that area to have contained a major meltwater channel.

The surface of the outwash plain has undergone various degrees of pitting due to meltout of underlying ice. Three different zones can be identified, each with a distinctive topography (Plate III). The southernmost zone lies south of the Shell River and the large northeast-southeast oriented meltwater channel cut into the outwash plain. There is no pitting of the outwash plain surface in this area. A few lakes are present, but are extremely shallow. The only landforms that interrupt the gradual southward decrease in elevation are the Wadena drumlins in the extreme southern portion of the study area. Even there the slope of the outwash plain can be traced between the drumlins.

The central zone contains several strings of lakes and drained depressions which are oriented northeast-southwest. Some of the chains of lakes are listed in Table 8. The southward sloping depositional surface of the outwash plain can be connected on both sides of these depressions, indicating that they were created after deposition of the outwash sediments.

TABLE 8. NE-SW ORIENTED CHAINS OF LAKES IN THE PARK RAPIDS OUTWASH PLAIN, CENTRAL ZONE

LAKES (listed NE to SW; elevations in parentheses, in feet)	LOCATION (associated landforms in parentheses)
Third Crow Wing Lake (1364) - Second Crow Wing Lake (1364) - Palmer Lake (1366) - Duck Lake (1366)	T 139N, R 33 W
Kettle Lake (1416) - Mow Lake (1405?) - Nagel Lake (1405?) - Mud Lake (1394) - Tripp Lake (1390)	T 139 N, R 32 W (meltwater channel)
Tenth Crow Wing Lake (1386) - Ninth Crow Wing Lake (1386) - Eighth Crow Wing Lake (1386) - Seventh Crow Wing Lake (1384) - Sixth Crow Wing Lake (1381) - Fifth Crow Wing Lake (1381)	T 140 N, R 33 W
unnamed lake (1395) - Hay Lake (1397) - Ham Lake (1395) - unnamed lake (1395) - unnamed lake (1387?) - Tamarack Lake (1387)	T 140 N, R 32 W (tunnel valley)

The orientation of the many depressions in this zone is the same as that of the drumlins in the Wadena Drumlin Field. Ice must have been present in the interdrumlin swales when the outwash sediments were deposited. Origin of this ice is not known for certain, but it appears likely that it was left behind after a brief advance of the Wadena Lobe as far as what is now the Shell River. Other possibilities have been suggested, however. For instance, the ice may have been remnants of the glacier that formed the Wadena Drumlin Field, which was the last glacier known to have advanced over that area. If that is the case, then a long time period of cold climate must be considered, if the two advances were separated by at least 10,000 and possibly up to 40,000 years as postulated by Florin and Wright (1969) and Wright (1962; 1972).

A third explanation is offered by Perkins (1977, p. 13). He suggests that flooding of the inter-drumlin areas was caused by ice dams formed between drumlins. This was followed by freezing of the temporary lakes, which were then covered with sediment. Alternating layers of ice and sediment were thus built up until the drumlins were completely buried by outwash sediments. Subsequent melting of the ice layers then caused the inter-drumlin depressions to form. Perkins' idea explains the presence of ice without requiring a glacial advance over the area, but he does not explain the mechanism for formation of the ice dams, nor does he offer any sedimentological evidence or examples from other glaciated areas.

The third and northernmost zone of the outwash plain is located between the Itasca Moraine on the north and the southern limit of Wadena Lobe diamictons and boulders on the south. The pitted surface in this zone is mostly randomly oriented. Many lakes are present, some of which are 40 m deep. There is very little suggestion of an underlying northeast-southwest streamlined topographic surface. Presumably this area was far enough up-glacier to be within the zone of quarrying when the Wadena Lobe terminus stood further south at the Shell River. Ice blocks which melted to create pitted lakes in this zone were derived from the brief advance of the Wadena Lobe into this area during the St. Croix Phase.

Physical Properties

Most of the Park Rapids outwash plain is composed of loose, poorly to well rounded, poorly bedded to massive sand and gravel, with sand predominating. Pebbles, cobbles and boulders are commonly found, but are restricted in their areal extent. They most likely were deposited in the beds of the larger outwash streams. The approximate surface distribution of large clasts in the core study area is shown in Plate III. Boulders are rarely to commonly present up to 4-5 km from the eastern head of the Park Rapids plain. Cobbles extend 6-7 km and pebbles are found up to 11-12 km distant. The boundaries delineating these zones approximately parallel the reconstructed contours of the outwash plain.

Color of surficial outwash sediments is typically yellowish-brown (10YR 5/4), very similar to the color of Oshawa plain and other Rainy Lobe deposits. This is due to oxidation, and also to leaching of the light-colored limestone component of the sediment. Below the leached and oxidized zones, the sediment has the distinctive "salt and pepper" appearance described previously for Itasca Moraine sediments.

Size analyses were done on 18 Park Rapids outwash plain samples. Averages of grain size distribution statistics for 9 of them are given in Table 7 (seven were considered to be eolian sands and were grouped and analyzed separately; one was altered by soil-forming processes and one was from a very coarse portion of a gravel pit, therefore, they were not used in calculating the statistics in Table 7). The overwhelmingly sand-dominated matrix, 99.5% sand, contains the least amount of silt and clay of any of the outwash plains. It also is the best sorted ($\bar{\sigma}_1 = 1.32$). It has a moderately peaked, coarsely skewed distribution.

Mean diameter was 0.71 phi (0.6 mm). This figure is not particularly meaningful, since mean grain sizes varied considerably from -0.77 to 1.86 phi (1.7 to 0.27 mm). Compared with distance from the sediment source (see Figure 17), however, mean grain sizes of Park Rapids outwash sediments are coarser than those of the Oshawa plain.

Helgesen (1977) reported the range of cumulative curves for grain size distributions of 83 test-hole samples drilled throughout the Pineland Sands surficial aquifer. From that information the range of graphic means can be plotted, following the method of Folk and Ward (1957) used in this report. Mean grain size from these samples ranges from -0.5 to 3.0 phi (1.4 to 0.125 mm). Helgesen found that grain size increases to the north and sorting increases to the south in the surficial aquifer.

Lithologic Composition

Relative percentages of rock types present in Park Rapids outwash sediments differ considerably from those in the Oshawa plain. They closely resemble the lithologic makeup of the Itasca Moraine, which had the same source of sediments (Tables 5 and 6). Eastern indicator rocks are present in low amounts ($\bar{x} = 5\%$ in the pebble fraction, $\bar{x} = 3\%$ in the 1-2 mm sand fraction) in the unleached samples. Carbonate fragments comprise an average of 15% of the pebble fraction, and 10% of the 1-2 mm sand fraction. Igneous plus metamorphic rock fragments are present in slightly greater amounts than aphanitic mafic rock types (42 and 34%, respectively, of the pebble fraction).

Pine River Outwash Plain

Geomorphology

A third outwash plain lies in the southeastern part of the study area, east of the St. Croix Moraine. It is here named the Pine River outwash plain after the town of Pine River located near its southern edge (section 31, T 138 N, R 29 W). It was deposited by the Brainerd Sublobe following a short retreat and repositioning of the ice margin.

The head of the Pine River plain trends approximately east-southeast through section 1, T 138 N, R 30 W, and section 7, T 138 N, R 29 W. In that area, it is 25 to 30 m above the lakefilled lowlands immediately north of it. The plain grades to the south and southwest at a slope of .005, gradually decreasing to .0025 at its furthest reaches in the study area. The plain grades westward for 13 km to the base of the St. Croix Moraine. To the south it merges with a Rainy Lobe ground moraine surface of slightly higher elevation. It is 9 km wide in that direction. The surface of the outwash plain is pitted due to melting of underlying ice which remained after the retreat of the Rainy Lobe, upon which the outwash plain was built.

Physical Properties

Pine River sediments are reddish- to yellowish-brown in color near the surface. Down to depths of approximately 1.0 m the sediment is often clayey and compact with large clasts common, resembling a flowtill in some places. This horizon is probably an artifact of soil-forming processes. With increasing depth the sediment lightens in color to yellowish-brown, and is typically loose in texture. Moderately sorted, poorly stratified sand and gravel beds were most commonly encountered, but well stratified beds do occur as do pebble- and cobble-rich layers. A leached horizon was reached at a few localities at depths below the surface between 1.8 and 2.6 m. Below the leached zone, the sediment was better sorted, very pale brown to salt and pepper in color, and weakly calcareous.

Although this outwash plain was not systematically sampled, its grain size distributions appear to differ considerably from those of the Oshawa plain. They are coarser, when distance from the head of the outwash is considered (Figure 17). The matrix distribution is also coarser (96% sand, 2% silt, 2% clay; Table 7). Although still poorly sorted, Pine River outwash sediments are better sorted ($\bar{\sigma}_1 = 1.66$), and have a slightly less peaked distribution ($\bar{K}_g = 1.44$) than the Oshawa outwash plain, also built by the Rainy Lobe. They have a coarsely skewed distribution ($\bar{Sk}_1 = -0.23$), whereas the Oshawa outwash sediments are finely skewed.

Lithologic Composition

The relative amounts of different lithologies present in Pine River outwash sediments are similar to those found in the Oshawa outwash plain. In the Pine River plain, however, carbonate clasts are present below a leached horizon, the depth of which is slightly greater than in other deposits associated with the Wadena Lobe in the study area. Unleached sediment was reached at three localities at depths of 1.8, 2.0 and approximately 2.6 m. At two of these locations, carbonate pebble percentages were found to be 9 and 6% (no sample was taken at the third location).

Lower carbonate content of the original sediment may be partly responsible for a greater depth of leaching as suggested by Wright (1962). Data obtained from this study support this idea. Figure 18 shows a decrease in depth of leaching with an increase in carbonate content, both in the pebble and sand fractions. These results are preliminary; more work is necessary to separate the effects of other physical parameters, such as mean grain size, permeability, depth of water table and climate, all of which may affect depth of leaching.

Igneous plus metamorphic rock fragments and aphanitic mafic rocks are present in nearly equal amounts in the pebble fraction of unleached samples (34 and 37%, respectively). Eastern indicator rock types make up an average of 20% of the pebble fraction and 7% of the 1-2 mm sand fraction of the samples which were counted. Although this is slightly lower than the average for St. Croix Moraine sediments, it is nearly the same as the average for the Oshawa outwash plain.

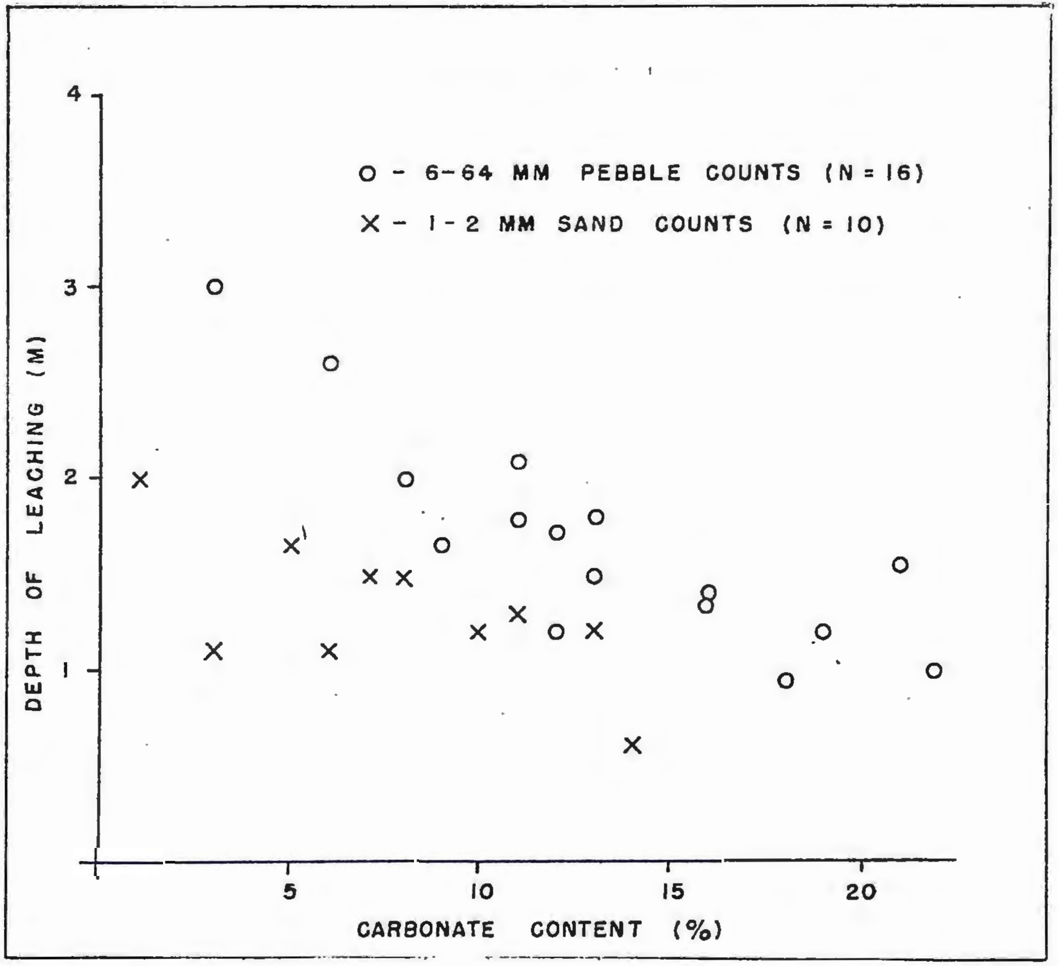


Figure 18. Carbonate content vs. depth of leaching

Hackensack Pitted Outwash Plain

Geomorphology

A fourth and final episode of extensive alluvial deposition occurred in the northeastern part of the study area, following retreat of the Wadena Lobe from the Pine River and eastern part of the Park Rapids outwash plains. The major sources of water and sediments for this last phase of outwash deposition were meltwater streams flowing from the stalled Wadena Lobe as it concurrently built the Itasca Moraine. The outwash plain originates at the southeastern edge of the Itasca Moraine and slopes in a southeasterly direction. It was deposited over dead ice of both the Wadena and Rainy lobes. The outwash plain is named after the town of Hackensack which lies in the middle of the plain in section 19, T 140 N, R 30 W.

The present land surface is extremely irregular. Large and small areas of hummocky ice stagnation topography, containing appreciable amounts of flowtill, rise above the outwash plain in several localities. One of the larger of these is the Deep Portage site, located in townships 139 N and 140 N and ranges 29 W and 30 W. It covers an area of 28 km^2 and rises to over 50 m above the surrounding outwash sediments. It is almost completely surrounded by lakes. One sample was analysed from this area. Lithologically, it is intermediate in composition between Wadena and Rainy lobe sediments (21% eastern indicators and 1% carbonate in the pebble fraction). The location of this area east of the northern part of the St. Croix Moraine, and its lithologic makeup suggest that it was deposited primarily by Rainy Lobe ice, with some contribution from underlying calcareous sediments. Mixing of ice and sediments between the Rainy and Wadena lobes along their common border could also have yielded this lithologically intermediate sediment.

Another area of hummocky terrain rises 30 m above the outwash plain. It covers an area of 3 km^2 in sections 6 and 7, T 140 N, R 30 W. Its position in the middle of the interlobate area, where the Wadena Lobe overrode Rainy Lobe drift, contributed to a complex intermingling of different sediment types. It is composed primarily of drift deposited by the Rainy Lobe, but in places it is crossed by carbonate-bearing fluvial sediments, which are lithologically more characteristic of Wadena Lobe sediments.

Other areas of hummocky terrain occur close to the Itasca Moraine in the northern part of the study area. Boundaries are less well defined than for the areas previously described, but elevations range from 12 to 30 m above the surrounding outwash sediments. Because of their lithologic makeup and their location close to the Itasca Moraine, these hummocky, morainic areas are thought to have been deposited by the Wadena Lobe during its wastage to the Itasca Moraine.

The Hackensack outwash plain is extensively pitted; original upland surfaces are rare in many parts of it. Classic kettle lakes with rounded regular shorelines are present, but are uncommon and mostly small. Most lake basins are the result of the meltout of a more widespread buried ice mass. Birch Lake and Ten Mile Lake, located in T 140 N, R 31 W, are large lakes of this type. Both are completely surrounded by sandy sediments and have complex lobate shorelines that appear to be the result of coalescing kettle basins. Birch Lake is shallow (maximum depth of 15 m), but Ten Mile Lake is deep. Its deepest point is 61 m below the lake surface and is the lowest elevation found in the study area (360 m above sea level). Surface drainage is almost completely absent throughout the pitted outwash plain.

Original depositional surfaces are much less common than in the other outwash plains, but they are present. By using the elevations of flat, gently sloping upland sand surfaces, the original outwash plain surface was contoured (Plate III). It grades southeast and south at an average gradient of .002 (10 feet per mile). Locally the gradient is considerably greater, such as near the Itasca Moraine (slope = .024), and where the outwash plain is constricted between the St. Croix Moraine and the hummocky terrain at the Deep Portage site (slope = .006). Elsewhere the outwash plain is almost flat, as in the Lake Hattie--Lake Ada area (T 139 N, R 29 W), where the southern end of the outwash surface is bounded by the head of the Pine River outwash plain.

Physical Properties

Loose poorly- to well-rounded, massive to bedded sands form the majority of the Hackensack outwash sediments, as in the other outwash plains. In this plain, however, there are several other sediment types present in significant amounts. Lacustrine silts and clays were found in the northern part of the plain. Coarse-textured alluvium is common, containing clasts ranging up to and including boulders. Poorly sorted to unsorted sediment is also present, probably the result of sediment flows directly off of melting ice.

Nine samples from the Hackensack pitted outwash plain were analyzed for grain size distribution (see Appendix B). Because of the wide variety of sedimentary environments sampled, the summary statistics shown in Table 7 may be misleading. They do show, however, that most of the sediments are poorly sorted.

Lacustrine sediments are exposed in several locations at the surface in the northern part of the study area. A 7 m roadcut through interbedded silt and clay beds is located in section 26, T 141 N, R 32 W (Figure 19). Climbing ripples in the silt layers are similar to type B ripple drift cross-laminated sediments described by Joplin and Walker (1968). This type of ripple is asymmetric with both stoss and lee side laminae preserved. Symmetrically rippled silt and clay beds (sinusoidal ripple lamination of Joplin and Walker) are also common. These sediment types are characteristic of a delta which is prograding in a lake basin, primarily by fallout from suspension onto a partly cohesive bed. Bedload movement was probably minimal in this sequence of sediments.

More lacustrine sediments are exposed 4 km further south. A 2 m section of interbedded silt and sand is illustrated in Figure 20. Sample ISC-18.3 was taken from a calcareous, very pale brown (10YR 7/3), unbedded sandy silt. Grain size distribution is given in Appendix B. The orientation of a 2 cm continuous clay layer indicated deposition from a shoreline to the southwest (strike, N 55° W; dip, 12° NE). Sediments became finer upwards in the exposed section, and also to the north along a 200 m continuous roadcut. Sand and silt beds underlie cross-laminated silts which are topped by dominantly clay beds further north. Sediment was probably derived from the backslope of the head of the Park Rapids outwash plain which is only 300 m southwest of the lake sediments.

Both of the lake basins just described are part of a larger irregular trough, located between the Park Rapids outwash plain and ice stagnation topography deposited by the Wadena Lobe during its retreat to the Itasca Moraine. The trough is 1.5 to 3.0 km wide and may be a large, poorly developed fosse of the type described previously which lies at the western edge of the St. Croix Moraine. This lowland may also have served

Figure 19. Cross-laminated lacustrine sediments, interlobate area (site ISC-5.11, NW¼, s. 26 T 141 N, R 32 W). (knife blade is 7 cm long)

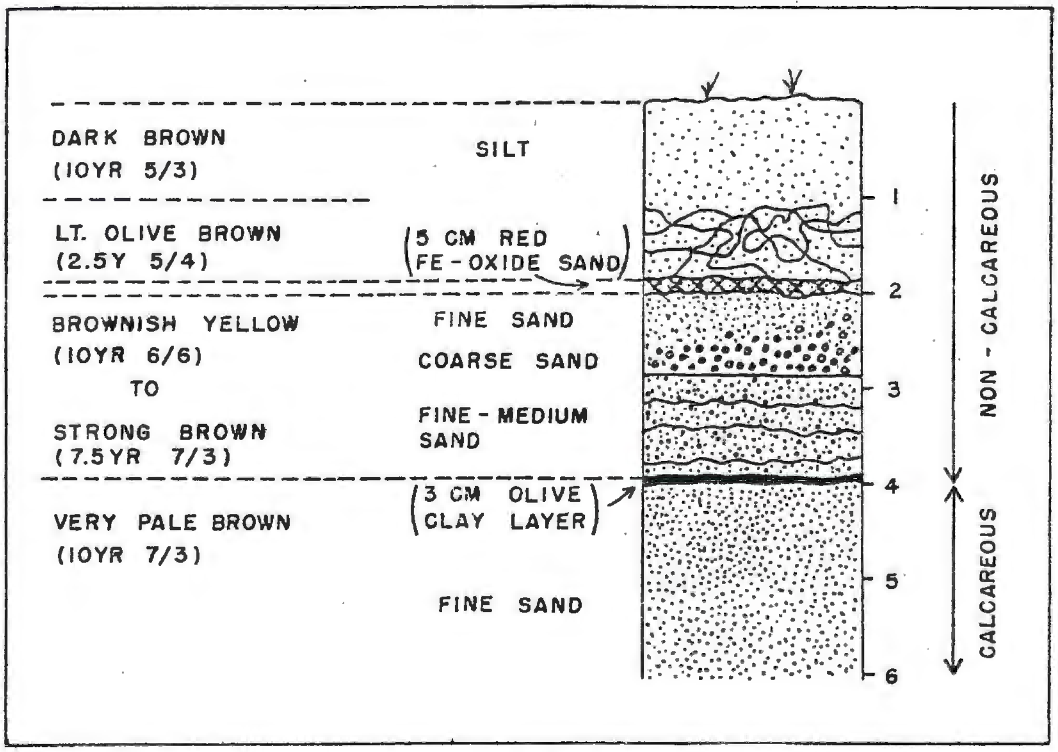


Figure 20. Weathering profile in silty lacustrine sediments, interlobate area (site ISC-18.3, NW¼, S. 11, T 140 N, R 32 W).

to channel meltwater to the head of the late glacial meltwater stream which eroded the large channel into the Park Rapids outwash plain (originating in sections 25 and 26, T 140 N, R 32 W). Owing to lack of surface exposures and topographic expression of the lake sediments, neither lake basin could be completely delineated. The southern basin covered an area of at least 3.7 km^2. The known extents are shown on Plate I.

Average depth of leaching in the Hackensack pitted outwash plain varies from 0.7 to 4.0 m in the areas examined. Shallow leached zones tended to occur in sediments with a high percentage of limestone (see Figure 18).

In the leached zone the sediments are usually yellowish-brown in color (10YR 5/4), but they range from dark brown (10YR 4/3) to brownish-yellow (10YR 6/6). Below the leached zone the sediments are typically salt and pepper colored. Munsell color determinations on silty sediment from this zone ranged from 10YR 7/3 (very pale brown) to 5Y 6/3 (pale olive). On the eastern edge of the interlobate area, calcareous gravels had a more brownish cast, probably the result of a higher percentage of reddish-colored eastern indicator clasts.

Lithologic Composition

Drift lithologies are variable and changes tend to parallel the direction of sediment transport. Carbonate content in the sediments decreases in a very irregular fashion towards the southeast. Carbonate clasts comprise from 22% to 8% of the pebble fraction and average 13% (Table 5). Eastern indicator stones are most common in the southeast part of the outwash plain, where they make up 17% to 30% of the pebble fraction. In the western part of the interlobate area which is underlain by Wadena Lobe drift, eastern indicator stones make up only 4% to

12% of the pebble fraction. Overall average of eastern indicators is 13%, which is intermediate between "typical" Wadena and Rainy lobe sediments. Irregularity of the lithologic makeup of the Hackensack outwash plain is probably due to complex intermingling of Wadena and Rainy Lobe sediments which occurred as these glaciers melted. Sediment was primarily derived from the still active Wadena Lobe, but significant contributions of Rainy Lobe sediments occurred where outwash streams flowed over stagnating Rainy Lobe ice.

Holocene Eolian Sands

Most of the surface sediments in the southwestern part of the study area are composed of moderately sorted fine sand. In many places the sand forms a thin blanket over Wadena drumlins which rise up to 10 m above the surrounding outwash plain. Larger clasts, up to boulders in size, are found scattered throughout the sediment, but they are a very minor component.

Leverett and Sardeson (1932) interpreted this area to have underlain the northern part of a large proglacial lake which they named Glacial Lake Wadena. They postulated a lake outlet south of Long Prairie at an elevation of 1350 feet. In the northern part of the lake basin, in the Itasca-St. Croix moraine study area, they describe an abrupt drop in elevation of 35 feet (11 m) just west of Chamberlain in the outwash plain (section 27, T 140 N, R 32 W) at an altitude of approximately 1450 feet (442 m). The area they described was not found during this study, either in the field or on 1:24,000 scale topographic maps which had not yet been made when Leverett was mapping the area. Nor were any shoreline features found in the study area that might have been formed by a large glacial lake.

Wright (1962) described a medium- to coarse-grained bouldery sand which covers Wadena drumlins in the southern part of the Itasca-St. Croix moraine study area. He interpreted the unstratified bouldery sand and its elevation above the outwash plain as having resulted from the winnowing action of waves and deposition from suspension over the drumlins in Glacial Lake Wadena. Boulders and other large clasts were presumably ice-rafted from the glacier front.

Six samples of this sediment were analyzed for grain size distribution. All but two of the samples (ISC-27.13 and ISC-27.14) were collected from sand covering Wadena drumlins which rise above the surrounding outwash plain. The very high percentage of sand in the matrix (98.5%, Table 7) is similar to that of Park Rapids outwash sands. Mean grain size, however, is much smaller (M_z = 2.33 phi). These sediments are better sorted (σ_1 = .90) and have a nearly symmetrical size distribution (Sk_1 = -.04).

Ahlbrandt (1979), in a major compilation of eolian sand studies, compared mean grain size of 175 inland dune samples to their sorting values (Figure 21). The six samples analyzed here fall within the range of values compiled by Ahlbrandt. They have similar means, but are slightly more poorly sorted and coarsely skewed than most of the dune sands in his study. This is not surprising, given the thinness of the sand blanket, the possibility of contribution from underlying Hewitt Till, and the likelihood of limited distance of transport of the sands. Ahlbrandt (1979, p. 27) states that inland dunes, compared to coastal dunes, "... have variable mean grain size and sorting values, because their source materials are normally from alluvial fan, glaciofluviatile, fluviatile, lacustrine or playa deposits."

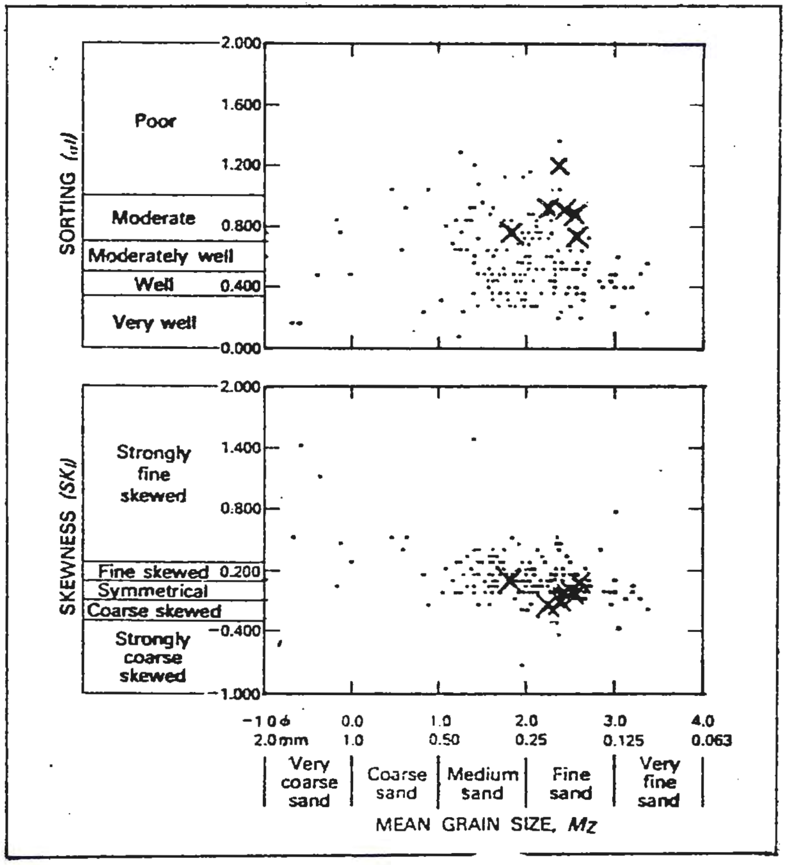


Figure 21. Grain size sorting parameters for eolian sediments (adapted from Ahlbrandt, 1979). (x = Park Rapids/Oshawa outwash plain eolian sediments)

Considerable disagreement exists concerning the ability to distinguish eolian from alluvial and lacustrine sediments on the basis of sorting parameters. Ahlbrandt (1979) concludes that for inland dunes, skewness and kurtosis are highly variable and are not diagnostic. Friedman (1961) found dune sands to be positively (finely) skewed, and better sorted than river sands. Ahlbrandt (1974), however, argues that skewness cannot be used as a distinguishing characteristic because of a dependence of skewness on mean grain size. In general, Ahlbrandt (1979) characterizes inland dune sediments simply as well to moderately sorted fine to medium sand.

Very well rounded and etched sand grains are common in some of the samples studied. This further supports an eolian source for these sediments. In addition, several ventifacts (wind cut boulders) were found at the surface of the buried drumlin in section 34, T 139 N, R 32 W. Origin of the boulders is unknown, but they may be derived from underlying Hewitt Till, or they may have been transported in meltwater streams from the Wadena Lobe during a period of high flow, perhaps frozen in a block of ice. Wright (1962) also mentions the presence of wind polished boulders in the medium- to coarse-grained sand blanket covering drumlins a few kilometers further south.

Irregularly developed dune forms separated by peat bogs are present near the eolian sands sampled in this study (Figure 22). They have a northwest-southeast aspect. A few of the landforms resemble barchan dunes, with a steepened slipface facing southeast. The dune forms cover an area of 40 km^2 in the lower half of T 139 N, R 32 W and the upper part of T 138 N, R 32 W.

Post-glacial sand dunes have been described at other localities in Minnesota. Cooper (1935) described the large dune field in the Anoka sand plain in east-central Minnesota. Olson et al. (1979) mention sand dunes formed in southwestern St. Louis County, east of this study area. Closer to the Park Rapids outwash plain, a post-glacial dune field located on the southeast shore of Lake Winnibigoshish was studied by Grigal et al. (1976). They examined and dated a sequence of five buried soils weakly developed between layers of dune sand. Dune forms visible on aerial photographs in that area are also indicative of prevailing northwesterly wind direction. The Lake Winnibigoshish dunes are less than 70 km northeast of the sands that cover the Wadena drumlins in the Park Rapids outwash plain.

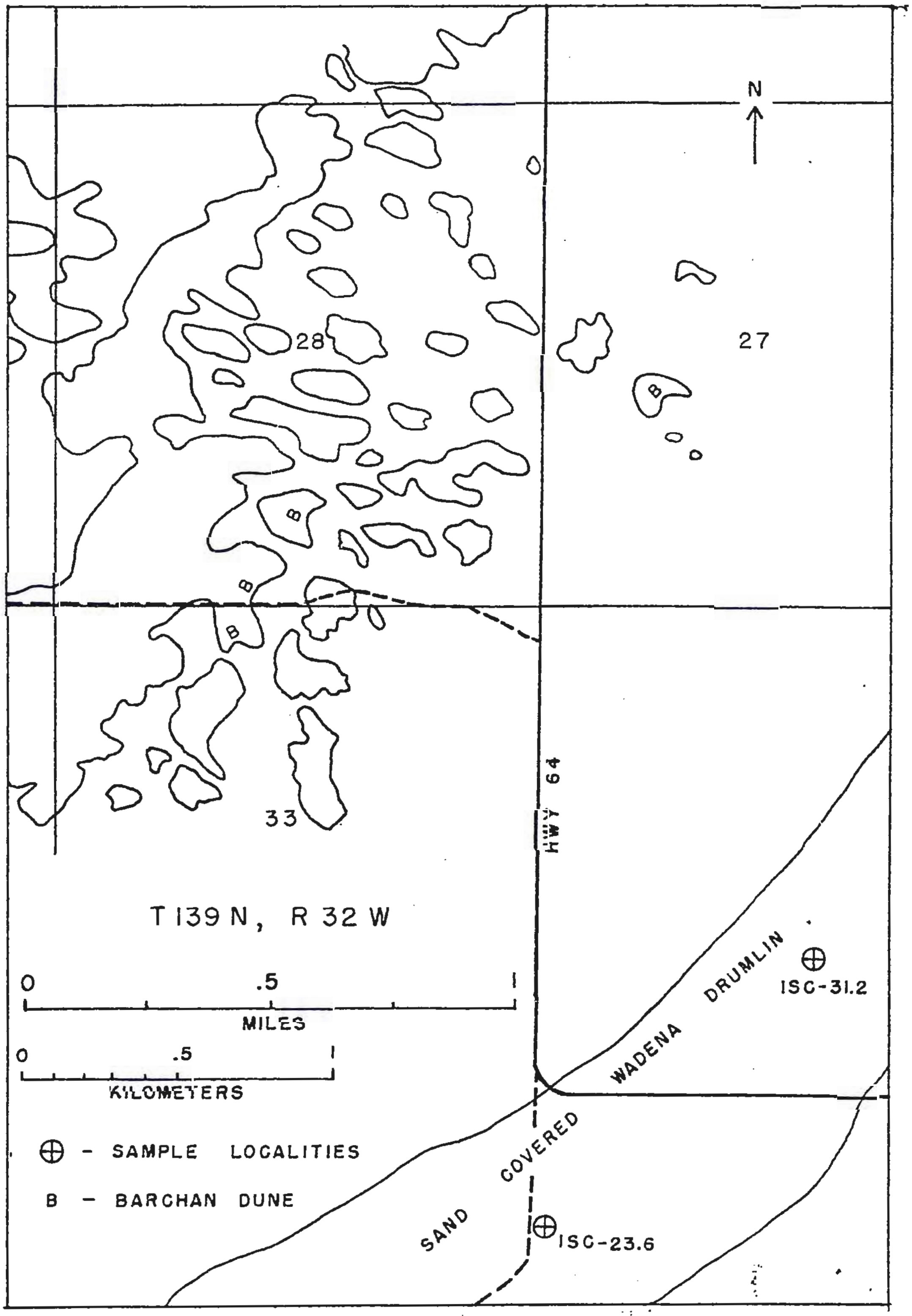


Figure 22. Outline of dune topography developed on Park Rapids outwash plain. Traced from ASCS aerial photographs BXU-2-115,116 and 117 (1939).

Age of Eolian Sands

Cooper (1935) stated that the Anoka Sand Plain dunes developed during the Late Pleistocene, very soon after glaciers receded from the area. Dunes in other areas may have formed more recently, probably during the Hypsithermal Interval during Middle Holocene time. Analysis of pollen from cores taken in lake sediments in northern Minnesota indicate a period of warming which followed the final melting of glaciers (Wright and Watts, 1969; Florin and Wright, 1969). At Portage Lake, near the northeast corner of the study area (section 32, T 142 N, R 27 W), J. H. McAndrews (1974, personal communication, in Grigal et al., 1976) dated this warming trend. An increase in *Quercus* (oak) began at 7,320 years B. P., followed by prairie vegetation typified by *Ambrosia* (ragweed), at about 7,000 B. P. A gradual return to cooler, moister climate resulted in a decrease in *Quercus* and the introduction of *Pinus* (pine) by 3,685 B. P. at Portage Lake.

Grigal et al. (1976) dated charcoal from the lowest of five soil horizons in the Lake Winnibigoshish dune field at 7,910 ± 155 B. P. An age of 5,040 ± 105 B. P. was obtained from organic matter from the middle soil. They concluded that sand dunes were active during the warm Hypsithermal interval from 8,000 to at least 5,000 years ago. Olson et al. (1979) concur with those dates for the formation of sand dunes in the northwest part of Glacial Lake Upham in St. Louis County.

In conclusion, considerable post-depositional movement of outwash sediment by wind seems very likely in the study area. Given the evidence of the nearby Lake Winnibogoshish site, it appears that a thin sand sheet developed during the Hypsithermal Interval between about 8,000 and 5,000 years ago. However, if the proper conditions existed (i.e. sparse vegetation, unfrozen, dry sediment and strong winds), there may also have been some eolian activity immediately following deglaciation.

DISCUSSION OF INTERLOBATE RELATIONSHIPS

Considerable debate has been generated concerning the paths of the glaciers which deposited the Itasca and St. Croix moraines. Determination of the direction of ice movement is important to interpretation of the St. Croix Phase glacial history in northern Minnesota, and it also may have implications for the origin of the underlying Hewitt Till. Greatly simplified, the two major hypotheses currently espoused are: 1) Both moraines were deposited by a single southwesterly advancing glacier over a non-uniform glacial till substrate (Sackreiter, 1975); and 2) The moraines were deposited by two distinct glaciers, one advancing from the northeast and the other from the northwest, which formed an interlobate junction (Wright, 1972). Chapter II of this report contains a more complete explanation of these theories. The following discussion will review differences and similarities between the two moraines and offer possible explanations for their formation.

Geomorphology

The Itasca and St. Croix moraines are distinctly different in form in several ways. The St. Croix Moraine is considerably smaller than the Itasca Moraine. It is narrower (5-7 km wide), lower in elevation (490 m maximum), and probably contains a lesser thickness of supraglacial sediments (24-43 m). This is in contrast to the more extensive Itasca Moraine, which is about 11 km wide, reaches elevations of over 550 m, and contains an estimated 27-70 m of supraglacial sediments.

The orientations of the moraines are also different. The St. Croix Moraine has a clear north-south trend, which varies slightly from N 0° E to N 10° E in the study area. The orientation of the Itasca Moraine is more difficult to determine just from its outline, because the glacier that deposited it apparently had a complex pattern of advances and retreats in the terminus region before stabilizing. Although the Itasca Moraine has a very irregular front, the overall trend is slightly south of east (N 83° W). The northern margin of the moraine is buried by more recent glacial sediments and is thus undefinable.

Long linear ridges are uncommon in the St. Croix Moraine and are randomly oriented. In the Itasca Moraine, however, numerous sets of linear ridges are present (see Figure 12). They appear to be transverse compressional ridges, which are thought to be oriented at right angles to the direction of ice movement (Sackreiter, 1975; Clayton et al., 1981). The largest and best developed of these ridges are broadly concave to the northeast and have an average strike of N 65° W. This would indicate that the major direction of ice movement during deposition of the Itasca Moraine was approximately S 25° W.

Smaller sets of linear ridges are developed elsewhere in the Itasca Moraine. These ridges have markedly different orientations from those described above. This suggests a glacier front whose normal flow path was disrupted, perhaps due to lateral stresses caused by interaction with the Rainy Lobe. In the interlobate area, some of these morainic deposits are separated from the major part of the Itasca Moraine by outwash sediments. There, most ridges are oriented further to the southeast; some are oriented north-south (Figure 13). These isolated areas suggest a major disruption of the glacier's southward movement in the area adjacent to the St. Croix Moraine.

The Itasca and St. Croix moraines do not meet at the surface anywhere in the study area. They are separated by glaciofluvial sediments which dominate the interlobate area. This dominance may be characteristic of interlobate areas, because of thickening of ice and concentration of meltwater which occur at the junction between two ice lobes. Black (1970) described a similar landscape in the Northern Kettle Interlobate Moraine area in Wisconsin. There, kames and other glaciofluvial features are concentrated in the interlobate area, and the hummocky stagnation moraines of the Green Bay and Lake Michigan ice lobes are located some distance back from the interlobate junction (Figure 23). Black explains this relationship as the result of stagnant, relatively clean ice in the interlobate area. Actively advancing ice, containing considerable amounts of sediment, gradually built up end moraines on either side of the stagnant ice mass in the interlobate area. Concentration of meltwater between the two ice lobes contributed to the impressive development of moulin kames there.

Outwash Plains

The volume of outwash sediments deposited in front of the Itasca and St. Croix moraines is roughly proportional to the different sizes of the two moraines. The Oshawa outwash plain, deposited in front of the smaller St. Croix Moraine, is thin and narrow compared to the Park Rapids outwash plain, deposited in front of the larger Itasca Moraine. The Park Rapids Plain can be traced for 40 km southward, and contains up to 45 m of outwash sediments. It buries the Oshawa outwash plain where they merge in the interlobate area.

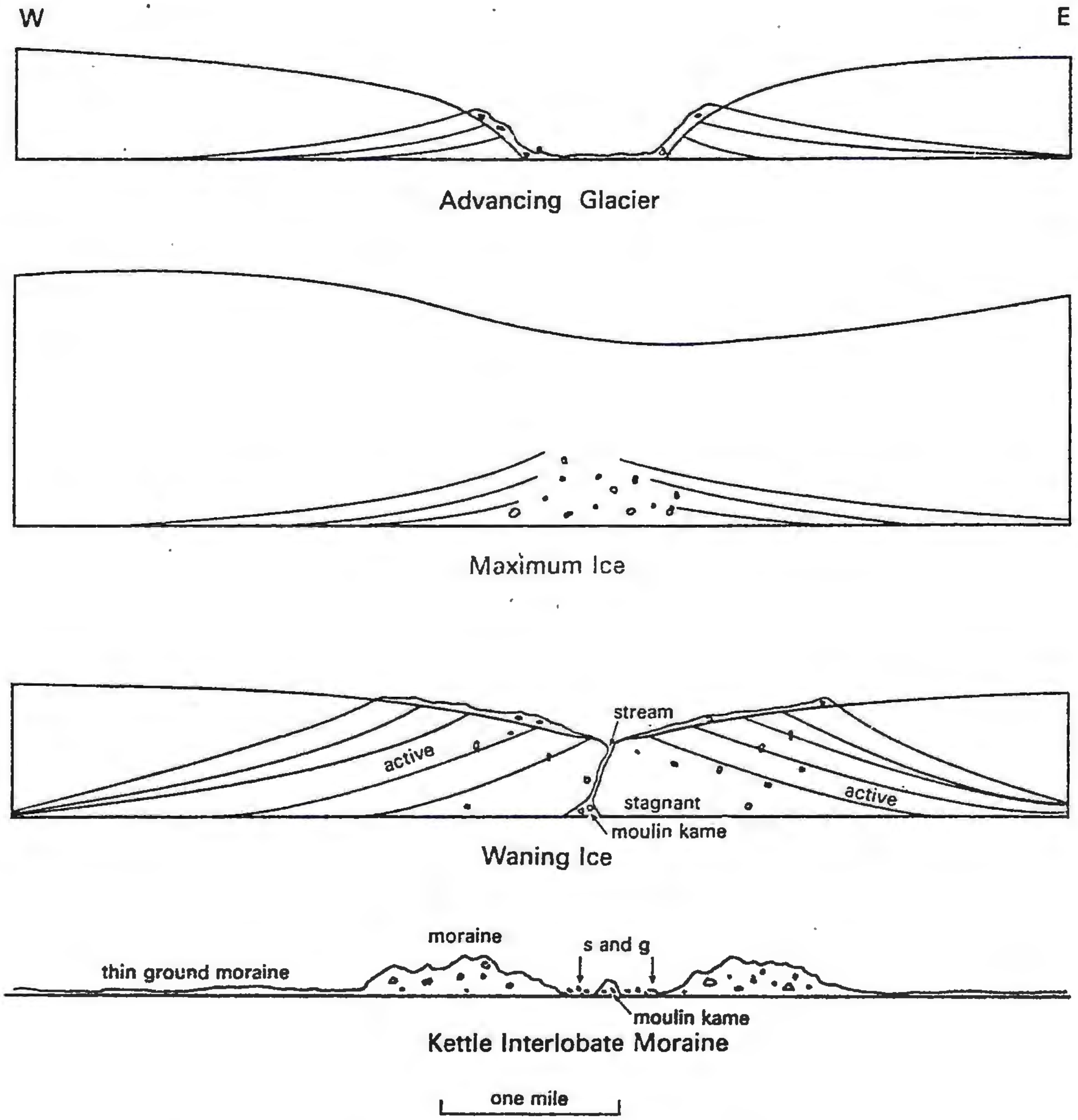


Figure 23. Hypothetical sequence of events postulated to explain the origin of some glacial features of the Northern Kettle Interlobate Moraine (from, Black, 1970). s = sand, g = gravel.

The Pine River outwash plain is located behind the St. Croix Moraine in the southern part of the study area. It was deposited by the Rainy Lobe during a standstill of the ice margin as it receded from its terminus at the St. Croix Moraine. Complete retreat of the Rainy Lobe from the interlobate area allowed deposition of the Hackensack pitted outwash plain by the still active Wadena Lobe. It originates from the Itasca Moraine and grades southeastward. Hackensack outwash sediments bury the northern part of the St. Croix Moraine and can be traced to the southeast where they partially fill a low area behind the St. Croix Moraine.

Texture

In the study area, the matrix of flowtill sediments in the St. Croix Moraine becomes finer-grained to the north (see Figure 12). Sackreiter (1975) found a continuation of this trend northwest of the interlobate area in the sediments of the Lower Red Lake Falls Fm. (see Figure 14). Within the interlobate area, however, there was no apparent trend in flowtill texture. There, texture varied widely, probably because of the increased role of fluvial activity in that area which resulted in a greater variety of sediment types. This could have obscured any regional textural trends that otherwise may have been present.

Coarsening of sediment from northwest to southeast across the region in the sediments of the Lower Red Lake Falls Formation and Brainerd Till does not appear to be related to the paths of the glaciers that deposited them. In general, till tends to become finer-grained with increased distance of transport (Dreimanis and Vagners, 1971). This would imply a southeast to northwest ice advance across the study area. Such an advance is clearly not supported by the orientations of the St. Croix and Itasca moraines. It seems more likely that the observed decrease in grain size is the result of incorporation of sediments from underlying till. This underlying till would have been deposited by a northwesterly moving ice advance, possibly of the Superior Lobe. The glaciation would most likely have occurred prior to the Hewitt Phase, because of the close similarities in lithology between the Hewitt Till and the overlying Brainerd and Lower Red Lake Falls tills. Matsch (1972) ascribed the Hawk Creek Till in southwestern Minnesota to an Early or pre-Wisconsinan advance of the Superior Lobe out of the Lake Superior Basin. If that ice sheet also covered western Minnesota, it may have moved in a northwesterly direction through the study area and deposited the Unit 2 (Sackreiter, 1975) and Unit A (Perkins, 1977) tills (see Table 2). Further support for such an advance comes from Leverett and Sardeson (1932, p. 41), who described an exposure of "red drift of the Patrician type" (i.e., Superior Lobe drift) underlying northwest source "Keewatin drift" on the south shore of Lower Red Lake, about 80 km northwest of the study area. This further supports the idea of a major Early or pre-Wisconsinan advance of the Superior Lobe across the study area.

Lithologic Composition

Lithology of glacial sediments, as measured by pebble and sand grain counts, varies across the study area. Within each of the two moraines, however, representation of different rock types remains fairly constant and a distinctive assemblage can be identified. Brainerd Till in the interior of the St. Croix Moraine contains an average of 29% of pebbles derived from a northeastern source area. It also contains a uniformly low amount of buff chert, and in a few localities a small amount of carbonate clasts. Chert and carbonates are indicative of a northwestern source area; in the Brainerd Till they were probably derived from previously deposited glacial sediment. The Lower Red Lake Falls Till in the Itasca Moraine is distinguished from the Brainerd Till by a low percentage of eastern indicator rocks ($\bar{x}$ = 10%, pebble fraction) and a higher carbonate content ($\bar{x}$ = 22%, pebble fraction).

In the interlobate area, sediment lithologies are intermediate between the two moraine "end-member" types. A gradual shift can be seen from the carbonate-dominated sediment of the Itasca Moraine to sediment dominated by eastern indicators in the St. Croix Moraine. Unfortunately, occurrences of flowtills, which would have undergone the least amount of transport after active ice movement ceased, are relatively uncommon in the interlobate area, which is dominated by outwash and other glaciofluvial sediments. Fluvial sediment transport was primarily to the south and southeast in the interlobate area, which may have caused the observed displacement of high carbonate content in that direction (see Figure 25).

Variations in the percentage of eastern indicator pebbles are shown in Figure 24. There is an abrupt decrease at the northern end of the St. Croix Moraine, reflecting the shift from eastern source till to outwash sediments derived mostly from the Wadena Lobe. In the interlobate area, eastern indicators range from 7% to 19% of the pebble fraction.

Carbonate content decreases to the southeast across the study area (Figure 25). Carbonate pebbles range from greater than 20% of the sediment in the Itasca Moraine to less than 5% in the St. Croix Moraine. The measured variations in carbonate content are more erratic than variations in eastern indicators, possibly due to postglacial dissolution of carbonate. Absence of carbonate in the St. Croix Moraine at all but one sample locality is probably the result of a very deep leached zone,

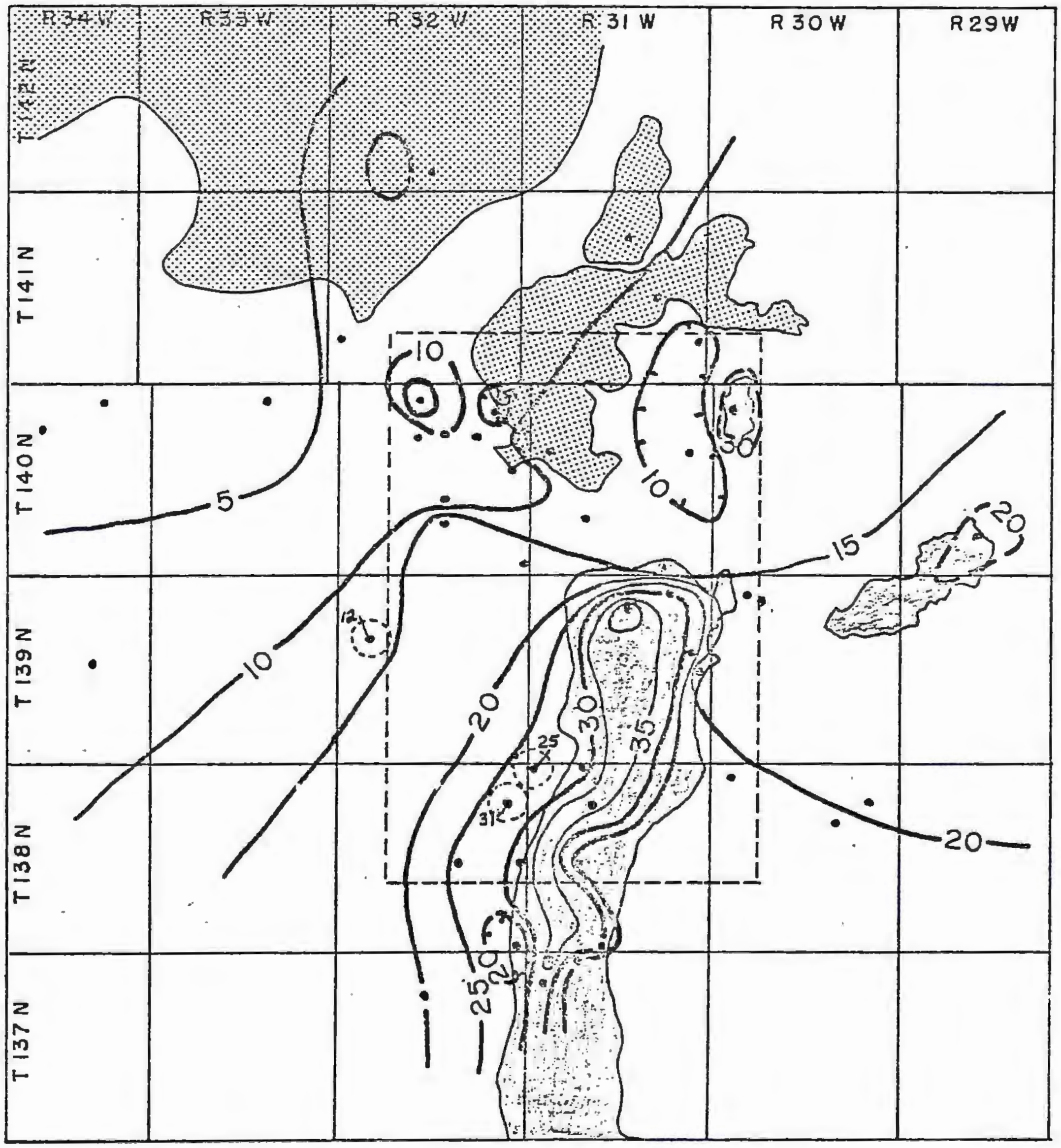


Figure 24. Variation of eastern indicator content in the pebble fraction (6-64mm) in the study area. Samples taken from the underlying Hewitt Till are enclosed by a dashed circle and were not used in contouring the data. They are included for comparison purposes only. Contours are in percent. The Itasca Moraine is stippled; the St. Croix Moraine is shaded.

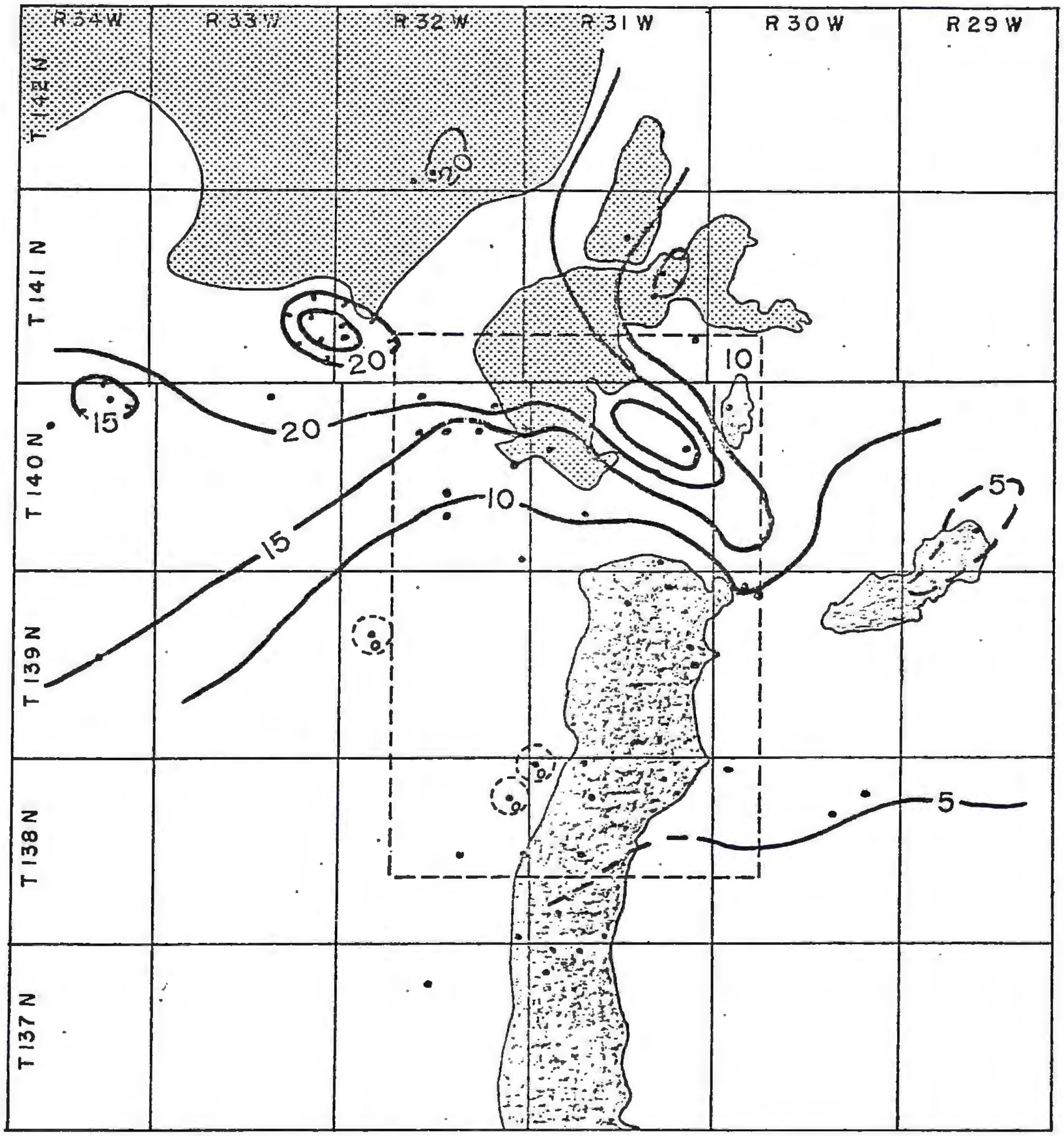


Figure 25. Variation of carbonate content in the pebble fraction (6-64 mm) in the study area. Samples taken from the underlying Hewitt Till are enclosed by a dashed circle and were not used in contouring the data. They are included for comparison purposes only. Contours are in percent. The Itasca Moraine is stippled; the St. Croix Moraine is shaded.

reaching below normal sampling depths.

A high carbonate tongue extends southeastward from the east end of the Itasca Moraine. This reflects the carbonate content of outwash sediments deposited in the Hackensack outwash plain. Near the head of the outwash plain at the Itasca Moraine, sediments have a relatively high carbonate (and low eastern indicator) content. Further downslope, however, outwash streams likely crossed stagnant ice and sediments of the Rainy Lobe. Incorporation of these sediments resulted in a progressive dilution of carbonates and enrichment of eastern indicators in a southeasterly direction across the outwash plain.

Sackreiter (1975) found a gradual decrease in carbonate in the Lower Red Lake Falls Till from northwest to southeast (see Figure 14). Carbonate content, both in the sand and pebble fractions, continues to decrease through the Itasca-St. Croix moraine interlobate area, as shown in Figure 25. This trend is suggestive of glacial flow towards the southeast, due to comminution and dilution of the glacial sediment (Dreimanis and Vagners, 1971). However, Sackreiter states that the glacier that deposited the Lower Red Lake Falls Till advanced from the northeast, not the northwest. He bases his argument on the very high content of crystalline rocks in the Lower Red Lake Falls Till and the orientation of linear ridges in the Itasca Moraine. If his conclusion of a northeast to southwest glaciation is correct, then the observed gradual change in carbonate content must be the result of contamination by an underlying till, deposited by a southeastward moving glacier. Such an advance apparently did occur during Early or pre-Wisconsinan time, depositing a shale-free calcareous till which underlies the Hawk Creek Till in southwestern Minnesota (Matsch, 1972), and the Unit 1 calcareous-rich till described by Sackreiter.

Changes similar to those described above for the pebble fraction also occur in the lithologic composition of the very coarse sand fraction. Because the sand fraction contains a lower amount of eastern indicators and carbonate than the pebble fraction at any one location (see Figure 3), variations are less pronounced. Contoured data for the 1-2 mm sand fraction are therefore not included in this report, but they do follow essentially the same patterns of change in eastern indicator and carbonate content found in the pebble fractions.

Conclusions

In summary, the form and orientation of the Itasca and St. Croix moraines and their distinct lithologic characteristics strongly suggest that they were deposited by two different glaciers. Locations of the several outwash plains in the study area provide a record of some of their different positions. Spatial relationships between outwash plains and moraines in the study area further support the idea that there were significant differences in activity between the northern and eastern ice masses.

The St. Croix Moraine was probably deposited by a southwestward advance of the Brainerd Sublobe of the Rainy Lobe, described by Wright (1972). It passed over Precambrian terrain of extreme northeastern Minnesota, where it picked up significant amounts of basalt, felsite, gabbro and iron formation. The Brainerd Sublobe apparently did not advance through the southern part of the Lake Superior Basin, since sandstones and siltstones from that region are uncommon components of the till. Close to the study area, the glacier incorporated small amounts of northwestern source material (e.g., carbonate) from the underlying till surface.

Whether or not the northern glacier was ultimately from the northwest as proposed by Wright (1962) is more difficult to ascertain. The Itasca Moraine does contain carbonate, presumably derived from a northwesterly bedrock source. However, the carbonate could also have been incorporated from an underlying till. Most transverse compressional ridges in the Itasca Moraine are concave to the northeast, indicating an advance from that direction. Ridges in the interlobate area, however, have markedly different orientations which may be the result of lateral compressional forces generated when the two glaciers merged in the interlobate area. This evidence that the Rainy Lobe did cause some diversion of the path of the Wadena Lobe during the St. Croix Phase supports Wright's (1962) theory of the same occurrence during the earlier, more extensive Hewitt Phase advance of the Wadena Lobe. In the terminus area of the Wadena Lobe in southwestern Minnesota, the Hewitt Till and its extramorainic equivalent, the Granite Falls Till, contain significantly more carbonate and fewer Lake Superior Basin rock types than the underlying Hawk Creek Till. This fact is also indicative of a northern, if not northwestern, provenance of the Wadena Lobe.

Unfortunately, sediments to the north and northeast related to the St. Croix and Itasca moraines have been buried by a later advance of the St. Louis Sublobe during the Alborn Phase, making it difficult to trace the path of the glaciers further up-ice.

LATE QUATERNARY HISTORY

Pre-Hewitt Phase Glaciations

North-central Minnesota was probably glaciated several times during the course of the Quaternary Period, but only the most recent episode of glaciation, the Wisconsinan Stage, is well recorded. Glacial sediments and landforms from earlier stages of glaciation were either eroded or deeply buried prior to or during the Wisconsinan Glaciation. Near the study area in north-central Minnesota, the oldest glacial sediments are Early to possibly pre-Wisconsinan in age and are found only by drilling.

Two distinct till units were intersected in drill holes north of the study area (Sackreiter, 1975). They occur beneath glacial sediments which are correlative with the Hewitt Till, and are considered to be Early or pre-Wisconsinan in age (Sackreiter, 1975; Clayton and Moran, 1981). The lower of these two tills is a gray, silty, shale-free calcareous till and was referred to by Sackreiter as "unnamed Unit 1." It may correlate with the slightly calcareous basal till in northeastern Minnesota (Winter, 1971), and the gray, shale-free calcareous clay loam till described by Matsch (1972) which lies beneath the Hawk Creek Till in southwestern Minnesota (see Table 2). The path of the glacier that deposited Unit 1 is unknown; there are no surface features to mark its path and its subsurface extent is very speculative. The abundance of carbonate and absence of shale fragments in the till suggest a southeastward moving glacier, which crossed the carbonate bedrock of southern

Manitoba, and passed north of the Cretaceous shales of North Dakota.

The upper of the two pre-Hewitt Phase tills may have been deposited by a southeastward ice advance from the Lake Superior region. This till ("unnamed Unit 2" of Sackreiter, 1975) was also encountered in drill holes north of the study area. It is sandier and contains a larger proportion of crystalline rock types than Unit 1. Perkins (1975) encountered a similar till west of the study area, which he referred to as "unit A."

The glacier that deposited Unit 2 may have covered all of Minnesota at its maximum extent. The Hawk Creek Till in southwestern Minnesota may be correlative with Unit 2. It is a reddish-brown to pink, slightly calcareous, sandy till, containing many rock types characteristic of the Lake Superior region. The same glacial advance may also have deposited the Hampton drift in southeastern Minnesota (Savina et al., 1979). The age of Unit 2 is not known for certain, but Clayton and Moran (1981) consider it to be part of ice advances during "Phase B" glaciation and assign it to the Early Wisconsinan Stage.

Hewitt Phase

The oldest glacial sediment exposed at the surface in the study area is the Hewitt Till (Wright, 1962). It may have been deposited during the Early Wisconsinan or possibly during the beginning of the Late Wisconsinan Substage. The older age is postulated by Wright (1972), who considers the Hewitt Till to be between 30,000 and 60,000 years old. This is based on a ^{14}C date of greater than 40,000 B. P. from organic silts which cover the Hewitt Till south of the study area (Wright, 1972). Matsch and Schneider (in preparation) state that the till may be younger, based on weathering characteristics. Clayton and Moran (1981) reject the ^{14}C

date of greater than 40,000 B. P. because of the possibility of contamination by lignite. They assign the Hewitt Till to "Phase D" glaciation which they consider to have reached its maximum about 20,000 B. P. With the absence of firm radiocarbon dates, the age of the Hewitt Till remains uncertain.

The Hewitt Till was deposited by a glacier which advanced in a southwesterly direction across the study area. The till surface was drumlinized in the study area. As the glacier advanced, it also spread laterally. This is recorded in the fanning of the Wadena Drumlin field and also the arcuate form of the Alexandria Moraine, which marks a major standstill of the glacier.

The provenance of the ice sheet north of the study area is unclear. Burial and/or erosion of the Hewitt Till by more recent glaciations has made it difficult to trace the glacier's path. Wright (1962) postulated that the Hewitt Till was deposited by a glacier advancing from the northwest (the Wadena Lobe), which encountered an ice advance from the east (the Brainerd Sublobe of the Rainy Lobe). The Wadena Lobe was diverted to the southwest and "contaminated" by rocks from northeastern Minnesota which were being transported by the Brainerd Sublobe.

The Wadena Drumlins are not covered by a thick layer of englacial or supraglacial sediment (Figure 26). This suggests that retreat of the glacier at the end of the Hewitt Phase was rapid, perhaps even occurring as a widespread stagnation of the glacier (Clayton and Moran, 1974). The final recessional position of the Wadena Lobe prior to the onset of the next phase of glaciation is not known, but it must have been north of the study area. The next glaciation is clearly marked by a realignment of ice margins.

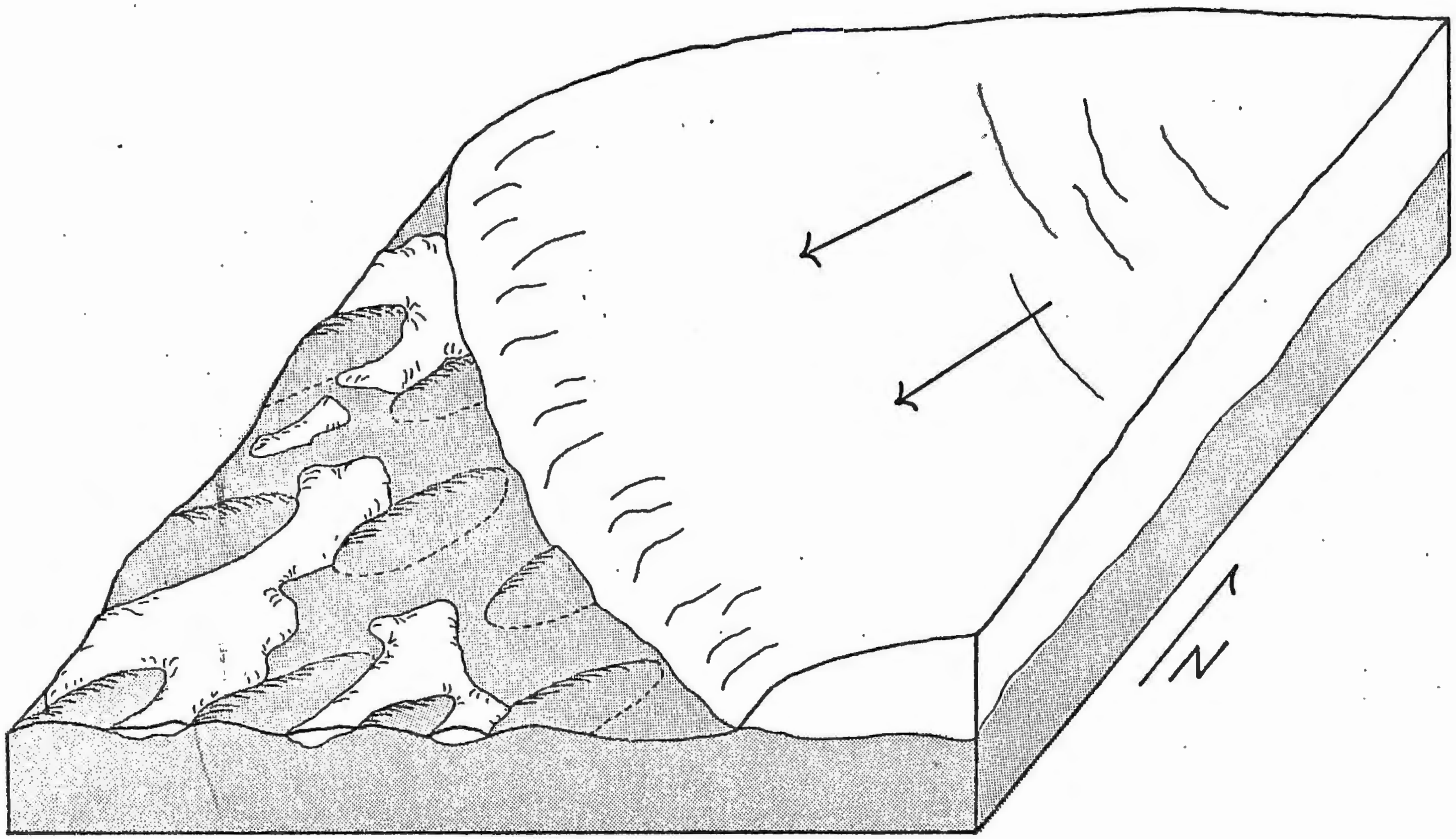


Figure 26. Hewitt Phase-retreat of the Wadena Lobe

St. Croix Phase

During the next period of glaciation (the St. Croix Phase), the Brainerd Sublobe of the Rainy Lobe advanced from the northeast, stalled, and built the St. Croix Moraine and Oshawa outwash plain at its terminus in the study area. Its northern edge merged with the eastern margin of the Wadena Lobe which concurrently advanced from the north. Unlike the Brainerd Sublobe, the Wadena Lobe retreated several kilometers from its terminal position before stabilizing and building the Itasca Moraine (Figure 27).

Meltwater streams flowing from the Wadena Lobe deposited large coalescing outwash fans which buried the drumlinized Hewitt Till for several kilometers. Blocks of ice, localized in the low areas between drumlins, were also buried by outwash sediments. The ice blocks probably remained from the brief advance of the Wadena Lobe south of the Itasca Moraine. The Brainerd Sublobe deposited a smaller outwash plain in front of its terminus than did the Wadena Lobe. In many places, Hewitt Phase drumlins only 1-2 km from the ice front were not completely buried by outwash sediments. At the interlobate junction, large volumes of meltwater were concentrated, resulting in the formation of a single large outwash fan which radiates southwestward from the junction.

The first glacier to recede from the terminus region was the Brainerd Sublobe. It retreated eastward, leaving an ice-cored end moraine and a low area behind the moraine, which was the result of quarrying at the base of the glacier as it built the St. Croix Moraine. Along the common border between the Brainerd and Wadena lobes, only scattered areas of morainic terrain were developed.

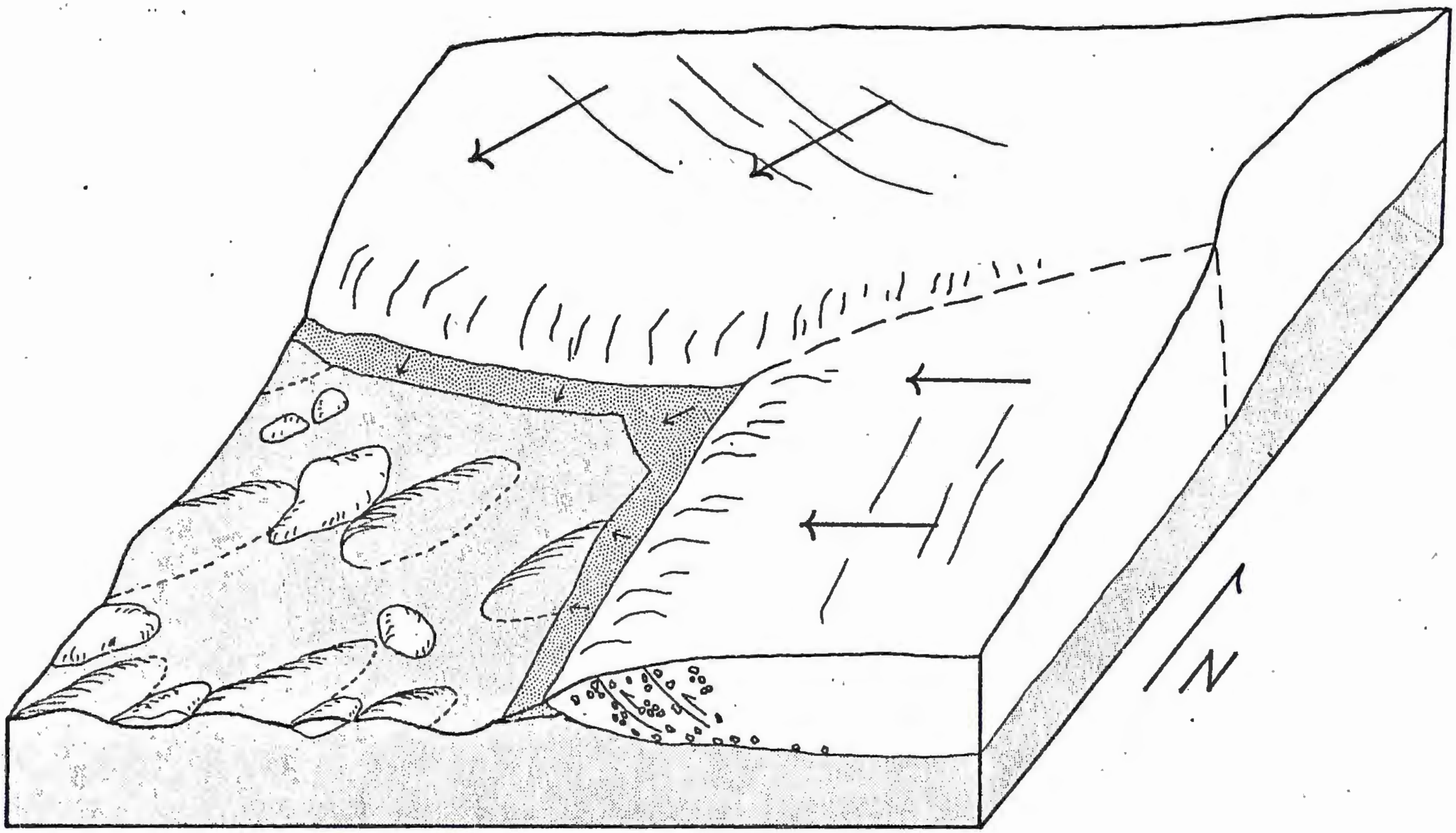


Figure 27. St. Croix Phase - maximum advance of Wadena and Rainy ice lobes.

A pause in the retreat of the Brainerd Sublobe was recorded by deposition of the Pine River outwash plain behind the St. Croix Moraine. Outwash sediments from the Wadena Lobe were deposited across the interlobate area and southeastward behind the St. Croix Moraine following complete removal of the Brainerd Sublobe from the interlobate area.

At the end of the St. Croix Phase, the Wadena and Rainy lobes retreated from the area. Downwastage of the ice-cored St. Croix and Itasca moraines continued, with frequent topographic reversals, sediment flows and fluvial activity (Figure 28). Outwash plain surfaces became pitted as underlying ice melted. The large outwash fan in front of the interlobate junction was left headless as the relatively clean ice at the margins of the glaciers melted. In the interlobate area, isolated segments of morainic topography emerged, surrounded by a complexly pitted outwash plain surface.

Late in the meltout stage, a large meltwater stream formed a channel in the pro-glacial outwash fan in front of the interlobate junction. Concurrent melting of inter-drumlin buried ice blocks probably created low areas which affected the course of this southwesterly flowing stream. Much of the water for this stream was probably derived from melting of relatively clean buried ice in the interlobate area, particularly the huge block of ice that created the Ten Mile Lake Basin.

St. Croix Phase glacial activity in the study area probably occurred during the middle of the Late Wisconsinan Stage. The age of the onset of glaciation is not precisely known, but Clayton and Moran (1981) report several ^{14}C dates from wood in glacial tills related to this advance. Most of the dates are from north and west of the study area and range from 24,490 ± 200 B. P. (GSC-205) from southeast Alberta, to 28,000 ± 1000 B. P. (W-2450) from north-central North Dakota. The maximum extent

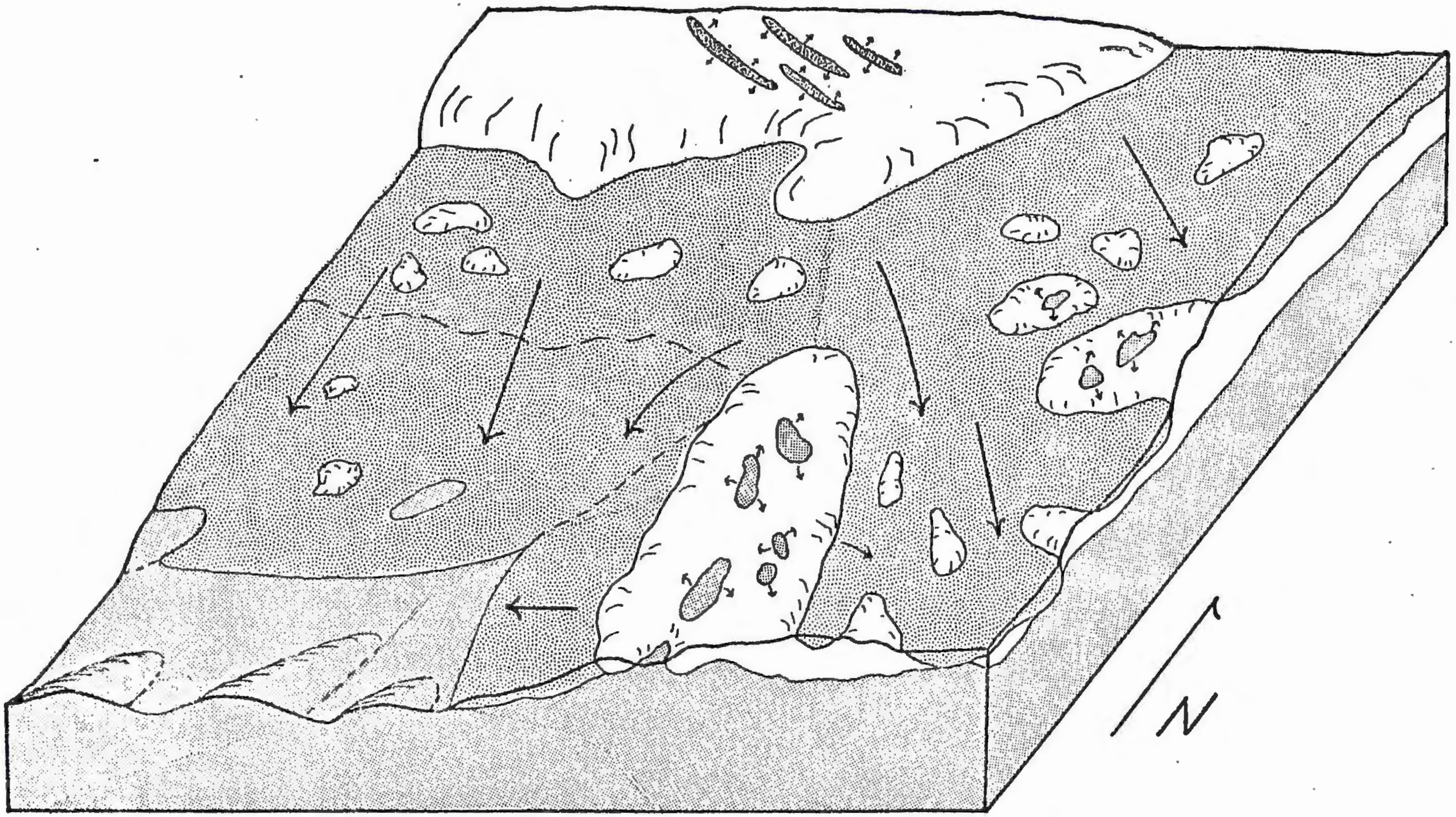


Figure 28. St. Croix Phase - formation of outwash plains

of glaciation is thought to have occurred several thousand years later in northwestern Iowa, based on a date from wood in till of 20,000 ± 800 B. P. (O-1325; Ruhe, 1969).

The age of the cessation of glacial activity at the end of the St. Croix Phase is also poorly defined. It is based primarily on age dates from organic-rich basal lake sediments. Birks (1976) reported an age of 20,500 ± 400 B. P. from basal lake sediments at the Wolf Creek site in the Pierz Drumlin Field. The Pierz drumlins were also formed during the St. Croix Phase, and are closely correlative with the formation of the St. Croix Moraine. Birks acknowledges the possibility of contamination by ^{14}C-deficient material (such as lignite), which may have caused an increase in the apparent age of the basal sediments, but he considers the error not large enough to reject the date entirely. Thus the age of 20,500 B. P. should be considered a maximum age for the end of St. Croix phase activity of the Brainerd Sublobe in the study area. Basal lake sediment dates from other areas in northeastern Minnesota cluster around 15,000 to 16,000 B. P. (Wright and Watts, 1969). These dates are from lakes developed on tills that are younger than the St. Croix Phase, and therefore support an end of the St. Croix Phase sometime prior to 16,000 B. P.

Alborn Phase

During the Late Wisconsinan Alborn Phase, the St. Louis Sublobe of the Des Moines Lobe advanced from the west, depositing a clayey, calcareous- and shale-bearing till across most of northern Minnesota. The Wadena and Rainy lobes must have retreated completely from northern Minnesota to allow the eastward advance of the St. Louis Sublobe. The Des Moines

Lobe eventually covered all of western Minnesota except for the Itasca Moraine and an area south of it which includes the study area. The Itasca Moraine may have been high enough to create a barrier to ice flow, causing the St. Louis Sublobe to separate from the main part of the ice sheet. As it advanced eastward beyond the Itasca Moraine, the St. Louis Sublobe spread laterally southward. It terminated in northeastern Minnesota about 12,000 B. P. and deposited the Alborn and Culver moraines (Wright, 1972).

Post-glacial Landform Development

Tundra-like vegetation, consisting largely of herbaceous plants, shrubs and small trees, probably dominated the post-glacial landscape in northern Minnesota for many thousands of years. At the Wolf Creek site, this type of vegetation dominated until about 13,600 B. P. (Birks, 1976), when Picea (spruce)-dominated forests became established. At Weber Lake, about 100 km northeast of Duluth, tundra vegetation persisted longer - until 10,000 B. P. (Wright and Watts, 1969).

Continued warming and migration of plant species through late Wisconsinan and early Holocene time occurred throughout north-central Minnesota. This resulted in a gradual change in the dominant forest types. At Bog D in the Itasca Moraine (section 25, T 143 N, R 34 W), a change to oak savannah was marked by a sharp increase in Quercus (oak) pollen about 8,400 B. P. (McAndrews, 1966). This was followed by an increase in prairie vegetation, marked by Ambrosia (ragweed) at about 7,000 B. P. At Portage Lake, east of Leech Lake (section 32, T 142 N, R 27 W), the Quercus rise occurred at 7,320 B. P., followed by the Ambrosia increase at 7,000 B. P.

During mid-Holocene time, lake levels dropped in the study area (Almendinger, personal communication) and elsewhere in Minnesota (Wright and Watts, 1969). Many lakes probably dried up completely. Wind-blown sand formed dunes in the southern part of the outwash plains in the study area, and Wadena drumlins which rose above the outwash plain surface were covered with a thin sheet of eolian sands. The southern part of the Park Rapids outwash plain was amenable to eolian activity because of the abundance of easily transported fine-grained sand, and a long fetch for northwesterly winds.

Gradual return to a cooler and moister climate is recorded by the re-establishment of Picea and introduction of Pinus (pine) migrating into the area from the east. Peat began to accumulate in poorly drained areas about 4,000 years ago. Large peat bogs developed on the flat, fine-grained sandy outwash sediments in the southern part of the study area. Small isolated bogs also formed in the many ice-block lakes in the pitted outwash plains and in depressions in the moraines. Many of these lakes are completely filled in with peat today.

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APPENDIX A

A Characterization of Soils on Three Glacial Tills of the Itasca-St. Croix Moraine Complex [1]

Introduction

This study was designed to provide descriptions of the soils developed on the Hewitt, Brainerd and Lower Red Lake Falls tills. These descriptions might be useful in sorting out the spatial relationships of the tills and in recognizing areas where mixing of the tills may have occurred.

Methods

Profiles from excavated soil sections were sampled and described, one on each of the three tills. By choosing sites of similar topography and vegetation, an attempt was made to isolate parent material as the principal factor responsible for soil differences. Each soil was sampled at a well-drained site on the top of a gentle hill. The Lower Red Lake Falls and Brainerd soils were sampled at sites included within the same "soil landscape unit," as mapped by the Minnesota Soil Atlas Project (University of Minnesota, 1968). This unit, the XLWL unit, represents "loamy over mixed sandy and loamy, well-drained light-colored soil." The Hewitt soil was sampled from within a similar soil landscape unit, the SSWL unit, which represents "sand over sandy, well-drained, dark colored soils." The Lower Red Lake Falls and Brainerd soils were sampled

[1] Excerpted from an unpublished report for the Department of Geology, University of Minnesota, Duluth, By Karen V. Noyce, 1981.

under mixed stands of pine (Pinus resinosa, Pinus strobus) and aspen (Populus tremuloides). The Hewitt soil most likely developed under similar vegetation, however, much of its exposure is presently farmed. The site sampled for this project was in a farm pasture.

Sampling was made from a pit or trench excavated to expose fresh surfaces. Horizon depths and boundaries were designated in the field. Color, structure, mottling, and percent pebbles were described. pH of each soil horizon was measured using a soil pH field kit. A sieved sample of pebbles (6.4 - 32 mm) was collected from the C horizon as well as a grab sample from each horizon. A crude volumetric sampler made from a tin can was used to sample 87 cc of soil from each horizon for determination of bulk density.

Moist, wet, and air-dry consistence were described in the lab (Buol et al., 1973). A moist sample of each horizon was examined under a dissecting microscope for the presence of iron staining, illuvial clay, organic material, and for carbonate reaction to 10% HCl. Samples were split, oven-dried, and sieved for textural analysis. The sand fraction was sieved into 1-2 mm and less than 1 mm fractions for A and B horizons. C horizon sands were separated into five fractions, sieved at single phi intervals. Pipette analysis was used to determine silt and clay content. Lithologies of the C horizon pebble samples were determined using a minimum of 200 pebbles.

Results

Profile descriptions of the Hewitt, Brainerd and Lower Red Lake Falls soils are presented in Tables 1, 2, and 3. Changes with depth in pH, bulk density and percent clay in the matrix are shown graphically in Figure 1.

Table 4 presents the pebble count results. Most notable is the fact that lithologies of the Hewitt and Brainerd tills were quite similar. Both were non-calcareous and contained high percentages of basalt, eastern indicators, and felsic crystalline rock types. The Lower Red Lake Falls till, in contrast, was low in eastern indicators and high in limestone.

Textural analysis of soil horizon samples is presented in Table 5. Analysis included only matrix material, i.e. it included only sand, silt, and clay fractions and excluded the coarser fraction. The Brainerd soil was notably coarser than either the Hewitt or Lower Red Lake Falls soils in all but the B2t horixon, and sand-sized particles made up a much greater percentage of the matrix. Also, within the sand fraction, coarse and medium sands predominated instead of medium and fine sands. An exception to this was the B2t horizon. In each of the three soils, a B2t horizon was present in which clay content was higher than in the other horizons. In the Brainerd soil, the B2t horizon was much higher in silt and clay than in the B2t horizon of either of the other soils.

Table 1: Profile description of the Hewitt Soil at site ISC-32.1, NW¼, section 6, T 138 N, R 31 W.

Horizon	Depth (cm)	Description
01	4.5 - 3.5	Accumulated plant material, mostly grasses
02	3.5 - 0	Thick mass of sod roots and humus
A1	0 - 11.5	Dark brown (10YR 3/3, moist) fine sandy loam; 5% pebbles; crumb structure; very friable, moist; slightly hard, dry; slightly sticky and slightly plastic, wet; abundant organic material; quartz grains clean; bulk density 1.99; pH 5.6; non-calcareous
A2	11.5 - 18.0	Dark brown (10YR 3/3, moist) mottled with yellowish brown (10YR 5/4, moist) fine sandy loam. Mottles are coarse, distinct, and common; less organic material than A1.
B2t	18.0 - 71.0	Yellowish brown (10YR 5/4, moist) mottled with dark brown (10YR 3/3, moist) sandy loam; mottles are coarse, distinct, and common; 5% pebbles; crumb structure; friable, moist; slightly hard, dry; non-sticky and non-plastic, wet; quartz grains slightly stained orange; bulk density 1.93; pH 5.6; non-calcareous
B3	71.0 - 170	Light brownish gray (2.5Y 6/2, moist) and yellowish brown (10YR 5/4) mottled sandy loam; mottles are very coarse, prominant, and many without a dominant matrix color; gray zones are coarse-grained with clean quartz grains; brown zones are finer-grained with yellow-coated quartz grains; 5 - 10% pebbles; crumb structure; friable, moist; hard, dry; non-sticky and non-plasitc, wet; bulk density 1.97; pH 5.4; non-calcareous
C	>170	Brown (10YR 4/3, moist) sandy loam; 5 - 10% pebbles; no mottling; compact with medium platy structure; friable, moist; hard, dry; slightly sticky and slightly plastic, wet; quartz grains not stained, but some coated with gray clay; bulk density 2.62; pH 6.4; non-calcareous

Table 2: Profile description of the Lower Red Lake Falls Soil at site 33.1, SW¼, section 34, T 141 N, R 32 W.

Horizon	Depth (cm)	Description
01	3.5 - 2.0	Leaf and pine needle fragments
02	2.0 - 0	Fine roots and humus with some mineral matter
A1	0 - 15	Dark brown (10YR 3/3, moist) sandy loam; 5% pebbles; medium crumb structure; very friable, moist; soft, dry; slightly sticky and slightly plastic, wet; abundant organic material; quartz grains mostly clean, but some coated with clay; bulk density 1.38; pH 6.0; non-calcareous
A2	15 - 68	Brown (10YR 4/3, moist) sandy loam: 5% pebbles; medium crumb structure; friable, moist; slightly hard, dry; slightly sticky and slightly plastic, wet; less organic than A1; quartz grains clean; bulk density 1.69; pH 5.6; non-calcareous
B2t	68 - 85	Yellowish brown (10YR 5/4) sandy loam; 5% pebbles; coarse crumb structure; friable, moist; slightly hard to hard, dry; slightly sticky to sticky and slightly plastic, wet; quartz grains in light gray clayey matrix; bulk density 1.43; pH 5.4; non-calcareous
B3	85 - 175	Dark brown (7.5YR 4/4, moist) mottled sandy loam; mottles are coarse, faint and many; 20% pebbles; coarse crumb structure, friable, moist; slightly plastic and slightly sticky, wet; hard to very hard, dry; pebbles and cobbles are highly weathered and disintegrating, mostly crystallines; quartz grains coated with orange staining; bulk density 1.40; pH 6.6; calcareous
C	>175	Light olive brown (2.5Y 5/4, moist) sandy loam; sandier than B3; 20% pebbles; medium platy structure; friable, moist; slightly hard, dry; slightly sticky and non-plastic, wet; quartz grains mostly clean, but some have $CaCO_3$ adhering to them: bulk density 1.76; pH 7.2; calcareous

Table 3: Profile description of the Brainerd Soil at site ISC-32.3 SE¼, section 6, T 137 N, R 31 W.

Horizon	Depth (cm)	Description
01	4.0 - 2.5	Mixture of leaf, pine needle, twig, and catkin fragments
02	2.5 - 0	50% mineral matter, 50% fine roots and humus
A11	0 - 10	Dark brown to brown (10YR 3/3 to 10YR 4/3, moist) sandy loam; 5% pebbles; crumb structure; very friable, moist; loose, dry; slightly sticky and slightly plastic, wet; abundant humus and fine roots; quartz grains not iron-stained but many coated with silt or clay; bulk density 0.84; pH 5.4; non-calcareous
A12	10 - 24	Dark yellowish brown to dark brown (10 YR 4/4 to 7.5YR 4/4, moist) loamy sand; 10% pebbles; crumb structure; friable, moist; loose, dry; non-sticky and non-plastic, wet; much less organic matter than in A11; quartz grains stained brownish-orange; bulk density 1.72; pH 5.4; non-calcareous
A2	24 - 86	Reddish brown (10YR 5/8) coarse sand; 10% pebbles; structureless; very friable, moist; loose, dry; non-sticky and non-plastic, wet; quartz grains stained yellowish-orange; bulk density 1.70; pH 5.8; non-calcareous
B2t	86 - 102	Dark brown to yellowish brown (7.5YR 4/4 to 10YR 5/4, moist) mottled loam; mottles coarse, distinct, and many, without a dominant matrix color; structure granular; 5% pebbles; firm, moist; hard, dry; very sticky and very plastic, wet; quartz grains less stained than in A2; bulk density 1.43; pH 5.8; non-calcareous
C	>102	Yellowish brown to dark yellowish brown (10YR 5/4 to 10YR 4/4, moist) sand; 5% pebbles; crumb structure; very friable, moist; loose, dry; non-sticky and non-plastic, wet; quartz grains clean or only very lightly stained yellowish-orange; bulk density 2.13; pH 6.0; non-calcareous

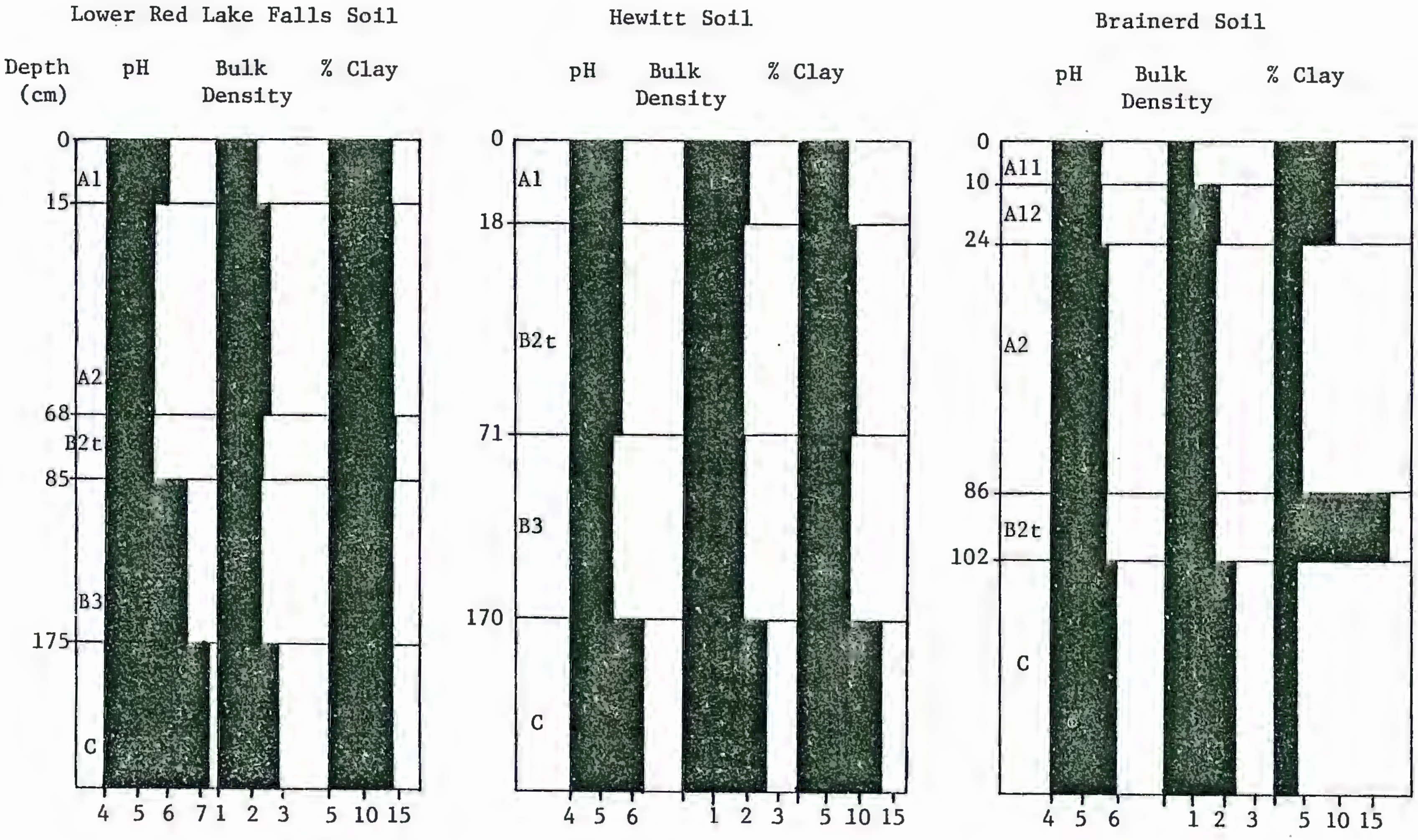

Figure 1: pH, bulk density, and % clay in matrix of Itasca, St. Croix, and Hewitt soils

Table 4. LITHOLOGY OF PEBBLES GREATER THAN 6.4 mm, TAKEN FROM THE C HORIZON OF HEWITT, BRAINERD AND LOWER RED LAKE FALLS SOILS.

Lithology	Hewitt	L. Red Lake Falls	Brainerd
* Eastern Indicators	23.1 %	8.0 %	28.3 %
Granite and Quartz	29.5	32.3	29.3
Metamorphics	2.8	5.3	3.8
Greenstones	40.6	31.4	32.5
Iron Formation	0.8	0.4	1.3
Cretaceous Shale	0.0	0.0	0.3
Carbonates	0.0	18.1	0.0
Buff Chert	2.0	3.5	1.6
Sandstone	0.8	0.0	1.6
Other	0.4	0.9	1.3

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* These include vesicular and/or black, purple, or reddish basalts and rhyolites, gabbro, diabase, colored chert, agate, and granophyre.

Table 5: TEXTURAL ANALYSIS OF SOILS

						% In Each Sand Fraction		
Horizon	% sand	% silt	% clay	(mm) 1-2	.5-1	.25-.5	.125-.25	.0625-.125
Hewitt Soil:								
A1	68.6	22.8	8.7	3.4				
B2t	75.5	14.7	9.8	8.3				
B3	75.2	15.1	9.6	7.8				
C	72.0	13.8	14.3	9.5	17.9	32.4	26.7	13.5
L. Red Lake Falls Soil								
A1	66.4	24.6	9.3	7.9				
A2	64.7	25.4	9.7	8.2				
B2t	65.3	24.3	10.5	6.8				
B3	60.1	30.0	9.3	8.5				
C	76.5	14.5	9.0	9.8	19.2	34.2	25.3	11.5
Brainerd Soil								
A11	96.9	14.8	8.5	11.4				
A12	81.6	10.0	8.5	14.5				
A2	95.6	1.0	3.3	11.9				
B2t	45.0	36.1	19.0	6.1				
C	91.5	5.5	3.0	10.5	28.6	43.5	13.4	4.1

APPENDIX B: GRAIN SIZE ANALYSES

SMAPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R,)	GRAIN SIZE (%)				SORTING STATISTICS[c]				SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
			MATRIX[b]								
		GRAVEL[a]	SAND	SILT	CLAY	MEAN(ϕ) (Mz)	SORTING (σ_1)	SKEWNESS (Sk_1)	KURTOSIS (Kg_1)		
					I.	HEWITT TILL					
14.1	NE16,137,32	6	70	14	16	3.47	3.79	+.47	1.49	60	NR[d]
17.1f	NE18,139,32	8	80	12	8	2.30	2.81	+.23	2.06	75	NR
32.1	NW6,138,31	18	72	13	15	1.87	4.25	+.15	1.70	200	NR
Average of 3 samples =		11	74	13	13	2.55	3.62	+.28	1.75		
Standard deviation =		6.4	5.3	1.0	4.4	.83	.74	.17	.29		

[a] Total percentage of sample containing clasts larger than 2 mm; includes gravel, pebbles, cobbles and boulders.

[b] Recalculated to 100 percent after removal of gravel and larger size fractions.

[c] According to Folk and Ward, 1957; see Table 1, p. 12 of text.

[d] NR = not reached; ND = reached, but not determined.

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	GRAIN SIZE (%)				SORTING STATISTICS				DEPTH (cm)	LEACHING (cm)
		GRAVEL	MATRIX			MEAN(Ø) (Mz)	SORTING (o_1)	SKEWNESS (Sk_1)	KURTOSIS (Kg_1)		
			SAND	SILT	CLAY						
IIa. BRAINERD TILL - FLOWTILL											
1.2	SW18,137,31	17	93	3	4	.54	2.03	-.10	1.73	50	NR
14.5	NE36,137,31	6	64	20	16	3.53	3.79	+.44	1.32	120	NR
20.2	SW35,140,31	11	79	12	8	2.02	3.25	+.22	2.13	90	NR
20.4	SW2,139,31	17	75	15	10	1.80	3.69	+.15	1.77	80	NR
20.5	SW2,139,31	10	73	14	13	2.71	3.72	+.34	1.87	210	NR
22.1	SE28,139,31	5	73	16	11	2.81	3.21	+.45	1.60	170	NR
24.1	NE5,138,31	17	82	15	3	1.42	2.91	-.14	1.74	40	NR
24.5	NW9,138,31	21	84	13	3	1.06	2.92	-.10	1.26	100	NR
30.1	NE5,137,31	13	80	13	7	1.64	3.08	+.19	1.71	140	NR
32.3	SE6,137,31	10	92	5	3	1.15	1.90	+.02	1.92	100	NR
Average of 10 samples=		13	79	13	8	1.87	3.05	+.15	1.71		
Standard deviation =		5.2	8.9	5.1	4.6	.92	.66	.22	.26		

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	GRAIN SIZE (%)				SORTING STATISTICS				SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
		GRAVEL	MATRIX			MEAN(ϕ) (Mz)	SORTING (σ_1)	SKEWNESS (Sk_1)	KURTOSIS (Kg_1)		
			SAND	SILT	CLAY						
IIb. BRAINERD TILL - GLACIOFLUVIAL											
2.6	SE6,140,30	47	94	3	3	-.89	2.24	+.03	.73	50	NR
10.7	SW33,139,31	7	86	10	4	1.79	2.22	+.16	1.60	220	NR
12.1b	NW10,139,31	4	74	13	13	2.96	3.32	+.50	1.75	140	NR
20.8	SW13,139,31	19	87	10	3	.87	2.65	-.06	1.36	90	NR
20.9	SW13,139,31	12	81	16	3	1.78	2.63	+.10	1.69	70	NR
20.12	SE13,139,31	30	80	17	3	.25	3.13	-.21	.88	30	NR
24.6	NE20,138,31	11	96	3	1	.92	1.51	-.22	1.56	100	NR
Average of 7 samples =		19	86	10	4	1.10	2.55	+.04	1.37		
Standard deviation =		15.2	7.8	5.6	3.9	1.2	.60	.25	.40		
IIc. BRAINERD TILL - BASAL TILL											
20.16	SW18,138,30	18	80	17	3	1.39	2.94	-.03	1.46	75	NR
IIIa. LOWER RED LAKE FALLS TILL - FLOWTILL											
1.7	SE5,142,31	15	73	15	12	2.22	3.86	+.23	1.75	180	ND
2.4	SW29,141,33	9	74	16	12	2.51	3.39	+.36	1.94	ND	ND

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	GRAIN SIZE (%)				SORTING STATISTICS				SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
			MATRIX								
		GRAVEL	SAND	SILT	CLAY	MEAN(ϕ) (Mz)	SORTING (o_1)	SKEWNESS (Sk_1)	KURTOSIS (Kg_1)		
3.4	NE36,140,32	7	75	16	9	2.51	3.14	+.41	1.62	150	NR
5.14	SW25,141,32	4	45	33	23	4.99	4.17	+.24	.95	70	70
6.5	SW13,140,32	10	85	12	3	1.89	2.33	+.03	1.54	60	NR
6.11	SW 6,140,31	22	84	14	2	.80	3.04	-.18	1.26	60	NR
(6.15)[f]	SW31,141,31	(2)	(31)	(36)	(33)	(6.06)	(4.34)	(+.17)	(.79)	30	30
8.7	SE10,141,33	8	80	15	5	2.03	2.52	+.31	1.58	170	105
17.6	NW9,140,32	1	17	34	50	7.84	4.00	-.07	.80	60	60
17.7	NE5,140,32	3	61	29	10	3.53	3.09	+.37	1.21	150	150
18.9	NW18,140,31	7	82	10	8	2.02	2.73	+.35	2.11	210	150
19.1	NW31,140,31	5	67	20	13	3.25	3.49	+.40	1.34	150	NR
30.3	NW15,141,31	7	45	43	13	4.06	3.65	+.05	1.23	280	150
33.1	SW34,142,32	13	76	14	10	2.17	3.48	+.24	1.81	195	85
Average of 13 samples =		9	66	21	13	3.06	3.30	+.21	1.47		
Standard Deviation =		5.6	19.9	10.3	12.3	1.71	.56	.19	.38		

[e] Not determined (previous page)

[f] Solum; () - indicates sample was not used in calculating summary statistics.

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	GRAIN SIZE (%)				SORTING STATISTICS				SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
			MATRIX								
		GRAVEL	SAND	SILT	CLAY	MEAN(Ø) (Mz)	SORTING (o_1)	SKEWNESS (Sk_1)	KURTOSIS (Kg_1)		
IIIb. LOWER RED LAKE FALLS TILL - GLACIOFLUVIAL											
6.12	NW6,140,31	22	94	4	2	.46	2.20	-.20	1.13	50	NR
6.14	SE36,141,32	12	91	7	2	1.24	2.02	-.03	1.35	80	NR
8.11d	SE32,142,32	7	98	1	1	.42	.98	-.07	1.28	300	135
Average of 3 samples =		14	94	4	2	.71	1.73	-.10	1.25		
Standard deviation =		7.6	3.5	3.0	0.6	.46	.66	.09	.11		
IVa. OSHAWA DUMP RIDGE											
(1.3)[g]	SW13,137,32	(7)	(92)	(6)	(2)	(1.57)	(1.71)	(0.0)	(1.40)	60	NR
3.2	NW29,139,31	27	82	12	6	.75	3.17	-.14	1.15	125	NR
12.5a	NE7,138,31	44	92	4	4	-.62	2.50	0.0	.72	150	NR
27.8	NW24,138,32	43	84	9	7	-.27	3.19	+.14	.84	100	NR
Average of 3 samples =		38	86	8	6	-.05	2.95	+.03	.90		
Standard deviation =		9.5	5.3	4.0	1.5	.71	.39	.09	.22		

[g] located 100 m east of ridge crest.

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	GRAIN SIZE (%)				SORTING STATISTICS				SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
			MATRIX								
		GRAVEL	SAND	SILT	CLAY	MEAN(Ø) (Mz)	SORTING (o_1)	SKEWNESS (Sk_1)	KURTOSIS (Kg_1)		
IVb. OSHAWA OUTWASH PLAIN											
23.9	NW19,139,31	7	78	13	9	2.48	2.97	+.31	1.87	210	NR
23.11	NW32,139,31	6	74	14	12	2.84	3.37	+.40	1.86	180	NR
23.13	SE1,138,32	4	77	18	5	2.91	2.38	+.27	1.66	40	NR
23.15	NW11,138,32	4	99	1	-	1.44	1.05	-.12	1.24	100	NR
27.6	NE22,138,32	17	82	10	8	1.64	3.05	-.02	1.48	70	NR
Average of 5 samples =		8	82	11	7	2.26	2.56	+.17	1.62		
Standard deviation =		5.4	9.9	6.4	4.5	.68	.92	.23	.27		
IVc. PARK RAPIDS OUTWASH PLAIN											
2.1	NE10,140,34	41	98	1	1	-.77	1.79	-.18	.88	200	ND
(15.3)[g]	SE9,140,34	(60)	(98)	(1)	(1)	(-1.72)	(1.89)	(+.31)	(.67)	500	115
(18.2)[i]	SW11,140,32	(23)	(84)	(9)	(7)	(.66)	(2.92)	(+.04)	(1.68)	90	NR
23.2	SE9,139,32	9	99	1	-	1.26	1.56	-.25	1.05	110	NR
23.5	SE11,139,32	1	99	1	-	1.86	.93	-.11	1.01	160	NR
25.2	SE27,140,33	10	100	-	-	.48	1.23	-.25	1.59	220	120
25.4	SE28,140,34	2	100	-	-	1.33	1.00	-.14	1.19	370	55
25.7	NE27,140,32	33	99	1	-	-.39	1.88	-.20	.90	50	NR
26.4	SW24,140,32	6	100	-	-	.84	1.15	-.23	1.10	140	110
27.1	SW4,139,32	3	99	1	-	.50	.94	+.05	1.18	280	270

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R,)	GRAIN SIZE (%)				SORTING STATISTICS				SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
			MATRIX			MEAN(Ø) (Mz)	SORTING (σ_1)	SKEWNESS (Sk_1)	KURTOSIS (Kg_1)		
		GRAVEL	SAND	SILT	CLAY						
28.3	SW16,140,32	9	100	-	-	1.31	1.42	-.36	1.70	110	NR
Average of 9 samples =		13	99	1		.71	1.32	-.19	1.18		
Standard deviation =		14.3	0.7	0.5	0.3	.86	.36	.11	.29		
IVd. PINE RIVER OUTWASH PLAIN											
20.14a	NE6,138,30	9	99	1	-	.92	1.25	-.22	1.32	ND	ND
(20.14c)[i]	NE6,138,30	(12)	(71)	(22)	(7)	(2.47)	(3.21)	(+.21)	(1.37)	ND	ND
20.15	NW18,138,30	1	100	-	-	1.44	.74	-.24	1.16	60	NR
20.18	SW20,138,30	20	97	2	1	.33	1.60	-.28	1.00	¯70	NR
32.5	SE10,138,30	20	86	7	7	.48	3.05	-.01	2.13	190	NR
32.6	NE11,138,30	16	96	1	3	.59	1.67	-.39	1.58	310	ND
Average of 5 samples =		13	96	2	2	.75	1.66	-.23	1.44		
Standard deviation =		8.2	5.6	2.8	2.9	.44	.86	.14	.44		
IVe. HACKENSACK OUTWASH PLAIN											
1.9	SW15,140,29	66	97	2	1	-1.98	1.89	+.55	.75	210	150
2.5	NW31,141,30	1	5	55	40	7.74	3.15	+.35	.73	200	ND
5.15	SW25,141,32	2	94	5	1	1.62	1.20	+.18	1.47	ND	ND
(7.5)[j]	NE25,140,31	(3)	(43)	(17)	(40)	(5.86)	(4.70)	(+.23)	(.66)	30	120
7.6b	SE5,139,30	27	88	7	5	.13	2.79	-.04	1.33	100	300

[i] Solum.

[j] Solum.

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R,)	GRAIN SIZE (%)				SORTING STATISTICS				SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
			MATRIX								
		GRAVEL	SAND	SILT	CLAY	MEAN(Ø) (Mz)	SORTING (σ_1)	SKEWNESS (Sk_1)	KURTOSIS (Kg_1)		
IVe. HACKENSACK OUTWASH PLAIN (cont'd)											
9.11	SE6,140,30	64	96	3	1	-1.88	2.20	+.74	.71	210	ND
10.3	SW22,139,30	15	100	-	-	.44	1.32	-.20	1.01	245	230
18.3	NW11,140,32	0	34	63	4	5.01	1.57	+.24	.87	40	NR
20.1	NW35,140,31	2	100	-	-	1.30	.97	-.09	1.12	30	NR
Average of 8 samples =		22	77	16	7	1.55	1.89	+.22	1.00		
Standard deviation =		28.0	36.4	26.2	13.4	3.33	.78	.32	.29		
V. EOLIAN SANDS											
(17.1b)[k]	NE18,139,32	(8)	(80)	(13)	(7)	(2.30)	(2.81)	(+.23)	(2.06)	15	NR
23.16	NW3,138,32	-	97	2	1	2.55	.90	-.03	1.09	110	NR
27.3	SE8,138,32	-	98	1	1	2.40	.88	-.08	1.09	60	NR
(27.10)[l]	NW12,138,32	(3)	(78)	(16)	(6)	(2.84)	(2.32)	(+.35)	(1.74)	25	NR
27.13	SW29,139,32	1	96	3	1	2.35	1.18	-.11	1.29	70	NR
27.14	NE19,139,32	1	98	1	1	1.82	.76	+.10	.99	320	NR
31.1	SW26,139,32	-	99	1	-	2.28	.93	-.16	1.20	90	NR
31.2	SE34,139,32	-	99	1	-	2.57	.73	+.04	1.28	120	NR
Average of 6 samples =		0.3	98	1	0.5	2.33	.90	-.04	1.16		
Standard deviation =		.5	1.2	.8	.5	.27	.16	.10	.12		

[k] and [l] Solum.

APPENDIX C. RESULTS OF STONE COUNTS (in percent)

PART 1: PEBBLE FRACTION (6-64 mm)

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	EASTERN INDICATORS														
		FEL-SITE[a]	GABBRO	SAND-STONE	IRON FM.	AGATE	CARB.	BUFF CHERT	GRF[b]	MRF[c]	MAFIC	SHALE	OTHER	ROCKS	SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
I. HEWITT TILL																
17.1e	NE18,139,32	2	7	1	1	1	-	1	50	6	29	-	1	368	75	NR[d]
27.10b	NW12,138,32	9	13	6	3	-	-	6	30	8	25	-	-	64	40	NR
32.1a	NW6,138,31	16	7	1	1	-	-	2	30	3	41	-	-	251	200	NR
Average of 3 samples=		9	9	3	2	.2	-	3	37	6	32	-	.3			
Standard deviation =		6.9	3.1	3.0	1.3	.4	-	2.6	11.5	2.5	8.3	-	.6			
IIa. BRAINERD TILL - LEACHED																
12.1b	NW10,139,31	16	18	-	6	2	-	2	26	4	24	2	-	50f[e]	140	NR
14.3	SE33,138,31	23	5	1	1	1	-	2	36	4	28	-	-	171	300	ND[f]
14.5	NE6,137,31	21	12	1	2	1	-	3	22	3	35	-	1	113	120	NR
20.2	SW35,140,31	6	5	1	1	1	-	4	45	1	36	-	1	289	90	NR
20.4	SW2,139,31	16	10	1	2	1	-	2	27	2	38	-	-	305	80	NR

[a] See p. 11 of text for complete description of lithologic categories.

[b] Granitic rock fragments. [c] Metamorphic rock fragments. [d] Not reached. [e] Field pebble count.

[f] Reached, but not determined.

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	EASTERN INDICATORS FEL-SITE	GABBRO	SAND-STONE	IRON FM.	AGATE	CARB.	BUFF CHERT	GRF	MRF	MAFIC	SHALE	OTHER	# OF ROCKS	SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
IIa. BRAINERD TILL - LEACHED (cont'd)																
20.8	SW13,139,31	19	6	1	2	-	-	2	24	6	39	-	-	173	90	NR
20.10	SW13,139,31	11	5	1	1	1	-	4	41	2	31	2	3	271	30	NR
24.1	NE5,138,31	13	15	1	1	-	-	1	20	3	44	-	2	324	40	NR
24.5	NW9,138,31	16	18	1	2	1	-	2	23	3	33	1	1	372	100	NR
24.6	NE20,138,31	11	11	1	1	1	-	2	29	3	41	-	2	354	100	NR
32.3	SE6,137,31	17	11	2	1	1	-	2	29	4	33	1	1	314	100	NR
Avg. of 11 samples =		15	10	1	2	1	-	2	29	3	35	1	1			
Std. deviation =		4.9	4.9	0.4	1.6	0.6	-	0.9	8.1	1.3	5.8	0.8	1.0			
IIb. BRAINERD TILL - UNLEACHED																
21.7	SW5,139,30	10	5	1	1	-	13	2	31	3	35	-	-	214	190	180
24.10g	NE5,137,31	21	3	-	1	1	3	3	29	2	38	-	1	270	420	330
33.7	SW28,140,29	6	14	1	1	-	1	2	35	7	33	1	1	288	125	ND
Avg. of 3 samples =		12	7	0.3	1	0.1	6	2	32	4	35	1	1			
Std. deviation =		7.9	6.0	0.3	0.2	0.2	6.4	0.6	3.1	2.6	2.5	0.2	0.6			
IIIa. LOWER RED LAKE FALLS TILL - LEACHED																
13.2	SW13,140,32	2	6	-	-	-	-	-	54	2	36	-	-	50f	60	NR
19.1	NW31,140,31	4	10	1	1	-	-	1	30	13	37	3	-	71	150	NR

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	EASTERN INDICATORS												# OF ROCKS	SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
		FEL-SITE	GABBRO	SAND-STONE	IRON FM.	AGATE	CARB.	BUFF CHERT	GRF	MRF	MAFIC	SHALE	OTHER			
IIIb - LOWER RED LAKE FALLS TILL - UNLEACHED																
13.4	SE33,142,32	4	5	1	-	1	24	3	35	3	25	-	-	185	300	250
17.5	SW9,140,32	5	2	1	tr	tr	16	4	36	4	31	-	1	278	200	140
17.7	NE5,140,32	7	8	2	-	-	21	2	27	2	31	-	-	114	150	ND
18.7	SE12,140,32	5	3	3	-	-	16	3	38	3	30	-	-	37	250	135
18.9	NW18,140,31	7	2	1	1	2	13	2	45	1	25	-	1	262	210	150
33.1	SW34.142.32	2	6	-	tr	-	18	4	32	5	31	-	1	226	195	85
33.3	NW10,141,31	tr	6	-	tr	-	17	2	34	7	29	-	5	239	200	ND
33.4	SW23,141,31	3	9	-	1	-	5	3	33	5	40	-	1	153	180	ND
Average of 8 samples		4	5	0.8	0.5	0.4	16	3	35.0	4	30	-	1			
Standard deviation		2.5	2.6	1.0	0.4	0.7	5.7	0.8	5.2	1.9	4.7	-	1.6			
IVa - OSHAWA OUTWASH PLAIN - LEACHED																
14.2	NE9,137,32	10	8	1	-	-	-	2	34	1	43	-	1	146	30	NR
14.6	SE36,138,32	15	4	-	-	-	-	2	20	10	47	-	2	104	300	NR
27.6	NE22,138,32	17	7	1	1	-	-	2	28	1	43	-	1	314	20	NR
27.8a	NE24,138,32	26	7	1	tr	-	-	1	26	3	35	-	-	292	100	NR
Average of 4 samples		17	6	1	0.3	-	-	2	27	4	42	-	1			
Standard deviation		6.5	1.9	0.6	0.5	-	-	0.5	5.8	4.3	5.0	-	0.8			

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	EASTERN INDICATORS												# OF ROCKS	SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
		FELSITE	GABBRO	SANDSTONE	IRON FM.	AGATE	CARB.	BUFF CHERT	GRF	MRF	MAFIC	SHALE	OTHER			
IVb - PARK RAPIDS OUTWASH PLAIN - LEACHED																
25.7	NW27,140,32	4	11	2	1	1	-	1	35	8	35	-	-	344	50	NR
IVb - PARK RAPIDS OUTWASH PLAIN - UNLEACHED																
1.4	SW14,139,34	6	1	-	-	-	15	2	35	0	42	-	-	176	300	ND
15.1	SW10,140,32	3	7	-	-	-	12	-	27	9	37	5	-	59f	400	ND
15.2	SW2,140,34	2	1	-	-	-	12	4	42	4	35	-	tr	270	180	170
15.3	SE9,140,34	1	1	-	-	tr	19	2	51	4	22	-	-	301	500	120
15.4	SE3,140,33	1	1	1	-	-	24	4	41	2	26	-	tr	188	ND	ND
15.5	SW30,141,32	1	3	-	1	1	12	5	36	11	30	-	-	207	160	120
26.3	NW22,140,31	3	2	1	-	1	11	5	30	4	43	-	-	120	240	210
Average of 7 samples		2	2	0.3	0.1	0.2	15	3	37	5	34	1	0.2			
Standard deviation		1.7	2.2	0.5	0.2	0.3	4.8	1.9	8.1	3.8	7.9	1.9	0.2			
IVc - PINE RIVER OUTWASH PLAIN - LEACHED																
32.5	SE10,138,30	9	9	2	1	-	-	3	35	4	37	-	-	330	190	200
IVc - PINE RIVER OUTWASH PLAIN - UNLEACHED																
20.14b	NE6,138,30	10	8	3	1	-	9	1	26	7	37	-	-	214	ND	ND
32.6	NE11,138,30	8	8	2	1	tr	6	2	30	6	38	-	1	329	280	ND

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	EASTERN INDICATORS					CARB.	BUFF CHERT	GRF	MRF	MAFIC	SHALE	OTHER	# OF ROCKS	SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
		FELSITE	GABBRO	SANDSTONE	IRON FM	AGATE										
IVd - HACKENSACK OUTWASH PLAIN - LEACHED																
18.2	SW11,140,32	4	1	2	tr	-	-	2	44	4	42	-	1	329	280	ND
IVd - HACKENSACK OUTWASH PLAIN - UNLEACHED																
13.3	SE2,140,32	3	1	-	-	-	21	1	45	1	28	-	-	100	180	155
16.1	NW13,140,31	3	3	tr	tr	tr	22	2	29	6	35	-	-	283	140	100
19.9	NE29,140,31	6	4	2	-	1	11	3	38	6	31	-	-	411	210	180
21.6	SE5,139,30	6	9	1	-	tr	8	4	37	7	28	-	-	319	220	200
33.5	SE26,141,31	4	3	-	-	tr	13	4	37	2	36	-	-	295	500	ND
33.6	SE6,140,30	24	4	1	1	-	2	6	30	4	29	-	-	180	210	ND
Average of 6 samples		7	2	1	1	0.3	-	2	72	1	13	-	1			
Standard deviation		2.8	0.7	0.8	0.3	0.4	-	1.2	6.6	1.1	3.6	-	0.6			
PART II: SAND FRACTION (1-2 mm)																
I - HEWITT TILL - LEACHED																
14.1	NE16,137,32	5	3	-	-	-	-	1	79	1	11	-	1	284	60	NR
IIa - BRAINERD TILL - LEACHED																
2.6	SE6,140,30	6	2	1	1	-	-	1	74	1	16	-	-	384	50	NR

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	EASTERN INDICATORS												# OF ROCKS	SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
		FEL-SITE	GABBRO	SAND-STONE	IRON FM	AGATE	CARB.	BUFF CHERT	GRF	MRF	MAFIC	SHALE	OTHER			
20.5	SW2,139,31	8	3	2	tr	-	-	2	73	1	12	-	-	268	210	NR
20.9	SW13,139,31	6	3	1	1	1	-	3	74	-	13	-	-	284	70	NR
20.12a	SE13,139,31	4	2	tr	-	-	-	-	82	3	7	-	1	232	90	NR
20.16	SW18,138,30	12	2	1	tr	tr	-	1	67	-	15	-	1	240	75	NR
22.1	SE28,139,31	9	2	2	1	-	-	3	63	1	17	-	1	215	170	NR
Average of 6 samples		7	2	1	1	0.3	-	2	72	1	13	-	1			
Standard deviation		2.8	0.7	0.8	0.3	0.4	-	1.2	6.6	1.1	3.6	-	0.6			
IIIa - LOWER RED LAKE FALLS TILL - LEACHED																
2.4	SW29,141,33	1	1	tr	-	tr	-	3	80	1	15	-	-	306	ND	ND
6.11	SW6,140,31	4	2	tr	tr	-	-	2	78	3	11	-	-	281	60	NR
6.12	NW6,140,31	9	2	2	1	-	-	3	63	1	17	-	1	215	170	NR
Average of 3 samples		3	1	0.2	0.1	0.3	-	2	79	2	13	-	-			
Standard deviation		1.6	0.9	0.2	0.2	0.3	-	0.6	1.2	1.0	2.0	-	-			
IIIb - LOWER RED LAKE FALLS TILL - UNLEACHED																
6.15	SW31,141,31	1	2	1	-	1	13	3	71	2	8	-	1	120	30	ND
8.7	SE10,141,33	3	tr	1	1	1	6	2	74	1	12	-	-	244	170	ND
8.11d	SE32,142,32	tr	1	1	-	1	11	2	66	0	17	-	-	264	300	130
30.3	NW15,141,31	2	2	-	-	tr	7	1	67	7	13	-	1	290	280	150

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	EASTERN INDICATORS												# OF ROCKS	SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
		FEL-SITE	GABBRO	SAND STONE	IRON FM.	AGATE	CARB.	BUFF CHERT	GRF	MRF	MAFIC	SHALE	OTHER			
IIIb. LOWER RED LAKE FALLS TILL - UNLEACHED (cont'd)																
Average of 4 samples		7	1	1	0.2	1	9	2	70	3	13	-	1			
Std deviation		0.9	0.9	0.5	0.4	0.3	3.3	0.8	3.7	3.1	3.7	-	0.6			
IVa. OSHAWA OUTWASH PLAIN - LEACHED																
1.3	SW13,137,32	7	1	1	-	-	-	3	74	2	13	-	tr	268	60	NR
27.8a	NE24,138,32	8	2	1	1	-	-	2	68	6	13	-	-	402	100	NR
IVb. PARK RAPIDS OUTWASH PLAIN - LEACHED																
27.3	SE8,138,32	4	1	1	-	1	-	1	78	-	14	-	tr	204	60	NR
27.13	SW29,139,32	2	-	-	-	-	-	1	73	-	25	-	-	282	70	NR
28.3	SW16,140,32	2	2	-	-	-	-	1	79	-	16	-	-	228	110	NR
Avg of 3 samples =		3	1	0.2	-	0.3	-	1	77	-	18	-	tr			
Std deviation =		1.2	0.9	0.3	-	0.6	-	0	3.2	-	5.9	-	0.3			
IVb. PARK RAPIDS OUTWASH PLAIN - UNLEACHED																
15.3	SE9,140,34	tr	tr	-	-	1	13	3	70	-	12	-	-	371	500	120
25.2b	SE27,140,33	tr	-	tr	-	1	10	3	72	-	13	-	-	338	220	120
25.4d	SE28,140,34	2	tr	-	-	1	14	4	61	-	19	-	-	270	370	60
26.4	SW24,140,32	3	1	tr	-	tr	3	3	73	-	17	-	tr	236	140	110
Avg of 4 samples =		1	0.4	0.2	-	1	10	3	69	-	15	-	tr			
Std. deviation =		1.3	0.3	0.2	-	0.4	5.0	0.5	5.5	-	3.3	-	0.2			

SAMPLE NUMBER (ISC-)	SAMPLE LOCATION (sec,T,R)	EASTERN INDICATORS												# OF ROCKS	SAMPLE DEPTH (cm)	DEPTH OF LEACHING (cm)
		FEL-SITE	GABBRO	SAND STONE	IRON FM.	AGATE	CARB.	BUFF CHERT	GRF	MRF	MAFIC	SHALE	OTHER			
							IVc. PINE RIVER OUTWASH PLAIN - LEACHED									
20.14c	NE6,138,30	2	4	-	-	-	-	2	76	-	11	-	-	188	ND	ND
20.15	NW18,138,30	3	1	-	-	-	-	1	81	1	13	-	-	230	60	NR
20.18	SW20,138,30	4	2	1	-	1	-	2	71	3	16	-	-	290	70	NR
Avg. of 3 samples =		3	3	0.3	-	0.2	-	2	76	3	13	-	-			
Std. deviation =		1.0	1.2	0.6	-	0.4	-	0.6	5.0	2.0	2.5	-	-			
							IVc. PINE RIVER OUTWASH PLAIN - UNLEACHED									
20.14a	NE6,138,30	7	2	1	tr	tr	5	4	70	1	12	-	-	339	ND	ND
							IVd. HACKENSACK OUTWASH PLAIN - LEACHED									
7.5	NE25,140,31	2	2	-	-	tr	-	3	77	1	16	-	tr	356	30	100
20.1a	NW35,140,31	2	2	1	-	1	-	1	82	-	11	-	tr	330	30	NR
							IVd. HACKENSACK OUTWASH PLAIN - UNLEACHED									
1.9	SW15,140,29	9	1	tr	tr	tr	8	2	61	2	17	-	1	254	210	150
9.11	SE6,140,30	5	2	1	-	tr	1	1	71	2	17	-	-	287	210	ND
10.3	SW22,139,30	4	2	1	-	1	1	2	75	2	13	-	tr	351	250	230
Avg. of 3 samples =		6	2	1	0.1	1	3	2	69	2	16	-	0.3			
Std. deviation =		2.9	0.2	0.5	0.2	0.3	4.0	0.6	7.2	0	2.3	-	0.5			