LATE-WISCONSIN STRATIGRAPHY
AND GLACIAL HISTORY OF SOUTHWESTERN
ST. LOUIS COUNTY, MINNESOTA

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ABSTRACT

The stratigraphy and landforms of southwestern St. Louis County indicate that during Late-Wisconsin time, the area was affected by glacial advances of the Rainy Lobe, the Superior Lobe, and the St. Louis Sublobe, as well as two glacial lake phases. Sedimentologic signatures, stratigraphic relationships, fabric analyses, thin sections of till, and landforms were studied in an effort to monitor the interactions of each of the ice advances in relation to previous deposits and to reconstruct the depositional environment and origin of landforms associated with each lobe. Modern developments and theories based on the deformable nature of sediment at the base of glacier ice as well as the role of glaciotectonics in the glacial environment provided insight and assistance in interpreting important sedimentary features and landforms.

The earliest Late-Wisconsin ice advance deposited the gray-brown, sandy (sand/silt/clay: 62/32/6) Independence Till of the Sullivan Lake Formation during the St. Croix phase of the Rainy Lobe, approximately 20,000 yrbp. Rock fragments indicate a northern provenance, and geomorphic features related to this advance include drumlins, eskers, and tunnel valleys. Recumbent folds and boudinage structures discovered in beds of sand exposed in a drumlin indicate the stress present at the base of glacier ice.

Approximately 18,000 yrbp the Superior Lobe advanced in a west-southwest direction in the Automba phase and deposited the Upper
Cromwell Formation. In the study area this formation is made up dominantly of red-brown, sandy (sand/silt/clay:60/31/9) supraglacial material and is exposed in the massive Highland Moraine. Exposures of subglacial sediment are rare although one exposure in the moraine revealed intensely deformed glacial strata and stone fabric parallel to ice movement. An up-glacier depression and a related down-glacier ridge suggests the formation of a hill-hole pair. This, combined with deformed subglacial strata and the massive amount of material in the Highland Moraine reflects the compressional nature of ice flow at the glacier margin.

The new rock-stratigraphic name "St. Louis Formation" is here introduced for till and outwash associated with the St. Louis Sublobe. This sublobe, a southeast extension of the Des Moines Lobe, advanced approximately 12,000 yrbp. The Alborn Till Member contains a gray, sandy, calcareous component (sand/silt/clay:60/22/18) of western provenance and a red-brown, fine-textured mixture (sand/silt/clay:35/34/31) of far-transported and locally eroded sediment typically displaying laminations. As the sublobe advanced from the northwest, it encountered earlier deposited fine-grained lake sediments. Consequently, the lake sediments were deformed and incorporated into the glacier as the ice thinned and became overextended. Evidence for this theory includes deformation structures, laminated till, a lack of major outwash features, and the small size of the Culver Moraine. The sublobe's anvil shape is also a possible consequence of the deformable substrate.
The rock-stratigraphic term "Meadowlands Formation" is here introduced for lacustrine sediments contained within the Glacial Lake Upham Basin. Rhythmites, lake clay, wave modified till, and beach deposits are included in this formation.
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INTRODUCTION

General Statement

Southwestern St. Louis County was affected by not less than three glacial advances in Late-Wisconsin time. This complex glacial history has left a myriad of glacially derived sediments of different age, genesis, and composition deposited adjacent to and/or upon one another. Glacial sediment in the area represents an advance from the northeast by the Rainy Lobe, an advance from the east out of the Superior Basin by the Superior Lobe, and an advance from the northwest by the St. Louis Sublobe of the Des Moines Lobe. Lake sediments attributed to Glacial Lake Upham II are also present in the study area.

No recent detailed studies have been done in the area affected by these lobes of ice. The present study is concerned with detailed analysis of the sedimentologic, stratigraphic, geomorphic, and glaciotectonic information contained in the glacial sediments. This should add to a better understanding of the glacial history and stratigraphy in northeastern Minnesota, as well as to our knowledge of ice sheet physics and glacial processes.

Location

The primary study area, covering approximately 410 square miles (1045 sq. km.) is located in the southwestern corner of St. Louis County, Minnesota (Figure 1). The Floodwood, Prairie Lake, McCarty
Figure 1. Index map of study area.
River, Gowan, Brookston Northwest, Martin Lake, Brookston, and Alborn Quadrangles, United States Geological Survey 7.5 minute topographic map series, contain the area of detailed study. Exploration in the surrounding quadrangles proved helpful in explaining relationships in the primary study area. Three of these, Meadowlands, Payne, and Independence Quadrangles, contained important exposures which added valuable information.

Objectives

The following objectives were developed for this project: (1) to determine the compositional signature of the easternmost portion of the St. Louis Sublobe with modern developments and theories in mind; (2) to monitor the interactions of each of the ice sheets in relation to deposits of older advances; (3) to reconstruct the depositional environment and origin of landforms within the deposits of each lobe; and (4) to investigate the role of glaciotectonics in the glacial environment.

Methods of Investigation

Field Methods

The field work was conducted during the summer of 1987 with final checks made in the spring of 1988. United States Geological Survey 7.5
minute topographic maps were used as base maps. The major data
gathering localities were exposures in gravel pits, road cuts, drainage
ditches, and stream valleys. Over 200 samples were collected from
approximately 100 sites. A soil auger and soil core sampler were used
to check and sample sediment in areas that lacked exposure.

Field analysis of sediment included description of stratigraphic
relationships, texture, possible depositional environment, and color
using Munsell soil color charts. A Brunton compass was used to measure
the strike and dip of fault planes as well as trend and plunge of fold
axes. Counts of the relative roundness and lithology of pebble size
clasts as well as fabric analyses of the long axis of stones (length to
width ratio of 1.5:1 or greater) were tabulated at numerous exposures.
The St. Louis County Soil Conservation Service provided preliminary soil
survey maps (scale 1:24,000) which were used to help determine mapping
unit boundaries in areas lacking adequate exposure.

Laboratory Methods

One-hundred twenty-eight samples were analyzed to determine grain
size distributions. Samples were soaked overnight in 20 ml of
dispersing agent (100 mg sodium hexametaphosphate and 10 mg sodium
carbonate in one liter of de-ionized water) after which standard methods
of sieve and pipette analysis, as described by Folk (1980), were
followed.

A new method of lithologic analysis was applied to samples of
till. Preparation of the samples is detailed in Appendix A. This method entailed the impregnation of till in order to make petrographic thin sections. Forty-two of these sections were then placed in a point counting apparatus and examined quantitatively with a binocular petrographic microscope. An additional 18 thin sections were made and examined qualitatively.

For quantitative descriptions, approximately 600 points, both fragments and matrix, were counted on each thin section. Silt-size material (<0.0625 mm) was counted as matrix. The sand-size particles (0.0625 - 2.0 mm) were identified by lithology and grouped into the following categories:

1) Rock fragments
   A) North Shore Volcanic Group (Green, 1972)
      1) Mafic volcanics, including vesicular and amygdaloidal basalt.
      2) Felsic volcanics, including felsite and porphyritic rhyolite.
      3) Banded agate
   B) Duluth Complex (Phinney, 1972)
      1) Gabbro and diabase
      2) Red granophyre
   C) Red to pink sandstone of the Fond du Lac and Hinckley Formations (Morey, 1972)
   D) Northeastern Minnesota and Canadian Shield rocks (Sims, 1972; Ojakangas, 1972)
1) Felsic plutonics (mostly plagioclase/quartz granitic material)

2) Schist and gneiss

3) Greenstone and volcanioclastics (derived from metavolcanic belts in northern Minnesota and southern Canada)

4) Cherty iron formation (from the Mesabi Iron Range).

E) Winnipeg Lowland and northwestern source rocks (Austin, 1972; Clayton and others, 1974)

1) Limestone and chert (from the Winnipeg Lowlands)

2) Siliceous shale (largely from the Pierre Formation in North Dakota)

F) Graywacke and slate (Morey and Ojakangas, 1972), derived largely from metasediments of the Thomson Formation, outcropping north, west, and southwest of Duluth, as well as from the Rove and Virginia Formations associated with Lower Proterozoic Iron Formations.

2) Mineral fragments

A) Quartz

1) rounded (largely due to water transport but possibly recycled sedimentary rock fragments).

2) angular (largely due to glacial transport but possibly crushed from felsic igneous rock fragments).

B) Feldspar
1) Plagioclase (from felsic and mafic plutonic rocks).
2) Orthoclase (from felsic plutonic rocks)
3) Microcline and Perthite (from felsic plutonic rocks).

C) Opaques
1) Hematite
2) Magnetite

D) Heavy minerals
1) Amphibole
2) Pyroxene
3) Epidote
4) Olivine
5) Other

3) Matrix

This category includes particles less than 0.0625 mm in diameter, independent of matrix type. A qualitative distinction was made, however, between samples with and without carbonate material in the matrix.

In general, Superior Lobe deposits should contain a higher percentage of rock fragments from the North Shore Volcanic Group (Green, 1972), as well as red sandstone from Keweenawan sedimentary rocks that overlie the volcanics. Rainy Lobe deposits should contain more clasts from the Duluth Complex and northeastern Minnesota and Canadian Shield rocks. The St. Louis Sublobe, which advanced out of the Winnipeg and Red Lakes Lowlands, should contain more Paleozoic and Mesozoic carbonate
and shale rock types, as well as crystalline rocks from northwestern Minnesota. Deposits with an intermediate assemblage of the above rock types should indicate deposition by ice flowing over deposits of earlier advances.

A limited number of grain counts were done on the 1.0 - 2.0 mm sand fraction. The results of these are compared and contrasted with the petrographic work.

A Siemens Diffractometer (Ni-filtered CuKα radiation) was used for X-ray diffraction analysis of the clay fraction (<0.002 mm). Two samples of clay from till in deposits of each lobe, as well as a sample of clay from a sequence of rhythmites, were analyzed for mineralogy.

Regional Geology

Bedrock Geology

The study area is underlain primarily by slate and graywacke of the Middle Precambrian Thomson Formation (Morey and Ojakangas, 1970). A variety of other bedrock lithologies cropping out in Minnesota, North Dakota, and Canada, have had a dramatic effect on the composition of till in the study area. A map of the bedrock geology is shown in Figure 2.

Quaternary Geology

Much work has been done on the Quaternary geology and glacial history of Minnesota. The presently accepted chronology of glacial
Figure 2. Map of bedrock geology of Minnesota and adjacent states (from Wright, 1972b, p. 519).
events has evolved from research spanning the past 100 years.

The earliest reports, published before the turn of the century, laid the groundwork for determining the glacial history of the state (Upham, 1894; Winchell, 1899). Leverett (1929, 1932) expanded on these earlier ideas and developed a glacial history which "embraced the entire State of Minnesota and adjacent parts of Wisconsin, Iowa, and North and South Dakota." These early studies identified several ice advances from different lobes of the Laurentide Ice Sheet and discussed the glacial and lacustrine features associated with them.

Detailed research began approximately thirty years ago with the work of H. E. Wright Jr. (1955, 1969, 1972a, 1972b, 1973, 1976); Wright and others (1965, 1969, 1973); Arneman and Wright (1959); Baker, (1964); and Saarnisto (1974). More recent investigations and correlations (Gross, 1982; Norton, 1982; Attig and Clayton, 1985; Farrand and Drexler, 1985; Lannon, 1986; Matsch and Schneider, 1986; Goldstein, 1987) have added fine detail to the understanding of glacial events in Minnesota and especially the Lake Superior Basin. A map of the Quaternary Geology of Minnesota published by the Minnesota Geological Survey (Hobbs and Goebel, 1982) reflected the knowledge of the glacial history of Minnesota up to that time. The following discussion is based largely on work by the above authors relative to the present study area.

The lobes of ice which repeatedly shaped the land surface of Minnesota were but small southern appendages (Figures 3,4) from the much larger Laurentide Ice Sheet (Flint, 1971). One of these, the Superior Lobe, advanced out of the Superior Basin not less than four times during
Figure 3. Postulated sequence of glacial-geologic events in west-central Minnesota (see text). A, pre-Wisconsin advance from the northwest depositing the Browerville (BT) and Kandiyohi (KT) tills; B, pre- or early-Wisconsin advance of the Superior Lobe depositing the Hawk Creek till in southwestern Minnesota and equivalent beneath the Wadena drumlin region; C, early- or mid-Wisconsin advance of the (Wadena) Rainy Lobe; D, St. Croix phase advance of the Rainy and Superior Lobes to the St. Croix moraine; E, retreat of the Rainy lobe and advance of the Superior Lobe; F, advance of the Des Moines Lobe from the northwest (modified from Goldstein, 1987, p. 10).
Figure 4. (A) St. Croix phase of the Rainy and Superior Lobes with formation of the Toimi Drumlin field and St. Croix Moraine; (B) Automba phase of the Superior lobe with formation of the Highland and Mille Lacs Moraines and development of Glacial Lakes Aitkin I and Upham I; (C) Nickerson-Alborn phase of the Superior and St. Louis Sublobes, respectively; (D) Formation of Glacial Lakes Aitkin II and Upham II (modified from Wright, 1972b, pp. 521-522).
the Pleistocene Period. The earliest advance (Figure 3B), which
deposited the red-brown Hawk Creek Till, reached as far as southwest
Minnesota in mid-Pleistocene time (Matsch, 1972). Following the
stagnation of this ice, the (Wadena) Rainy Lobe advanced out of the
northwest (Figure 3C) and deposited the yellow-brown Granite Falls Till
in southwestern Minnesota (Matsch, 1972; Goldstein, 1987). This advance
is also responsible for the formation of the Alexandria Moraine complex
as well as the fan-shaped Wadena drumlin field.

Approximately 20,000 yrbp (Wright and others, 1973), the Superior
Lobe again moved out of the Superior Basin in the St. Croix phase. The
Rainy Lobe advanced contemporaneously with and adjacent (to the north)
to the Superior Lobe and together, formed the St. Croix moraine system
in central Minnesota (Figures 3D, 4A). The Superior Lobe in this phase
deposited a red sandy till, included in the Lower Cromwell Formation,
while the Rainy Lobe deposited the brown, sandy and bouldery,
Independence Till of the Sullivan Lake Formation (Wright and others,
1970; Gross, 1982). The Independence Till makes up only 7% of the
surficial sediment in the study area, although it locally underlies all
younger deposits. It is exposed as a carapace of subglacial meltout
till on drumlins of the Toimi Drumlin field.

With the deglaciation of the St. Croix phase, ice again moved out of
the Superior Basin in the Automba phase, only this time the Superior
Lobe moved in a more westerly direction, while the Rainy Lobe advanced
to the Vermilion Moraine in northeastern Minnesota (Figures 3E, 4B).
Wright (1972b) theorized that the Superior Lobe must have been a much
thicker body of ice than the Rainy Lobe and thus advanced to a more extended position. He also hypothesized that absence of Rainy Lobe ice moving adjacent to the Superior Lobe allowed for a more westerly course taken by the latter.

The Upper Cromwell Formation is the name given to include the red, silt-rich till deposited by the Superior Lobe in the Automba phase (Wright and others, 1970). This till, exposed mostly in the massive Highland Moraine, is the surficial unit in approximately 30% of the study area. This moraine marks the northern boundary, while the Milles Iacs Moraine in central Minnesota marks the western terminus of the Automba phase of the Superior Lobe (Wright, 1972b). No absolute dates have been published for this advance. However, based on dates obtained from the preceding St. Croix phase, and the following Split Rock phase, the Automba phase is thought to have occurred approximately 18,000 yr BP (Wright and others, 1973).

As Automba phase ice melted, the Highland Moraine acted as a dam and water was ponded to form Glacial Lakes Upham and Aitkin II (Figure 4B) (Wright, 1972b; Hobbs, 1983). Deposits of a later ice advance across this area are rich in red clay, giving evidence for this glacial lake event (Baker, 1964).

After retreat of the Automba phase ice, the Superior Lobe again advanced, this time in the Split Rock phase (Wright and others, 1973). Ice of the Split Rock phase, which did not move as far out of the Superior Basin as earlier advances, deposited a clayey till named the Barnum Till (Baker, 1964). The clayey texture is ascribed to erosion of
glacial lake sediment deposited in the Superior Basin following the Automba ice wastage. Lannon (1986), however, questioned the existence of a Split Rock phase. He believed the "Barnum Till" to be a supraglacial facies of the Automba phase. Radiocarbon dates estimate the time of advance of the Split Rock phase at 16,000 yrbp (Wright and others, 1973).

The final advance of the Superior Lobe, the Nickerson phase, deposited a red, clay-rich till and formed the Thomson-Nickerson Moraine system southwest of Duluth (Wright, 1972b). The Des Moines Lobe was also active at this time and sent the St. Louis Sublobe through a narrow passage near Grand Rapids on the southwestern end of the Mesabi Range, in the Alborn phase, reaching almost as far as the Superior Basin (Figure 4C) (Baker, 1964; Hobbs, 1983). This sublobe terminated in a broad body of ice which spread south to the Mille Lacs Lake area, north to the Giants Range, and east to the Highland Moraine (Wright, 1972b).

In the study area, deposits of the St. Louis Sublobe lap up onto the northern flank of the Highland Moraine and bury the western edge of the Toimi Drumlin field. Approximately 60% of the study area is covered by till or wave-washed sediment attributed to the St. Louis Sublobe and its after effects.

Two different tills represent deposition by Alborn phase ice. A gray (yellow when weathered), sandy till, rich in Paleozoic limestone and Cretaceous marine shale, was derived from a northwestern source area. A red, clay-rich till, containing clasts of Superior Basin origin as well as northwest source rocks, indicates erosion of lake sediment
deposited in Glacial Lakes Upham and Aitkin I. Baker (1964) named the gray till Prairie Lake Till and the red till, Alborn Till. Both tills have since been grouped together as Alborn drift (Wright, 1972b). Absolute dates place the advance of the Alborn phase of the St. Louis Sublobe and the Nickerson phase of the Superior Lobe at approximately 12,000 years B. P. (summarized in Hobbs, 1983).

Following the stagnation of the St. Louis Sublobe, Glacial Lakes Upham and Aitkin II formed in northeastern Minnesota (Figure 4D) as did Glacial Lake Agassiz in northwestern Minnesota and Canada. The formation of these lakes is attributed to the final, large-scale retreat of the Laurentide Ice Sheet (Wright, 1971). The study area contains exposures of beaches and wave-washed sediment attributed to Glacial Lake Upham II. This lake stood at several different elevations (Hobbs, 1983) and received calcareous sediment eroded from deposits of the St. Louis Sublobe. Some of this sediment is exposed as rhythmites in the central portion of the lake basin. Final draining of the lake occurred through the St. Louis River approximately 9000 years ago (Hobbs, 1983).

Today, much of the study area is covered by peat, black spruce and tamarack forest, and lowland forest.
Classification, Terminology, and Origin of Glacial Sediments

Glacial sediment, including till, is formed and deposited by a wide variety of processes. The proglacial, subglacial, and supraglacial environments are complex and can be host to a wide variety of sediment types. Many workers have described and classified sediments in these environments based on their genetic, textural, or stratigraphic characteristics (Boulton, 1968; 1971; Andrews, 1970; 1971; Goldthwait, 1971; Dreimanis, 1971; 1982; 1988; Francis, 1974; Lawson, 1981). The latest classification by Dreimanis (1988) is shown in Figure 5 and is based on the depositional environment of till.

The term till is defined by the International Union for Quaternary Research (INQUA) as "a sediment that has been transported and deposited by or from glacier ice, with little or no sorting by water" (Dreimanis, 1982). For several discussions on the terminology used for glacial deposits and their landforms, see the final report of the INQUA Commission on Genesis and Lithology of Glacial Deposits (Goldthwait and Matsch, 1988). Following is a brief description on the origin and characteristics of certain sediments associated with glaciers.

Subglacial tills form beneath glaciers either by lodgement or basal meltout (Boulton, 1971). Lodgement till is sediment released in the zone of traction between moving ice and the glacier bed by either pressure melting against bedrock or by basal drag. Basal meltout till is sediment released in the basal debris-rich area by the melting of supporting ice. Melting can occur beneath an active or stagnant ice
Figure 5. Genetic classification of till (from Dreimanis, 1988, p.36).

<table>
<thead>
<tr>
<th>I. ENVIRONMENT</th>
<th>II. POSITION</th>
<th>III. PROCESS</th>
<th>IV. TRANSPORT</th>
<th>V. DERIVATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLACIOTERRESTRIAL</td>
<td>ICE MARGINAL</td>
<td>LOWERING OF SUPRAGLACIAL DEBRIS</td>
<td>SUPRAGLACIAL</td>
<td>SUPRAGLACIAL-EXOGENOUS</td>
</tr>
<tr>
<td></td>
<td>SUPRAGLACIAL</td>
<td>MELTING OUT</td>
<td>ENGLACIAL</td>
<td></td>
</tr>
<tr>
<td>GLACIOAQUATIC</td>
<td>SUBGLACIAL</td>
<td>SUBLIMATION</td>
<td>BASAL (IN ICE)</td>
<td>SUBGLACIAL</td>
</tr>
</tbody>
</table>

**NOTE:** Each vertical column is independent from the other four, and no correlation horizontally is implied. Only some combinations are feasible. The process of deposition (Column III) includes also some transport immediately prior to the deposition.
sole. Both lodgement and basal meltout tills share similar characteristics, including: (1) intense consolidation; (2) clasts typical of local bedrock; (3) the presence of sand stringers along shear planes; (4) strong fabric parallel to ice flow direction (with long axes dipping up-glacier); and (5) fissility (Boulton, 1971; 1979b). Basal meltout till is not usually as compact as lodgement till, nor does it have as strong a fabric development due to reorientation during the meltout process. Lodgement till quite commonly contains shaped "bullet" boulders, which are small-scale roches moutonnees embedded in the till (Boulton, 1978).

Supraglacial tills form on top of glaciers by direct accumulation from debris sources above the ice (i.e., valley sides, nunataks), and by meltout of englacial debris. The latter may be concentrated by movement along shear planes in the compressive marginal zone of the glacier (Boulton, 1979a). The melting process releases the englacial and supraglacial material from its supporting ice and concentrates it as a cover of sediment on the glacier surface. If the sediment melts out in place and is not transported by water, it is called supraglacial meltout till. Flowtill is sediment melted out in an unstable supraglacial environment and transported downslope by water and gravity, much like a mudflow (Boulton, 1968).

Supraglacial meltout tills are commonly coarse in texture due to removal of fine material by water. They have moderate compactness and poor fabric development, display more variation in rock type, contain occasional bands of stratified debris (Boulton, 1979a). Flowtills are
remobilized bodies of sediment which have poorly to moderately developed fabric and are usually associated with stratified glacioaqueous sediments (Boulton, 1979b).

A large volume of sediment associated with glaciers is sorted and stratified by the action of water. The rock material is eroded by glacial meltwater directly from bedrock or from debris-laden glacier ice and transported in a supraglacial, englacial, subglacial or proglacial position (Shreve, 1972; Gustavson and Boothroyd, 1986). Two different systems are responsible for these deposits: the glaciofluvial system which erodes, transports, and deposits sediment; and the glaciolacustrine system which primarily traps sediment received from the glaciofluvial system.

Proglacial fluvial deposits are expressed as outwash fans, pitted and non-pitted outwash plains, and valley trains. Subglacial deposits occur as eskers and kames. Tunnel valleys are geomorphic features which represent intense erosion by meltwater in the subglacial environment.

Fine-textured lacustrine deposits form in both the supraglacial and proglacial environments. In the supraglacial environment, lake sediments are deposited in depressions (kettles) on the stagnant ice surface fed by supraglacial streams. Proglacial lakes form during and after ice stagnation and can be dammed by ice and topography. These lakes receive sediment and meltwater from the melting ice (Ashley, 1988).
Glaciotectonics

The study of glaciotectonic structures is a relatively new field of glacial geology and much work has been done recently to investigate their relationship to glacier movement and the origin of geomorphic features (Moran, 1971; Banham, 1977; Ruszczynska-Szenajch, 1980; Aber 1985; 1988; Croot, 1987a; 1987b;). Clayton and Moran's (1974) glacier model consisting of a frozen marginal zone and an unfrozen inner zone has been used by most workers to explain the position of glaciotectonic structures in relation to ice movement (Boulton, 1979a; Haeberli, 1981; Clayton and others, 1980; Moran and others, 1980; Bluemle and Clayton, 1984).

The majority of glaciotectonic features are large-scale structures associated with marginal zone sediments and represent thrusting events in the frozen, compressive, outer zone of the glacier (Boulton 1970a; 1970b; Moran, 1971; Banham, 1975; Berthelsen, 1979; Croot, 1987b). Large thrust fault systems, stacked thrust slices, and intensely folded sediments are features associated with the marginal zone area. Owing to their large scale, these features can be expressed geomorphically as large and small composite (thrust) ridges, cupola hills (stagnation-type topography), flat-lying megablocks, and hill/hole pairs (Aber, 1988). The formation of most of these features, especially hill/hole pairs, is aided by permeable sediments lying above an aquifer system. An excessive pore pressure builds up in the subglacial material which causes the material to be thrust up. This creates a hole and the sediment is
deposited down-glacier as a hill (Bluemle and Clayton, 1984). Folds and
faults can be seen within the strata making up these geomorphic features
(Boulton 1970a; 1970b; Moran, 1971; Kruger and Humlum, 1979).

Deformational structures which do not have a geomorphic expression
are much smaller in scale and represent folding and shearing events
behind the marginal zone of compression (Billings, 1972; Berthelsen,
1979; Lavrushin, 1980). Increased temperature and water content cause
an increase in pore pressure and thus a decrease in the shear strength
of the basal sediment (Banham, 1975; Boulton, 1979a). Recumbent folds,
drag folds, minor thrust faults, and boudinage structures are features
representative of thick ice sliding over sediments in the inner glacier
area. Commonly, ground moraine contains glaciotectonic features which
reflect the dynamic movement of glaciers (Lavrushin, 1970).

Banham (1975) classified glaciotectonic structures as "within till"
(endiamict), and "within sequence" (exodiamict). Endiamict structures
are small-scale features, while exodiamict structures can contain large
masses of thrust-faulted bedrock (megablocks) and form massive terminal
moraines (Ruszczynska-Szenajch, 1980).

Much work has also been done recently on glacier beds composed not
of lithified bedrock but of soft deformable sediment (Boulton, 1975;
1979a; 1979b; Ethelmeyer and Zhangxiang, 1987). Although the majority
of modern-day glaciers are moving over rigid bedrock, lobes of ice
extending from Pleistocene ice sheets advanced over non-cohesive
sediments. It has been shown that these sediments can be easily
deformed and eroded by increased ice thicknesses, accompanied by the
geologically rapid formation of subglacial landforms. Due to their non-cohesive nature, these sediments are sheared by and move subglacially with the overlying ice (Boulton, 1979a). Ethelmeyer and Zhangxiang (1987) showed that up to 80% of glacier movement is taken up by these beds of deformable sediment and that the effective glacier bed is somewhere below the ice/debris interface. Other work has suggested that temperature is the most important factor in determining the relative ease of deformation in this basal debris-rich zone (Banham, 1975). Sediment under high pore water pressure as well as frozen sediment is slightly easier to shear and thrust as blocks by overriding ice (Mackay and Matthews, 1964).

Other glaciotectonic features are associated with stagnant ice and include normal and reverse faults (McDonald and Schilts, 1975). Folds and faults developed subglacially and proglacially during ice movement can be destroyed by melting of interstitial ice during the stagnation process (Berthelsen, 1979).

As ice advances over an area of non-cohesive, erodible sediment, thrusting and stacking of sediment slices, assisted by buried aquifer systems, takes place in the marginal frozen zone of compression. As the ice advances, pore pressure is elevated by an increase in water content and ice thickness in the inner zone of the glacier. This causes the basal sediments and previously formed thrust packages to deform by shearing and folding. The final assemblage of glaciotectonic features includes thrust stacks and large folds in the terminal area and smaller recumbent folds, thrust faults, and boudinage structures indicative of
the inner zone. The sediments can then be further deformed by normal and reverse faults as the glacier stagnates and ice is melted from its sediment-supporting position.
LATE-WISCONSIN STRATIGRAPHY

Sullivan Lake Formation

General Characteristics

The earliest Late-Wisconsin ice advance affecting the study area deposited the gray-brown Independence Till during the St. Croix phase of the Rainy Lobe (Wright, 1969). This ice is responsible for forming drumlins of the Toimi Drumlin Field and the northern portion of the St. Croix Moraine in central Minnesota. Wright (1969) placed the minimum absolute age of the Independence Till at older than 16,000 years based on a radiocarbon date of basal organic lake sediments associated with a younger glacial phase. However, lake sediments in an interdrumlin depression of the St. Croix phase place this advance at 20,500 ± 400 yr bp (Wright, 1973). This date most likely represents the age of the St. Croix phase.

Based on numerous exposures of gray (unoxidized) to brown (oxidized) till and associated outwash near Sullivan Lake in Lake County, northeastern Minnesota, Gross (1982) reclassified and named deposits of the Rainy Lobe in the St. Croix phase the Sullivan Lake Formation. The Independence Till Member is retained in this study and refers only to the till of this advance. Very few exposures of the Sullivan Lake Formation are present in the primary study area, as it makes up only 7% of the surficial geology; however, it is assumed to underlie all younger
deposits.

Three types of glacial sediment are present: a subglacial till facies, a proglacial outwash facies, and an esker facies. Geomorphic features related to the Rainy lobe in the St. Croix phase include drumlins comprised mainly of till, eskers associated with tunnel valleys, and interdrumlin depressions underlain by outwash sands and swamp deposits. These landforms are partly modified by erosion and deposition of later advances.

Texture and Composition

Pipette analyses of till matrix (<2.0 mm) from samples at 5 separate localities yielded an average sand/silt/clay ratio of 62/32/6 (Figure 6).

Grain counts of cobble-, pebble-, and sand-sized clasts are presented numerically in Figure 7 and graphically in Figure 8. Clasts of cobble size are dominantly composed of granite and gabbro with lesser amounts of basalt and rhyolite. The pebble size fraction is dominated by clasts of basalt and granite with minor amounts of gabbro. The coarse sand fraction contains mostly granite and basalt with lesser amounts of quartz, gabbro, granophyre, rhyolite, and metamorphics. The difference in composition between clasts of different sizes is due to the breakdown of rock fragments into their constituent mineral components (Dreimanis and Vagners, 1971). Counts of cobble- and pebble-sized clasts have been used by many workers and, although
Figure 6. Grain size distribution of the Independence Till.
<table>
<thead>
<tr>
<th></th>
<th>Cobble 64-256 mm</th>
<th>Pebbles 2-64 mm</th>
<th>Coarse Sand 0.5-2 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basalt</td>
<td>6</td>
<td>62</td>
<td>54</td>
</tr>
<tr>
<td>Gabbro</td>
<td>14</td>
<td>14</td>
<td>31</td>
</tr>
<tr>
<td>Granite</td>
<td>18</td>
<td>47</td>
<td>80</td>
</tr>
<tr>
<td>Rhyolite</td>
<td>6</td>
<td>10</td>
<td>32</td>
</tr>
<tr>
<td>Granophyre</td>
<td>0</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>Metamorphics</td>
<td>2</td>
<td>11</td>
<td>39</td>
</tr>
<tr>
<td>Slate</td>
<td>4</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Limestone/Shale</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Quartz</td>
<td>0</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Feldspar</td>
<td>0</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>Opaques</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Other</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>50</td>
<td>150</td>
<td>330</td>
</tr>
</tbody>
</table>

Figure 7. Cobble, pebble, and coarse sand composition of the Independence Till.
Figure 8. Bar graph showing the composition of cobble, pebble, and coarse sand fractions, given in Figure 7.
somewhat undiagnostic in contact areas, these data help to determine provenance areas as well as erosional, transportational, and depositional characteristics of glacier ice (Arneman and Wright, 1959; Matsch, 1972). The composition of the rock material above is indicative of bedrock in northeastern Minnesota and along the North Shore of Lake Superior, the provenance area of the Rainy Lobe.

Results of petrographic work are shown in Figure 9. Rock fragments of the North Shore Volcanic Group average 22%; fragments of the Duluth Complex average 15%; and fragments from northern Minnesota and the Canadian Shield average 19%. These data also indicate erosion of bedrock cropping out inland of and along the North Shore as well as rocks within the Canadian Shield by ice of the Rainy Lobe.

Clast Morphology

The roundness of stones has been used by some workers to determine relative transport paths through ice (Bergersen, 1974; Boulton, 1978). Roundness is a factor of composition as well as transportation. Stones transported supraglacially and englacially should be less rounded due to lower concentrations of debris and thus fewer impact events. Additionally, supraglacial sediment is subjected to frost shattering (Boulton, 1978). Subglacially transported debris should be more rounded due to a higher volume of clastic material near the base of the ice and thus more abrasion.

Pebble counts done throughout the study area included the
Figure 9. Bar graph showing Independence Till composition obtained from point counts of 4 thin sections. Approximately 700 points counted for each section.
observation of whether the stones were subrounded or rounded. No site
where a pebble count was done contained less than 75% rounded stones. A
much more detailed analysis with numerical measurements would be needed
to draw any distinct conclusions from pebbles in the study area
concerning their transport paths through glacier ice.

Clay-Size Mineralogy

X-ray diffractograms of clay (<0.002 mm) obtained at the
Independence Cut are shown in Figure 10. Three samples, one untreated,
one glycolated, and one heated, were analyzed to determine the clay
mineralogy as described by Carroll (1970).

The diffractogram of untreated clay shows major peaks which
correspond to quartz [(101) at 3.34Å (angstrom)] and feldspar [(040)
and (002) at 3.2Å] and minor peaks which correspond to quartz [(100) at
4.25Å], illite/mica [(001) at 10Å] and possibly kaolinite [(001) at 7.1Å
and (002) at 3.5Å].

The glycolated sample was heated at 60 degrees Celcius for one hour
in a dessicator with ethylene glycol and then analyzed. It was
determined that no montmorillonite or any other expandable clays were
present due to the absence of a major peak at 12.7Å. The quartz and
feldspar peaks remained unchanged and the illite/mica peak at 10Å
anomalously disappeared.

The third sample was heated to 550 degrees Celcius for one hour and
then analyzed. This treatment destroys any kaolinite peaks and should
Figure 10. X-ray diffractograms of clay fraction from Independence Till. M/I is montmorillonite/illite; K is kaolinite; Q is quartz; and F is feldspar.
shift the montmorillonite peak to 9A. If chlorite was present, it may be destroyed and the illite/mica peak should intensify.

Although analyses of this clay were done several times, the results were less than expected. Quartz and feldspar are definitely represented in the clay fraction. Illite/mica is probably present but anomalously disappears in the glycolated and heated diffractograms. Kaolinite is another possible constituent of the clay and, although poorly represented in the untreated and glycolated diffractograms, it is absent in the heated diffractogram as it should be. Similar results were obtained by Horberg and Potter (1955) where quartz becomes the dominant component of the material <0.25 mm and quartz and illite dominate the clay fraction.

Color

Oxidized subglacial Independence Till is brown with a Munsell color of 10YR 3/3. In its unoxidized state, the till is more gray with a Munsell color of 10YR 4/2. The color and composition of till are directly related to the type of bedrock overridden by the glacier (Dell, 1975; Arneman and Wright, 1959).
Site Specific Characteristics

Independence Cut

In the summer of 1987, the MDOT was constructing an offramp from Highway 53 to Highway 33 South (SE1/4, SW1/4, S26, T52N, R17W, Independence Quadrangle). A cut was made in the side of a drumlin in the Tolim Drumlin Field and exposed approximately 4 feet of till overlying 6 feet of sorted and stratified sand (Figures 11 and 12). The till is compact, exhibits crude fissility, and contains a high percentage of pebbles and boulders in a sandy matrix (sand/silt/clay ratio of 52/41/7). Lenticular bodies of medium sand up to 10 inches in length and 0.5 inches thick are enclosed within the till.

Figure 13A is a plan view of the Independence Cut showing the oblique orientation of the exposure with respect to the drumlin axis. Pebble fabric was measured in 3 areas of the exposure and is shown stereographically and in rose diagram form (Figure 13B,C). The fabric represents a fairly strong N-S orientation which differs from the drumlin axis orientation by 40 degrees or more.

This till is considered to be a subglacial meltout till because of its high degree of compactness, strong fissility, presence of sand stringers (representing shear planes), strong fabric, and the absence of shaped clasts ("bullet boulders") typically produced during lodgement (Boulton, 1978).

The sand exposed beneath the till in the Independence Cut is brown,
Figure 11. Reproduced portion of the Independence Quadrangle showing location of the Independence Cut. Note the NE-SW drumlin orientation. Scale 1:24,000.
Figure 12. View of the Independence Cut showing Independence Till over stratified and sorted sand of the Sullivan Lake Formation. Located at SE1/4, SW1/4, Section 26, T52N, R17W (Independence Quadrangle).
Figure 13. Diagram of a Toimi Drumlin, oriented N40E-S40W. a, b, and c represent locations in the Independence Cut where fabric was measured. The stereographs (which show the dip of elongated stones) and rose diagrams show the fabric measured at each of the 3 locations. Note the steep dip of the stones in a down-ice direction in 13B.
medium-grained, well sorted, and contains abundant cross-beds (Figure 14). The contact between this unit and the till is sharp and undulating, except for boulders at the base of the till that penetrate into the sand at the contact.

The fine sand fractions of both the sand and the till were examined under a binocular microscope to determine the source of the sand relative to the till. Both were found to contain 35-40% quartz. This is evidence that the lower sand unit and the till have a similar source and that the sand was probably deposited by the same advance.

One interesting characteristic of the basal sand unit is a lag-type concentration of biotite on the crest of each crossbed and partway into the lee-side trough (Figure 14). These fragments most likely originated from the breakdown of rocks into their separate mineral components by the movement of glacier ice. This lag of biotite is characteristic of a fluvial-delta environment but can also be found associated with wind-deposited sand (Sharpe, 1963; Evans, 1962). The possibility that the Rainy lobe advanced over a series of eolian dunes is poor due to the thickness of exposed cross-beds and the abundance of meltwater associated with glaciers. It is more plausible that the cross-bedded sand unit was proglacially deposited in a low gradient braided stream system subsequently overridden by the ice.

Recumbent folds and normal faults are exposed in the sorted and stratified sands immediately below their sharp contact with the overlying Independence Till (Figures 15 and 16).

The recumbent folds are endiamict structures (within till) and are

39
Figure 14. Close-up view of Independence Cut showing faults, and bedding of mafic-rich layers within sand beneath the Independence Till.
Figure 15. Normal faults developed within sand below Independence Till at the Independence Cut.
Figure 16. Recumbent folds developed within sand below the Independence Till at the Independence Cut.
well-developed. The trends and plunges of 25 fold axes were measured and are shown plotted stereographically in Figure 17. Kruger and Humlum (1979) document fold axes oriented normal to ice flow direction. The fold axes in Figure 17 are generally perpendicular to the orientation of the Toimi Drumlins and thus represent ice flowing in a NE-SW direction.

Figure 18 shows folded beds of sand located below the recumbent folds. These structures are not as highly deformed and probably represent an area of decreased deformational stress.

The Rainy Lobe must have been thick enough at this location to have reached its pressure melting point and thus be a source for water in the basal sediment. This water was under high pressure which decreased the shear strength of the underlying sand. This, combined with the glacier movement, allowed the formation of recumbent folds in the upper layers of the sand. Similar fold structures have been produced beneath scale models of glaciers with thrust structures forming in the front of the model (Kupsch, 1962). The presence of semi-folded beds of sand beneath these recumbent folds indicates the deformable nature of non-cohesive material beneath glacier ice.

One additional feature to notice in Figure 16 is the "necking" of sand layers between the recumbent fold packages. This relationship gives the appearance of boudinage structures, another feature indicative of shearing beneath an active glacier (Berthelsen, 1979).

Normal faults are also present in the stratified and sorted sands at the Independence Cut (Figures 15 and 19). These faults have an offset of as much as 4 inches and the fault traces are as long as 2 feet. The
Figure 17. Stereographic plot of fold axes and poles to fault planes measured in sand at the Independence Cut. The drumlin axis is oriented N40E-S40W, the approximate orientation of poles to fault planes and perpendicular to fold axis orientation.
Figure 18. Folded beds of sand below Independence Till at the Independence Cut.
Figure 19. Close-up view of normal faults developed in sand beneath an embedded boulder at the Independence Cut.
strikes and dips of 25 fault planes were measured and are shown plotted stereographically in Figure 17.

Whether the normal faults formed during active glacier flow or during stagnation is difficult to determine. Their extensional nature could indicate overlying stagnant glacier ice causing melting of interstitial supporting ice in the pore spaces of the sand and subsequent differential settling.

Normal faults are also exposed beneath boulders which have been pressed from the till into the underlying sand by the weight of the glacier (Figure 19).

Other Exposures

Two other exposures of subglacial till of the Sullivan Lake Formation were investigated, one at the Independence Cemetery (SE1/4, SW1/4, NW1/4, S27, T52N, R17W, Independence Quadrangle), the other near the intersection of St. Louis County (SLC) road 847 and Highway 2 (NE1/4, NW1/4, NW1/4, S6, T50N, R18W, Martin Lake Quadrangle).

The exposure near the Independence Cemetery contains a lower unit of brown (10YR, 3/4) sandy till. It is very compact, unsorted, unstratified, and a minimum of 2 feet thick. It contains a large percentage of stones and is very sandy with a sand/silt/clay ratio of 68/28/4. Above this and in sharp contact is approximately 18 inches of well sorted, medium sand interstratified with finer sand and pebbles. This sandy unit is in very sharp contact with an overlying reddish
clayey till related to the younger St. Louis Sublobe. A large granite boulder, emplaced during a later advance, is exposed at this contact and has deformed the stratified sandy unit.

The till at this exposure is interpreted to be a subglacial meltout till due to its unsorted, unstratified nature as well as color and high degree of compactness. The sandy unit above the till likely originated as outwash from wastage of the Rainy Lobe although it is possible that this sand was remobilized by the advance responsible for depositing the red clayey till.

The exposure at the intersection of SLC road 847 and Highway 2 is very similar to that described above. The lowermost unit is a brown (10YR, 4/3) till, which is sandy (sand/silt/clay ratio of 61/32/7), unsorted, and unstratified. Fabric measured from the large percentage of stones is weak with a general orientation of NE-SW. Within this till are rare, thin lenses of fine to medium sand. Directly above this till, in sharp contact, is red clayey till.

This exposure is located further west into the area modified by a later advance. The brown sandy till is interpreted to be a subglacial meltout till deposited by the Rainy Lobe. The red clayey till was deposited by the later advance.

Interdrumlin outwash of the Sullivan Lake Formation is exposed in the northeast corner of the study area south of Schelin Lake (SE1/4, NE1/4, S31, T52N, R17W, and SE1/4, NE1/4, S32, T52N, R17W, Alborn Quadrangle). Large boulders of greenstone, gabbro, and granite, measuring up to 3 feet in length, make up the base of these exposures.
The boulders have been rounded and are set in a poorly sorted matrix of cobbles, pebbles, and sand. Above this poorly sorted unit in moderately sharp contact is approximately 1.5 feet of sorted and poorly stratified medium to coarse sand.

The graded nature of these exposures, with boulders at the base and sand at the top, indicates water melting from a rapidly retreating glacier. This would allow for the deposition of large clasts by fast moving water melted from nearby ice. Finer sediment would be deposited by slower moving water as the glacier retreated to a more distant position.

A cap of fine sand or silt, yellowish in color, rests in sharp contact above the sand unit. It is 6-8 inches thick and possibly represents a period of loess deposition documented by Wright (1969).

Areal Geology

After the advance of the Rainy Lobe in the St. Croix phase, the Sullivan Lake Formation is believed to have been the surficial geologic unit covering the study area. Due to deposition of sediment related to later advances, less than 10% of the study area contains the Sullivan Lake Formation as the surficial unit. Palimpsest drumlins and eskers formed by this advance can be seen topographically throughout the study area.

The boundary between the Sullivan Lake Formation and formations deposited later is based in part on the interpretation of ice marginal
features related to these later advances. These features include collapsed outwash and outwash deposited in low proglacial areas. Interruptions in topography and morphology also aided in the location of the formation boundary and relate to the deposition of terminal moraines of both the Superior Lobe and the St. Louis Sublobe.

Geomorphology

Drumlins

The Independence Till Member of the Sullivan Lake Formation is exposed in the form of drumlins of the Toimi Drumlin Field. They have an average relief of 40 feet and are 1-1.5 miles in length. The drumlins have an average orientation of N40E and thus suggest formation by ice moving in a NE-SW direction. Their presence is expressed topographically to the southwest where they are buried beneath younger glacial sediments.

Drumlin Formation

The genesis of drumlins has been a subject of debate for many years (Muller, 1974; Menzies, 1984; Stanford and Mickelson, 1985; Shaw and Sharpe, 1987). Models range from wholly depositional to wholly erosional. The only clear consensus is that they are formed beneath active glacier ice.
The bases of the ice lobes which advanced across mid-North America have been modelled as having a frozen margin and an unfrozen interior (Clayton and Moran, 1972; 1974). Quarrying and divergent flow dominate the marginal (frozen) zone, while sliding, abrasion, convergent and horizontal flow dominate the interior (unfrozen) zone. Additionally, in the inner zone a thin film of water, produced by basal ice warming to the pressure melting point by geothermal heat and heat of friction, separate the ice from the bed. This allows the glacier to slide more easily over the bed surface (Weertman, 1979).

The inner unfrozen zone is the area of formation of many subglacial landforms (Clayton and Moran, 1974; Muller, 1974; Aario, 1977a; 1977b; 1977c; Moran and Clayton, 1980). Assemblages of these geomorphic features represent zones in the basal ice, with flutings forming the inner zone, drumlins in the intermediate zone, and Rogen landforms and other ice contact features representing the marginal zone. Estimates on the time required to form drumlins is on the order of 100 to 200 years (Goldthwait, 1974; Aario, 1977a) but is dependent on the nature of the glacier’s substrate, that is, bedrock or soft sediment. Boulton (1979a) has done considerable research concerning beds of deformable sediment beneath glacier ice. He suggests that because such sediment is soft compared to the ice, it deforms readily to form streamlined features. If the sediment is heterogeneous, larger rock fragments can act as drumlin nucleation sites. Sediment is then deposited down-glacier from the nucleating center and is streamlined.

The drumlin investigated at the Independence Cut formed under the
ice and most likely by ice at the pressure melting point operating in both erosional and depositional modes. Aario (1977a; 1977b) hypothesized differential flow velocities for basal ice where erosion is accelerated by high velocity and deposition is favored in areas of lower velocity. Erosion creates inter-drumlin troughs by fast horizontal flow and upward, helical (spiral) flow in the lateral areas of the trough, while deposition forms the drumlin proper. Material can be eroded from the adjacent trough, deformed beneath the glacier, and accreted in the inter-trough (drumlin) area.

Evidence for this deformable nature was seen at the Independence cut. Recumbent folds and lenses of sand, mentioned previously, provide evidence for this deformation. Additionally, five gabbroic stones were found in the till which fit together like a jigsaw puzzle into two larger stones. These were found in a one-square-foot area and were randomly oriented. This observation suggests a deforming bed dominated by strong shear forces prior to deposition. Brecciation of clasts in the final stages of till emplacement has been documented by Harker and Giegengack (1989).

Many workers have done fabric studies of drumlins to help determine the origin of these subglacial landforms. Muller’s (1974) studies indicate growth of drumlins by accretion of till. Andrews and Smith (1970) suggest till fabric is generated by flow within subglacial till and not at the ice/till contact, more evidence of a deforming bed. Stanford and Mickelson (1985) discovered that fabric in some drumlins is parallel to ice flow in the central area of the drumlin. The fabric
becomes almost perpendicular at the margins with long axes of the stones pointing away from the drumlin axis.

Figure 13 shows the oblique orientation of the Independence Cut through the drumlin margin. Although the fabric is subparallel to the drumlin axis, the long axes of stones are directed toward the drumlin axis, opposite from fabric measured by Stanford and Mickelson (1985). Another point to notice concerning the fabric measured at the Independence Cut is the steep down-glacier dip of the stones (Figure 11B). Stones generally dip up-ice, as concluded by Wright (1973).

Why the fabric is oriented in this particular direction is unclear. What is clear is that the fabric is strong and definitely related to subglacial ice movement. One possible explanation is that the fabric is a result of early formation (deposition) of the drumlin. Aario (1977a) suggests that once a drumlin is formed, it is difficult to destroy. Although this is likely the case, it seems plausible that the drumlin can migrate in a down-glacier direction. This would occur as material is eroded from the up-glacier end of the drumlin and deposited in the down-glacier area, a process similar to the migration of sand dunes. This would, in effect, cause the drumlin to migrate as well as change shape. Perhaps the fabric measured at the Independence Cut represents an earlier period in the formation of this drumlin when ice was moving in a slightly different direction. Another possibility is that the fabric recorded here is related to pre-existing till deposited by an earlier advance, an idea suggested by Shaw and Sharpe (1987).

In any case, many different types and observations of drumlins have
resulted in a multitude of theories on their origin and distribution. It should be noted that the data collected and presented above could represent one or many processes involved in the genesis of drumlins.

**Tunnel Valleys and Eskers**

A series of tunnel valleys is associated with wastage of the Rainy Lobe in the St. Croix phase (Wright, 1972). In the study area they are characterized by northeast-southwest trending valleys with underfit streams. Two of these drainageways can be recognized on topographic maps (NW1/4, S31, T52N, R17W, Alborn Quadrangle; S23, T51N, R19W, Brookston NW Quadrangle). The latter tunnel valley contains small discontinuous ridges of an esker in the valley bottom which emerge on the opposite side of the St. Louis River as a large esker. This esker is approximately 9 miles in length, 40 feet in height, and 1000 feet in width.

Another tunnel valley, identified by Baker (1964), contains the southwest-flowing McCarty River. This tunnel valley grades into a north-south trending esker which forms a confluence with the esker discussed above. These eskers terminate at Prairie Lake and have a cover of till from a younger glacial advance.

Wright (1972) suggested that the formation of eskers within tunnel valleys reflects a decrease in hydraulic head due to ice wastage and thinning and thus a switch from subglacial erosion of a tunnel valley to deposition of an esker.
General Characteristics

A sandy to silty, reddish-brown diamicton called the Upper Cromwell Formation (Wright and others, 1970) was deposited by the Superior Lobe in the Automba phase, which involved an advance out of the Superior Basin in a west-southwest direction as far as Mille Lacs Lake in east central Minnesota (Figure 3b). No datable material associated with this advance has been discovered. However, based on radiocarbon dates from surface organic deposits overlying the Cromwell Formation, which range in age from 16,100 yrBP to 13,500 yrBP (Wright, 1973), the Upper Cromwell Formation is thought to have been deposited approximately 18,000 yrBP.

Lannon (1986) investigated this formation near Duluth. He separated the drift into a subglacial and supraglacial facies based on degree of fabric development. There, both the supraglacial and subglacial facies have the same average sand/silt/clay ratio (30/43/27).

Supraglacial sediment is most commonly associated with an ice margin in continental glaciers because the marginal zone is dominated by upward flow and ablation which concentrate debris on the glacier surface. Therefore, when the glacier stagnates and melts, this supraglacial material becomes the dominant surficial deposit in the marginal area. Subglacial debris dominates the surficial geology of the inner zone, up ice from the margin.
Good exposures of subglacial material are rare owing to the huge volume of supraglacial material covering the area, and difficult to identify because textural differences are slight between subglacial and supraglacial debris in the study area. Reasons for these textural similarities and lithologic anomalies will be explained later. Degree of compactness, fabric development, and stratigraphic relationships were used to separate subglacial and supraglacial material.

Supraglacial Facies

The Upper Cromwell Formation is exposed as supraglacial till and associated outwash in the Brookston, Martin Lake, and Gowan (southern part) Quadrangles, where it comprises the western edge of the Highland Moraine. It lies stratigraphically above the Sullivan Lake Formation, for example in exposures on the west side of SLC Road 31 just north of the St. Louis River near Brookston (Wright and others, 1969).

The supraglacial environment is complex. Many workers have investigated sediment associated with active and stagnant ice surfaces and their depositional mode (Goldthwait, 1971; Boulton, 1971; 1972; Lawson, 1979; 1981; Wright, 1980). Most sediment in the supraglacial environment, with the exception of supraglacial meltout till, has been transported by water or gravity to areas of lower elevations. This sediment can insulate underlying ice, whereas ice without a sediment cover ablates readily. This process of differential melting creates kame and kettle topography and causes the repeated redistribution of
supraglacial sediment from high to low local elevations. The resulting deposits contain diamictons transported by gravity, characterized by their loose, sandy texture (removal of fine material) and weak to moderate fabric (Boulton, 1970b). Beds of water-sorted and deposited sand and gravel interlayered with flowtill, together with supraglacial lake sediments, are characteristic of the supraglacial environment of deposition.

**Texture and Composition**

Textural analyses of supraglacial till material 2.0 mm in diameter and finer yield an average sand/silt/clay ratio of 60/31/9 (Figure 20). The percentage of sand is only slightly higher than analyses of subglacial till.

Counts of cobbles and pebbles from supraglacial till are shown in Figures 21 and 22. The cobbles fraction contains mostly basalt, granite, and gabbro, with other clasts of rhyolite and red sandstone. Basalt and gabbro are the dominant pebble fragments with minor amounts of rhyolite, graywacke/ slate, and granite.

Petrographic point counts of thin sections made from supraglacial till are shown in Figure 23. Quartz and feldspar are the dominant mineral fragments, while clasts from the North Shore Volcanic Group and Duluth Complex make up the major rock fragment constituents. Other rock fragments include clasts from northern Minnesota and the Canadian Shield, red sandstone, and graywacke/slate. The high percentage of
Figure 20. Grain size distribution of the Upper Cromwell subglacial and supraglacial till facies.
<table>
<thead>
<tr>
<th></th>
<th>Subglacial</th>
<th></th>
<th>Supraglacial</th>
<th></th>
</tr>
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<tr>
<td></td>
<td>Pebbles 2-64 mm</td>
<td>Coarse Sand 0.5-2 mm</td>
<td>Cobbles 64-256 mm</td>
<td>Pebbles 2-64 mm</td>
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<td>7</td>
<td>14</td>
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<td>29</td>
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<td>7</td>
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<td>4</td>
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</tr>
<tr>
<td>Total</td>
<td>150</td>
<td>306</td>
<td>58</td>
<td>212</td>
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</table>

Figure 21. Cobble, pebble, and coarse sand composition of the Upper Cromwell subglacial and supraglacial till facies.
Figure 22. Bar graph showing composition of cobbles and pebbles from supraglacial till of the Upper Cromwell Formation, given in Figure 21.
Figure 23. Bar graph showing composition of supraglacial till of the Upper Cromwell Formation obtained from point counts of 5 thin sections. Approximately 3000 points counted.
quartz, the majority of which is rounded, is probably related to the erosion and abrasion of the Precambrian Hinckley Sandstone.

The unexpected number of rock fragments from northern Minnesota and Canada together with the sandy texture of the supraglacial (and subglacial) till is directly related to both the direction of ice movement of the Superior Lobe in the Automba phase and to the material making up the glacier bed.

With the stagnation and retreat of the Superior Lobe in the St. Croix phase, a proglacial lake formed in the western Superior Basin and fine hematite-rich sediment was deposited (Saarnisto, 1974). When the Superior Lobe readvanced in the Automba phase, it moved in a southwesterly direction. This allowed the erosion of lacustrine silts and clays along the central (axial) area of the glacier. Due to the orientation of this glacial advance, the northwestern flank had access to and eroded the previously deposited, sandy, Sullivan Lake Formation, with its constituent rock fragments. This hypothesis explains the silty texture of supraglacial till found in the proximal western Superior Basin as well as the sandy texture and presence of rock fragments from northern Minnesota and Canada found in the study area, a more distal portion of the ice.

Color

Supraglacial till of the Upper Cromwell Formation is red-brown with a Munsell color of 7.5YR 3/4.
Site-Specific Characteristics

The majority of the deposits of supraglacial origin are exposed in the Highland Moraine (Figure 24). They are generally composed of loose, sandy till with interstratified layers of sand and gravel. Supraglacial lake sediments are not uncommon, as at SW1/4, SW1/4, Section 3, T51N, R17W (Independence Quadrangle), where red, clay-rich material (sand/silt/clay ratio of 1/37/62) is exposed. The supraglacial meltout tills and flowtills are loosely consolidated and reddish-brown (Munsell color 7.5YR 3/4).

One exposure showing supraglacial material of the Upper Cromwell Formation is located at SE1/4, SE1/4, Section 11, T50N, R19W (Martin Lake Quadrangle). Exposed here is approximately 10 feet of moderately sorted and stratified diamicton interbedded with layers of sorted sand, pebbles, and cobbles (Figure 25). Contacts are moderately sharp. The diamicton has a sand/silt/clay ratio of 62/32/6 and is unconsolidated. Beds of sorted sediment, generally coarse sand, are 0.5 to 1.0 inches thick. This exposure was easily excavated and the sediment is not compact. Till clasts are not well embedded and the exposure is capped by up to 3 feet of leached and bioturbated material. Fabric measured at this location was determined to be moderately oriented (Figure 26A). A small normal fault, with approximately 3 inches of offset, was discovered in the lower area of this exposure (Figure 25).

The loose consolidation, associated sorted sediment, and moderate
Figure 24. Reproduction of the Martin Lake Quadrangle. Note the topography in the northwest quadrant (Sections 2, 3, 10, and 11) and the linear ridge in the southeast corner near Hardwood Lake (Sections 4 and 5). Scale 1:67,000.
Figure 25. Exposure of supraglacial material of the Upper Cromwell Formation at SE1/4, SE1/4, Section 11, T50N, R19W (Martin Lake Quadrangle).
Figure 26. (A) Rose diagram and stereographic plot of fabric measured in Upper Cromwell Formation supraglacial till shown in Figure 25. (B) Rose diagram and stereographic plot of fabric measured in Upper Cromwell Formation supraglacial till shown in Figure 27.
fabric are good evidence for a supraglacial origin. The fault was most likely produced during settling of the sediment.

Another exposure of supraglacial material is located at SE1/4, NW1/4, Section 32, T50N, R18W, Martin Lake Quadrangle. A gravel pit at this location contains up to 35 feet of stratified sand and pebbles exposed as kame-like features. Approximately 4-5 feet of till lies in the trough area between kames (Figure 27). This till is poorly to moderately sorted, contains an abundance of pebbles, and has a sand/silt/clay ratio of 60/32/8. It is also not compact, lacks jointing, and is faintly stratified. The contact between the till and underlying sediment is moderately sharp. Within the till are beds of well sorted, medium sand approximately 1-3 inches thick. Fabric measured in the till is poorly to moderately developed (Figure 26B).

Stratigraphic relationships, loose consolidation, weak to moderate fabric, and morphology of the surrounding area provide good evidence for a supraglacial origin.

Other notable exposures are located at SW1/4, NW1/4, Section 35, T51N, R18W (Brookston Quadrangle); NE1/4, SE1/4, Section 20, T51N, R17W (Brookston Quadrangle); SW1/4, Section 13, T50N, R19W (Martin Lake Quadrangle); and at center, Section 6, T50N, R17W (Brookston Quadrangle).

Subglacial Facies

As stated earlier, exposures of subglacial material are rare. A few
Figure 27. Exposure in gravel pit at SE1/4, NW1/4, Section 32, T50N, R18W (Martin Lake Quadrangle) showing kame-like features composed of stratified and sorted sediment with supraglacial till of the Upper Cromwell Formation in the trough area (behind pick-up truck).
gravel pits in the area contain deposits of subglacial till which generally overlies sorted and stratified sediment. The subglacial till in these exposures is fissile and displays a high degree of compactness, a feature noted also by Lannon (1986).

**Texture and Composition**

Textural analyses of subglacial material 2.0 mm in diameter and finer yield an average sand/silt/clay ratio of 57/34/9 (Figure 20).

Data from pebble counts are shown in Figures 21 and 28. This size fraction is dominated by clasts of basalt, gabbro, and graywacke/slate with minor amounts of rhyolite, red sandstone, and granite.

Coarse sand lithology, also shown in Figures 21 and 28, is similar to the pebble lithology and is rich in basalt, rhyolite, and gabbro, with lesser amounts of granite, granophyre, and graywacke/slate.

Data collected from point counts of thin sections of subglacial till are shown in Figure 29. Clasts of the North Shore Volcanic Group make up the highest percentage followed by clasts of the Duluth Complex, graywacke and slate, and bedrock types from northern Minnesota and the Canadian Shield. Red sandstone is present in minor amounts. Mineral fragments are mostly quartz and feldspar.

These lithologic data imply erosion of bedrock in and adjacent to the Superior Basin. Graywacke and slate fragments of the Thomson Formation are locally derived and generally increase in percentage from northeast to southwest, the general direction of ice movement.
Figure 28. Bar graph showing composition of pebble and coarse sand fractions from subglacial till of the Upper Cromwell Formation, given in Figure 21.
Figure 29. Bar graph showing composition of subjacent E12.

3 thin sections, approximately 2000 points counted.

Korth Shore Volcanic Group

<table>
<thead>
<tr>
<th>Material</th>
<th>Percent (%)</th>
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</thead>
<tbody>
<tr>
<td>Opaque</td>
<td>12</td>
</tr>
<tr>
<td>Feldspar</td>
<td>18</td>
</tr>
<tr>
<td>Quartz</td>
<td>8</td>
</tr>
<tr>
<td>Fond du Lac Sandstone</td>
<td>4</td>
</tr>
<tr>
<td>Winnipeg Formation</td>
<td>4</td>
</tr>
<tr>
<td>Minnesota/Canada Complex</td>
<td>16</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>28</td>
</tr>
</tbody>
</table>
Again, the relatively high percentage of rock fragments from northern Minnesota and Canada, together with the low percentage of red sandstone clasts, can be explained by the position of the investigated exposures with respect to the underlying bedrock and previously deposited drift.

Clay-Size Mineralogy

X-ray diffractograms of untreated, glycolated, and heated samples of clay (<0.002 mm) from subglacial till are shown in Figure 30. Composition is similar to that found in the Sullivan Lake Formation (Figure 10). The results are somewhat less anomalous with the exception of the absent mica/illite peak in the heated sample [(001) at 10A]. The diffractograms show quartz and feldspar are present in the clay fraction as well as a strong reflection from kaolinite [(001) at 7.1A and (002) at 3.5 A] in the untreated sample.

Color

Subglacial till of the Upper Cromwell Formation is red-brown with a Munsell color of 5-7.5YR 3/4, similar to the color of the supraglacial till.
Figure 30. X-ray diffractograms of clay fraction of subglacial till of the Upper Cromwell Formation. Symbols as in Figure 10.
Site-Specific Characteristics

Subglacial till associated with the Automba phase of the Superior Lobe is located at SW1/4, SW1/4, Section 3, T51N, R17W (Independence Quadrangle). Exposed in this gravel pit just east of the Cloquet River is reddish-brown till (7.5YR 3/4) overlying coarse outwash. Above the till is well-sorted red clay (5YR 3/4) capped by a thin layer of reddish till (5YR 3/4), stratified coarse outwash, and fine to medium sand. Contacts are sharp.

Beginning with the lowermost unit, the coarse outwash is a minimum of 20 feet thick and moderately sorted and stratified. Alternating beds of sand exist between beds of pebbles, cobbles, and boulders. This unit is uncohesive and excavated easily.

The till just above the outwash is 2-3 thick, poorly sorted, and has a sand/silt/clay ratio of 54/34/10. It is moderately jointed and contains numerous stones, some of which show striations. Fabric was measured in this unit and found to be strong with a NW-SE orientation.

The red clay overlying the till is approximately 3 feet thick, very well sorted, and has a sand/silt/clay ratio of 1/37/62. It is well jointed and easily excavated. Few stones are present.

The capping unit is approximately one foot of stratified and sorted beds of sand and pebbles, with a thin interbed of poorly consolidated, moderately sorted red till.

Based on the texture and composition of the units above, as well as the strong fabric in the till, this exposure contains evidence of both
subglacial and supraglacial deposition. The lower outwash unit was deposited beyond the margin of the Superior Lobe and was subsequently overridden. Subglacial till was deposited by ice moving in a SE to NW direction, indicated by the strong fabric, poor sorting, and consolidation. The clay unit above the till was likely deposited in a supraglacial lake on the surface of the stagnating glacier. The thin till layer and upper outwash were deposited during a later stage of ice stagnation.

Another exposure of subglacial material, complete with glaciotectonic features (folds and faults), is located at NW1/4, Section 34, T50N, R18W (Brookston Quadrangle). Figure 31 is a photograph of this exposure in a private gravel pit. Till overlying sand and gravel is up to 8 feet in thickness. It appears sandy and has a sand/silt/clay ratio of 59/31/10. The till is fissile, compact, and red-brown (7.5YR 4/4). The contact between the till and underlying sand and gravel is sharp, although occasional stringers of sand are incorporated into the basal layer of the till. There is a cap of leached and bioturbated material up to 3 feet in thickness. The till contains an abundance of stones and yielded the strongest fabric measured in the study area. Figure 32 is a stereographic and rose-diagram presentation of the fabric. Stones are generally flat-lying and are oriented in a NW-SE direction.

Below the till is as much as 12 feet of sorted sediment. This sediment is exposed as beds of well sorted and stratified sand interlayered with beds of moderately sorted sand and pebbles, and
Figure 31. Exposure showing subglacial till of the Upper Cromwell Formation in the NW1/4, Section 34, T50N, R18W (Brookston Quadrangle). Contact with lower folded and faulted sand and gravel is sharp.
Figure 32. (A) Stereographic plot of fabric obtained from subglacial till shown in Figure 31. (B) Rose diagram of fabric shown in (A) above. A strong NW-SE orientation is apparent.
cobbles. There is evidence of intense deformation within this lower unit in the form of folds and faults. Figure 33 is a sketch of this exposure showing the sedimentary units and probable structures. The structures, particularly the faults, were difficult to observe in three dimensions because of the loose nature of the sediments. The trend and plunge of 15 fold axes were measured and are shown in Figure 34. The orientation of these fold axes is perpendicular to ice flow and represents compressive deformation in the margin of the Superior Lobe. Similar fold axes oriented normal to ice motion have been documented by Hicock and Dreimanis (1985).

This exposure of glaciotectonic features also gives some insight into the deformable nature of the glacier bed. Most ice movement in glaciers overlying noncohesive sediment takes place within the sediment and not at the ice-bed interface (Boulton, 1979b). In the outer margin of the glacier, this ice is frozen to its bed and, although there is little sliding, both the bed and the glacier can deform by thrusting and folding (Boulton, 1970 a; 1970b).

This exposure is thought to represent formation in the basal debris-rich zone of the glacier. Intense ice pressure and active ice movement compacted the till and deposited it subglacially. Evidence for this is the very strong fabric. Although the Superior Lobe moved regionally in a NE-SW direction, the northwest flank moved laterally out of the Superior Basin perpendicular (SE-NW) to the general ice flow (Wright and others, 1969; 1973).

This hypothesis also explains the deformed nature of the underlying
Figure 33. Field sketch of sedimentary units and structures shown in Figure 31. The exposure revealed a complex fold relationship which appeared to converge and diverge. Vertically dipping beds of sand are present within this fold. Complex, fault-bounded, wedges of sand, not shown in this sketch, are located in the lower area of the exposure.
Figure 34. Stereographic projection of the trend and plunge of 15 fold axes measured at exposure shown in Figure 31. The orientation of the fold axes is perpendicular to ice movement (see Figure 32.)
sands and gravels. Boulton (1970; 1971) observed similar characteristics in subglacial tills and believes they form by either lodgement beneath an active glacier sole or subglacial melt-out from stagnant basal ice.

Areal Geology

The boundary between the Upper Cromwell Formation and sediment deposited by both earlier and later advances is based on the position of the Highland Moraine.

In the eastern portion of the study area, the Highland Moraine overlies sediment of the Sullivan Lake Formation. The boundary between the two formations can be recognized by a break in topography and a marked change in morphology. Further to the west-southwest, the boundary of the Upper Cromwell Formation is with sediment deposited by a later advance from the northwest. Here the boundary is more difficult to determine due to modification of the Highland Moraine by the St. Louis Sublobe. It is believed that the St. Louis Sublobe advanced onto the flank of the Highland Moraine and with stagnation, modified and "smoothed out" the Highland Moraine flank. The boundary in this area was traced based on field checks and the relative changes in topography caused by the later advance.
Geomorphology

Highland Moraine

The Upper Cromwell Formation is exposed partly as the massive Highland Moraine across the Brookston, Martin Lake, and Gowan Quadrangles. This extensive terminal moraine has up to 250 feet of relief and is characterized by kame and kettle topography (Figure 24). Some of the dome-shaped hills (kames) reach 1600 feet in elevation, while the kettles are marsh-filled or contain lakes. Martin Lake (Section 12, T50N, R19W) is less than 1/2 mile across but is over 70 feet deep. Numerous kettle lakes are present in the moraine as well as southeast flowing streams.

Adjacent and to the south, the Highland Moraine gives way to lower relief terminal and ground moraine. This area is characterized by rolling to hummocky topography with local relief of 70 feet or less. Shallow lakes are present as are extensive marsh areas dissected by small channels and streams.

Most of the topography within the Highland Moraine is randomly oriented with the exception of a linear asymmetrical ridge, discussed later, and drumlin-like features in the southwestern corner of the Martin Lake Quadrangle. The latter were included in the Automba Drumlins Field discussed by Wright and others (1969). These proximal drumlin-like features are 500-1000 feet in length, 100-200 feet wide, and 10-30 feet in height (Figure 24). Drumlins are exposed farther to
the south (center, Cromwell 15 minute Quadrangle) with approximately the same orientation.

Numerous features indicative of the dynamic interaction of ice and its bed are found associated with the Highland Moraine. To reiterate, continental glaciers, like the Superior lobe, are thought to have been frozen to the subglacial surface in the marginal area while being unfrozen from the bed in the axial, up-ice area (Clayton and Moran, 1974). This theory predicts the formation of folds and thrusts (compressional structures) in the marginal area and recumbent folds and boudins (shear features) forming in the axial, up-ice area. In the case of the Highland Moraine and associated geomorphic features, this deformational style was active on a much greater scale.

The exposure shown in Figure 31 is associated with a NE-SW oriented, asymmetrical, linear ridge approximately 4 miles long, 3/4 mile wide, and up to 80 feet high (Figure 24). In Carlton County farther to the southwest, the ridge grades into a series of hummocks which lie in a zone parallel to and northwest of Perch Lake. The ridge, lake, and hummocky zone are all parallel to the Highland Moraine and perpendicular to local ice movement. These orientations and associations represent some relationship between glacier processes in the marginal zone and development of geomorphic features.

This linear ridge has a steep down-glacier slope and a gradual up-glacier slope. This asymmetrical morphology is similar to push ridges discussed by Croot (1987b). The well-developed fabric (Figure 32) and the linearity of the ridge, however, suggest a subglacial
environment of formation. Aber (1988) suggests that these types of geomorphic features are small composite-ridges which form as crests of folds associated with deformation of soft subglacial sediment in the glacier margin.

The location of Perch Lake farther to the southwest, together with an irregular jumble of hills just to the northwest, provides further evidence for subglacial deformation. This association of features is similar to hill-hole pairs of Aber (1988) and Bluemle and Clayton (1984). When a glacier advances over impermeable sediment underlain by a zone of permeable sediment, water pressure can build up in the underlying material and blocks of the overlying impermeable material are thrust out and deposited downglacier as hills. Perch Lake represents a depression and the provenance area of the downglacier jumble of hills.

Other evidence related to the compressional nature of ice in the glacier margin can be inferred from the massive amount of material and high elevation of the Highland Moraine. Classical treatments of terminal moraines explain the moraine material as initially eroded from the valley side walls and let down by melting ice as well as proglacial sediment buldozed by the nose of the glacier. The lobes of ice which advanced across mid-North America had no valley walls to erode (Wright, 1980). The terminal moraine material must have been largely derived subglacially and transported into a supraglacial and proglacial environment by upward ice flow and thrusting. Recent workers have hypothesized that many previously interpreted end moraines are made up of tectonically emplaced rafts or blocks of subglacially derived
bedrock and non-cohesive sediment (Bluemle and Clayton, 1984; Aber, 1985; 1988; Ruszczynska-Szenajch, 1987).

The relief of the Highland Moraine could simply be reflecting the underlying bedrock surface. A gravity map of Minnesota (Geology of Minnesota: A Centennial Volume, Plate 2; 1972) shows a gravity high in this vicinity. If there is significant bedrock relief here, the northwestern flank of the Superior Lobe would have been impeded. Such blockage could cause thrusting, erosion, and transportation of bedrock and subglacial sediment by ice flowing compressively against and over the bedrock high. This subglacial material would eventually be transported upward into a supraglacial position to be melted out later during stagnation.

Thus, the geomorphic features present in the northwest margin of this advance likely represent topographic expressions of glaciotectonic structures. The linear ridge located behind the Highland Moraine possibly represents a deforming subglacial environment where sediment was thrust and folded into a subglacial ridge. As an alternative hypothesis to the classical model of formation of terminal moraines, the Highland Moraine could represent, at least partially, the accumulation and stacking of glacial sediment by ice thrust against a bedrock high bordering the Superior Lobe on the northwest.
**Esker and Fan**

A narrow, sinuous, sharp-crested esker and an associated fan are located in Sections 28 and 29, T51N, R17W (Brookston and Alborn Quadrangles). The esker is 20 feet in height, approximately 2 miles long, 100 feet wide, and is oriented normal to the Highland Moraine. Immediately to the north of the esker is an arcuate, flat-topped fan approximately one mile in length, 1/4 mile in width, and up to 80 feet in height. Spoil from a power pole hole in this fan is rich in basalt, red sandstone, gabbro, and rhyolite.

The presence of this ice-contact relationship can be used to determine the ice margin position (Thwaites, 1926). The esker terminates where a subglacial stream emerged from under the ice. The sediment in this stream then formed the delta at the immediate ice base. Just to the north of this arcuate delta is dissected and pitted topography representing eroded prodelta sediments.
St. Louis Formation

General Characteristics

The new rock-stratigraphic name "St. Louis Formation" is here introduced for the numerous exposures of red, clayey till and gray (yellow when weathered), sandy till and associated outwash extending north of Alborn, Minnesota, southwest to Prairie Lake, in southwestern St. Louis County. This name applies to all sediment associated directly with the St. Louis Sublobe deposited east of the western boundary of the Glacial Lake Upham basin.

The Alborn phase of the St. Louis Sublobe is the name given to the most recent Late-Wisconsin ice advance affecting the study area (Wright, 1972). This glacier was a southeast extension of the Des Moines Lobe which originated in northwestern Minnesota where the bedrock is dominated by Cretaceous shale and Paleozoic limestone. Radiocarbon dates of wood associated with the Alborn phase place this advance at 12,000 yr BP (Wright and others, 1969).

Leverett (1932) referred to till deposited by this advance as the "St. Louis Till". Wright and others (1969) grouped all sediment associated with this advance under the term "Alborn drift". These terms are abandoned because they are either too limited or too general in their application.

Till of the St. Louis Formation is here named Alborn Till after Baker (1964). He identified a red, clayey till and a gray (yellow when
weathered), sandy, calcareous till, to which he applied the terms Alborn Till and Prairie Lake Till, respectively. The latter term is here abandoned. The name Alborn Till is retained but divided into a western source component and an eastern source component. The eastern component represents locally eroded red, clayey lake sediments. These sediments were deposited earlier in Glacial Lake Upham I during and after the Automba phase of the Superior Lobe. As the glacier advanced across the lake basin, it eroded and incorporated the lake sediment into the ice. This lake sediment was then mixed with the western, gray, calcareous component eroded earlier in northwest Minnesota and Manitoba. Lenses containing pure western component are also found within the study area.

The St. Louis Sublobe overrode approximately 60% of the study area. Most of the investigated exposures in this portion of the study area contain till representing deposition in a subglacial environment. Very few exposures of supraglacial sediment were discovered. Reasons for this interpretation will be explained later.

Eastern Component Subglacial Facies

The dominant facies of the St. Louis Formation is locally eroded lake sediment redeposited as subglacial till. This till is red, compact, fine-textured, and well indurated. Commonly it is calcareous and reacts weakly with hydrochloric acid, most likely because of mixing with carbonate-rich sediment transported by the ice from the Winnipeg Lowlands to the northwest. It is not uncommon to find discrete layers
and lenses of this calcareous western component within the subglacial facies of the eastern component.

Texture and Composition

Pipette analyses of the eastern component of subglacial Alborn Till matrix (<2.0 mm) yield an average sand/silt/clay ratio of 35/34/31. These results are shown in Figure 35.

Lithologic analyses of the coarse sand fraction are shown in Figures 36 and 37. Granitic fragments comprise the major constituent, with lesser amounts of basalt and gabbro. The presence of quartz and feldspar is due to the breakdown of rock fragments into their mineral constituents (Dreimanis and Vagners, 1971).

Pebble counts are presented in Figures 36 and 37. The dominant lithologic constituents are basalt and granitic fragments, with lesser amounts of gabbro, metamorphics, and graywacke/slate.

Results from petrographic point counts are shown in Figure 38. In contrast to the Upper Cromwell Formation and Sullivan Lake Formation, this facies of the Alborn Till is deficient in fragments from the North Shore Volcanic Group and the Duluth Complex. It has a high percentage of granitic fragments, as well as limestone and chert fragments from the Winnipeg Lowlands and northwestern Minnesota.
Figure 35. Grain size distribution of the subglacial eastern and western components of the Alborn Till.
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Figure 36. Pebble and coarse sand lithology of supraglacial and subglacial Alborn Till, both eastern and western components.
Figure 37. Bar graph showing subglacial eastern and western component composition of the Alborn Till, given in Figure 36.
Figure 38. Bar graph showing composition of subglacial eastern and western components of the Alborn Till, obtained from point counts of 14 thin sections (eastern = 10, western = 4). Approximately 700 points counted per section.
Clay-Size Mineralogy

X-ray diffractograms of the eastern component of Alborn Till are shown in Figure 39. Except for a strong mica/illite reflection in the untreated, glycolated, and heated samples, the mineralogy is similar to the Upper Cromwell Formation (Figure 30). Quartz, feldspar, mica/illite, and kaolinite are present in this unit. No expandable clays are present and all mineral traces with the exception of quartz, feldspar, and mica/illite disappear in the heated diffractograms.

Color

The Munsell color of this component of the Alborn Till is 7.5YR 3/4, similar to the color of the Upper Cromwell Formation. This color and clayey texture are good evidence that the till was derived in large part by the erosion of lake sediments with an indirect Superior basin origin.

Wright and others (1969) hypothesized the presence of Glacial Lake Upham I associated with wastage of the Automba phase of the Superior Lobe. This lake occupied the same general position as Glacial Lake Upham II (Figure 4D). Baker (1964) gave direct evidence for these original lake sediments from drill cuttings.

When the St. Louis Sublobe overrode the Lake Upham I basin, it eroded and incorporated these red, clayey lake sediments including associated rock fragments which were transported earlier by the Superior Lobe. Subsequent mixing and finally deposition produced the Alborn
Figure 39. X-ray diffractograms of the eastern component of the Alborn Till. Symbols as in Figure 10.
Till.

Western Component Subglacial Facies

This facies component of the St. Louis Formation is generally sandy, oxidized yellow, and contains clasts of Paleozoic limestone and Cretaceous shale. It is found interbedded with and as random lenses and stringers in the subglacial facies described above. Only one exposure was found to contain only western component subglacial till.

Texture and Composition

Pipette analyses of the western component of subglacial Alborn Till yield an average sand/silt/clay ratio of 60/22/18 (Figure 35).

The coarse sand fraction was analyzed and is shown in Figures 36 and 37. Granitic fragments are dominant. This component has a higher percentage of quartz and limestone than does the eastern component.

Pebble counts yield granite and basalt as the major constituents with lesser amounts of metamorphic, limestone, and graywacke/slate fragments (Figures 36 and 37).

Results from petrographic point counts of the western subglacial facies of the Alborn Till are shown in Figure 38. The composition is similar to that of the eastern component, but with a higher percentage of rock fragments derived from bedrock sources in the Winnipeg Lowlands and northwestern Minnesota.
Clay-Size Mineralogy

X-ray diffractograms of this component are shown in Figure 40 and are similar to that of the eastern component. A strong reflection from calcite [(104) at 3.03Å] is present as well as quartz, feldspar, mica/illite, and kaolinite.

Color

The Munsell color is grayish/brown, 10YR 4/2 (yellow/olive-brown, 2.5YR 4/4, when weathered).

Site Specific Characteristics

The type locality of the Alborn Till is in a gravel pit located one mile west of County Road 7, near the town of Birch, Minnesota (SW1/4, NW1/4, Section 35, T51N, R18W, Payne Quadrangle). Here, beds of western component, 1/4 to 3 inches thick, are interstratified with beds of eastern component up to 3 feet thick (Figure 41). This interstratified till overlies outwash and in a few places, Independence Till of the Sullivan Lake Formation.

The contacts between both components are sharp. Eastern component till is red-brown (7.5YR 3/4), poorly sorted, moderately compact, and clayey (sand/silt/clay ratio of 38/36/26). Western component till is weathered yellow (2.5Y 4/4), less compact, and sandy (sand/silt/clay
Figure 40. X-ray diffractograms of the western component of the Alborn Till. Symbols as in Figure 10. C is calcite.
Figure 41. Type locality for the Alborn Till, located at SW1/4, NW1/4, Section 35, T51N, R18W (Payne Quadrangle). Note interstratified eastern and western components of Alborn Till (red/brown beds interstratified with oxidized yellow beds above and to the left of the backpack) exposed on the flank of esker gravels.
ratio of 55/29/16). Both components contain clasts of Cretaceous shale and Paleozoic limestone and react with hydrochloric acid. Lime solution channels exposed along fractures in the till are common. The top portion of the Alborn Till, which is up to 15 feet thick at some areas of this gravel pit, is well indurated due to cementation by secondary calcium-carbonate derived from the western component.

Beneath the Alborn Till at this exposure is coarse outwash and till of the Sullivan Lake Formation. The outwash is generally composed of boulders, cobbles, and pebbles, within a coarse sand matrix. The till is brown (10YR 4/2), sandy (sand/silt/clay ratio of 62/29/9), poorly sorted, and compact. It is in sharp contact with both the lower outwash and overlying Alborn Till.

Fabric was measured in the Independence Till and the Alborn Till (Figure 42). In the latter, the long axes of pebbles are strongly oriented in a WNW-ESE direction, which is consistent with the general regional ice movement. The strong fabric, compactness, and lack of bullet boulders indicate deposition of this facies as a subglacial meltout till. Fabric measured in the Independence Till is poorly oriented in a NE-SW direction. This pattern could represent an original fabric of subglacial till of the Sullivan Lake Formation or modification of subglacial till by overriding ice of the St. Louis Sublobe.

The coarse outwash in this gravel pit was likely deposited in an esker. The topographic expression of this area shows only a remnant of this landform which likely formed during stagnation of the Rainy Lobe in the St. Croix phase. Figure 41 shows subglacial Alborn Till exposed on
Figure 42. (A) Rose diagram and stereographic plot of fabric measured in subglacial Alborn Till. (B) Rose diagram and stereographic plot of fabric measured in subglacial Independence Till. Measured at type locality.
Another exposure of the Alb orn Till is in an extensive gravel pit near Gowan, Minnesota (NE1/4, NW1/4, NW1/4, Section 27, T51N, R20W, Gowan Quadrangle) developed in a large esker. This esker has a NE-SW trend and is associated with wastage of the St. Croix phase of the Rainy Lobe (Figure 43). The exposure is comprised mainly of coarse, stratified, and sorted glaciofluvial deposits capped by subglacial meltout till (Figure 44). The till is up to 15 feet thick with the upper 5-7 feet oxidized and bioturbated. The color is generally red-brown (7.5YR 3/4) with the oxidized zone being more brown in color (10YR 4/4). This eastern component till is well-jointed, compact, and contains abundant lime-solution channels. Cobble and boulder-size clasts are extremely rare while smaller clasts of limestone are evident. The till has a sand/silt/clay ratio of 34/35/31 and shows very faint stratification evident by color and possible texture change.

Fabric measured in the till is shown in Figure 45. The WNW-ESE orientation agrees with general ice movement, as well as the fabric measured at the type locality (Figure 42A).

A highly calcareous, yellow (2.5Y 4/4) bed of western component till was found within the eastern component till. This lense is up to 3 inches thick and is laterally discontinuous. It is sandy (sand/silt/clay ratio of 55/24/21) and is in sharp contact with the surrounding eastern component.

A very sharp contact exists between the eastern component till and the underlying outwash in most areas of this gravel pit (Figure 44).
Figure 43. Reproduction of the Gowan Quadrangle. Note the palimpsest esker trending through the center of the figure (Sections 6, 7, 12, and 14) and the esker in the northwest corner (Sections 33 and 34).
Scale 1:67,000.
Figure 44. Exposure of subglacial till of the St. Louis Formation in sharp contact with esker sand and gravel of the Sullivan Lake Formation. Located at NE1/4, NW1/4, NW1/4, Section 27, T51N, R20W (Gowan Quadrangle).
Figure 45. Rose diagram and stereographic plot of fabric measured in subglacial Alborn Till shown in Plate 44.
There is an increase in the amount of sand and pebble size material within the basal 1-2 feet of the till. Asymmetrical drag folds are present within this basal area and give evidence of incorporation of the underlying outwash (Figure 46).

The trends and plunges of 10 fold axes were measured and are plotted in Figure 47. Fold axes, which orient perpendicular to the direction of stress, can be used to determine ice flow direction (Hicock and Dreimanis, 1985). Most of the axes trend NE-SW which suggest ice movement in a NW-SE direction.

Numerous normal faults cut the upper beds of sand. These faults have up to 6 inches of offset, contain clastic dike injections, extend up to 30 inches, and become discontinuous near the contact with the Alborn Till. These faults are due to either an increase in normal pressure with increased ice loading or related to sediment adjustment during ice melt (Berthelsen, 1975; McDonald and Schilts, 1975).

The St. Louis Sublobe flowed up and over the sandy esker sediments in a compressive style and incorporated them into the base of the glacier. The asymmetrical folds represent layers of esker sand which were dislocated, folded and incorporated into the glacier bed.

Further evidence for the deformable nature of soft sediment is the sharp contact between the underlying outwash and the clayey Alborn Till (Figure 44). This contact represents a plane of decollement formed due to the compressive upward flow of the glacier over the esker landform.

Subglacial Alborn Till overlying glaciofluvial sediment is located in a small gravel pit (SW1/4, SE1/4, Section 30, T51N, R18W, Martin Lake
Figure 46. Exposure of drag folds developed within sand at base of subglacial Alborn Till. Same location as Figure 44.
Figure 47. Stereographic plot showing trends and plunges of 9 fold axes, oriented NE-SW, measured in stratified and sorted beds of sand exposed below subglacial Alborn Till at NW1/4, NW1/4, Section 27, T51N, R20W (Gowan Quadrangle). See Figure 46.
Quadrangle). The till is up to 6 feet thick, red-brown (7.5YR 3/4), and is well-indurated and jointed. Generally it is stone poor and has a sand/silt/clay ratio of 24/41/35. The basal area of the till is enriched in coarse sand and pebbles due to incorporation of the underlying outwash.

Beneath the till is coarse outwash up to 4 feet thick. It is in sharp contact with the till above and is moderately sorted and stratified. Symmetrical overturned folds are exposed in this outwash layer with fold axes trending N50E. This orientation represents ice flowing in a NW-SE direction.

Below the coarse outwash is a basal unit of medium sand up to 20 feet thick. It is well sorted and stratified and is in gradational contact with the unit above. This sand is most likely related to outwash of the Rainy Lobe.

An exposure of the subglacial facies of the St. Louis Formation is present in a gravel pit near Prairie Lake (SE1/4, SW1/4, Section 21, T50N, R20W, Prairie Lake Quadrangle). This gravel pit has characteristics similar to the pit near Gowan (discussed earlier). Exposed here is Alborn Till overlying esker sediment of the Sullivan Lake Formation. The basal unit is composed of moderately stratified and sorted coarse sand and pebbles. Cobbles and boulders are present but not abundant. In sharp contact above this unit is up to 6 feet of red-brown (7.5YR 3/4) subglacial meltout till. It has a sand/silt/clay ratio of 6/37/27 and is enriched in sand near its base. The till is compact, jointed, and contains lime-solution channels. Clasts of
limestone and Pierre Shale, from northwest Minnesota, are abundant. Fabric measured in this till is strong with a NW-SE orientation (Figure 48).

Above the subglacial till is up to 6 feet of loose, unconsolidated, red-brown (7.5YR 3/4) till with interstratified layers of discontinuous, weathered yellow (2.5Y 5/4) till. Sorted and stratified beds of medium to coarse sand are interbedded with the till. The eastern component (red-brown) has a sand/silt/clay ratio of 34/34/32 while the western component (yellow) has a ratio of 44/30/26. The contact between this upper till unit and the lower till is sharp while contacts between strata in the upper till are weak, irregular, and subhorizontal. Fabric is random in this till. Based on this information, this upper till is most likely a supraglacial meltout facies of the St. Louis Formation.

At the base of a road cut (NE1/4, SE1/4, SE1/4, Section 32, T50N, R20W, Prairie Lake Quadrangle) near Prairie Lake is well stratified and sorted coarse sand and gravel with interstratified beds of fine sand. Above these sediments is up to 3 feet of Alborn Till (Figure 49).

The contact between the till and the lower sediment is irregular and complex. Tongues of finer, semi-cohesive sand extend down into the sand and gravel and give adjacent areas a diapiric appearance. These structures seem to indicate a thawed bed and represent either diapiric intrusions of water-saturated coarse sand or the deformation of subglacial water channel fillings. Somewhat related features are "squeezed-up sand fillings" documented by Ruszczynska-Szenajch (1987).

Also exposed in the basal sediments of this road cut are boudinage
Figure 48. Rose diagram of fabric measured in subglacial Alborn till near Prairie Lake (SE1/4, SW1/4, Section 21, T50N, R20W, Prairie Lake Quadrangle).
Figure 49. Exposure showing Alborn Till over deformed, sorted, and stratified sand. Folds, faults, and boudinage structures are present in this cut at north-central, Section 32, T50N, R20W (Prairie Lake Quadrangle).
structures and numerous normal faults. Similar boudinage structures have been reported by Berthelsen (1975); they represent thinning and stretching of subglacial sediments. The normal faults are related to stagnation, ice melt and vertical settling.

**Eastern Component Supraglacial Facies**

This facies is composed of loose till and sorted glaciolacustrine sediments. The till is more sandy than its equivalent subglacial facies due to environment of deposition. It contains rock fragments found in the Superior Basin area as well as rare fragments of Paleozoic limestone and Cretaceous shale, probably derived from the Pierre Formation in northwestern Minnesota. The glaciolacustrine sediments, expressed topographically as flat-topped hills, are well sorted and stratified. Exposures of supraglacial eastern component are limited.

**Texture and Composition**

Pipette analyses of supraglacial till matrix (<2.0 mm) of the eastern component of the Alborn Till yields an average sand/silt/clay ratio of 38/34/28 (Figure 50).

Pebble counts from supraglacial eastern component are presented in Figures 36 and 51. Granite and basalt fragments are the major components with gabbro, metamorphic, graywacke/slate, and limestone clasts present in minor amounts.
Figure 50. Grain size distribution of the supraglacial eastern and western components of the Alborn Till.
Figure 51. Bar graph showing pebble composition of supraglacial eastern and western components, Alborn Till.
Petrographic analyses of supraglacial till thin sections are presented in Figure 52. The eastern component has over 50% quartz fragments, possibly due to abrasion of sandstone clasts from the Fond du Lac Formation. This quartz sandstone was initially eroded by the Superior Lobe, deposited proglacially, and later eroded by the St. Louis Sublobe. The major rock fragments are granitic, with lesser amounts from the North Shore Volcanic Group and Duluth Complex.

Color

The Munsell color of this till facies is the same as that of the subglacial facies (7.5YR 3/4).

Western Component Supraglacial Facies

This supraglacial facies of the St. Louis Formation is exposed as uncompacted diamicton, interpreted to be supraglacial meltout till. It is sandy in texture, contains clasts with a western source, and overlies stratified debris associated with the Rainy Lobe. It is exposed in few places in the study area and where found, exhibits a poor fabric.

Texture and Composition

The supraglacial till matrix of the western component of the Alborn Till has an average sand/silt/clay ratio of 67/18/15 (Figure 50).
Approximately 3,000 points counted.

Figure 52. Bar graph showing composition of supraglacial eastern and western components. Albion Till. Data obtained from eastern and western sections (eastern = 1, western = 4).
The pebble size fraction is dominated by granitic and limestone clasts and is shown in Figures 36 and 51.

Petrographic point counts of the western supraglacial component yield smaller percentages of granite and feldspar and is dominated by Cretaceous shale and Paleozoic limestone (Figure 52).

Color

The Munsell color of this till facies is the same as that of the weathered subglacial till (2.5Y 4/4).

Site Specific Characteristics

Supraglacial Alborn Till is exposed south of Highway 2 (NW1/4, NW1/4, NW1/4, Section 5, T50N, R19W, Gowan Quadrangle). The till is red-brown (7.5YR 3/4), has a sand/silt/clay ratio of 36/33/31, and is a minimum of 12 feet thick. It is massive, easily excavated, contains clasts of limestone, and reacts with hydrochloric acid. The long axes of 50 stones were measured (Figure 53A). This randomly oriented fabric is characteristic of supraglacial meltout till (Boulton, 1971).

Another exposure of supraglacial meltout till is exposed in a railroad cut (NE1/4, SE1/4, SE1/4, Section 12, T51N, R18W, Alborn Quadrangle) near the margin of the St. Louis Sublobe (Figure 38). Two areas were excavated in this cut, one on the north and one on the south. The northern excavation exposed 6 feet of red-brown (7.5YR 3/4),
Figure 53. (A) Rose diagram and stereographic plot of fabric measured in supraglacial Alborn Till located south of Highway 2 (NW1/4, NW1/4, NW1/4, Section 5, T50N, R19W; Gowan Quadrangle). (B) and (C) Rose diagrams and stereographic plots of fabric measured in supraglacial Alborn Till at north and south railroad cut excavations, respectively. Located at NE1/4, SE1/4, SE1/4, Section 12, T51N, R18W, (Alborn Quadrangle).
eastern component Alborn Till with a sand/silt/clay ratio of 36/44/20. This sediment is loose and is moderately jointed, with a semi-random fabric (Figure 53B). It overlies a basal unit of coarse sand which is a minimum of 6 feet thick.

The southern excavation shows more heterogeneous sediments. The basal unit is up to 6 feet of stratified and sorted coarse sand. Directly above this and in sharp contact is two feet of brown (10YR 4/3), sandy, cobbly drift with a sand/silt/clay ratio of 77/22/1, most likely Independence Till of the Sullivan Lake Formation.

Above the brown till is 3 feet of interstratified red-brown (7.5YR 3/4) Alborn Till (sand/silt/clay ratio of 62/28/10) and brown sandy to silty, sorted sediment. Individual beds are 10 to 20 inches thick. A random fabric was measured in the Alborn Till (Figure 53C).

The stratigraphic characteristics, random fabric, and sandy texture could represent incorporation of eroded Sullivan Lake Formation sediments and redeposition as meltout till or flowtill in the supraglacial environment of the St. Louis Sublobe.

In addition to till, the supraglacial facies of the St. Louis Formation includes perched lake sediments. These sediments are exposed in kame-like hills on the north and south sides of Highway 2 in the north half of the Martin Lake Quadrangle (Figure 24). An excavation in one of these hills (NE1/4, NW1/4, NW1/4, Section 6, T50N, R18W, Martin Lake Quadrangle) revealed up to 2 feet of red (5YR 3/4) clay. This unit is well-sorted (sand/silt/clay ratio of 4/40/56), massive, and easily excavated. Underlying this clay and in sharp contact is brown (10YR
4/3), sandy (sand/silt/clay ratio of 61/32/7) till of the Sullivan Lake Formation.

This exposure most likely represents sediment deposited in a supraglacial lake basin on the surface of the St. Louis Sublobe. Subsequent melting superimposed the clay-rich sediment on previously deposited Independence Till.

Areal Geology

The boundary between the St. Louis Formation and sediment deposited by the Superior and Rainy Lobes in earlier advances is based on the position of the Culver Moraine, an ice marginal feature deposited by the St. Louis Sublobe. On the up-glacier side of the moraine is the boundary between the St. Louis Formation and the Meadowlands Formation, which consists of sediment deposited in a glacial lake environment.

In the eastern portion of the study area, the Culver Moraine overlies sediment of the Sullivan Lake Formation. The boundary between the two formations is based on a change in morphology, collapsed outwash, and outwash deposited in lows within the proglacial area. Further to the west-southwest, the boundary lies between the St. Louis Formation and the Upper Cromwell Formation. The boundary in this area was placed based on relative changes in morphology between the Highland Moraine and the Culver Moraine, the latter having modified the former. It is important to note palimpsest drumlins, eskers, and tunnel valleys (formed by the Rainy Lobe) and kame and kettle topography (formed in the
Highland Moraine by the Superior Lobe) which are exposed topographically within the St. Louis Formation boundary.

In the west and northwest portion of the study area, the boundary of the St. Louis Formation is with the Meadowlands Formation. These glacial lake sediments extend to an elevation of approximately 1330 feet a.s.l. and mark the boundary between the two formations.

Geomorphology

The most notable geomorphic feature related to the advance of the St. Louis Sublobe is the low-relief Culver Moraine (Wright and others, 1969). The Culver Moraine is an ice margin feature which buried and modified previously formed ice margin features along the northwest flank of the Highland Moraine (Figure 43). It has an average relief of 30 feet and blankets a 1-4 mile wide marginal area. In the northeast part of the study area, it cuts across the Tilli Drumlin Field (Figure 54). It is represented by areas of low relief kame and kettle topography separated by marsh-filled ground moraine. Its topography is more subdued than that of the Highland Moraine because the drift is generally much thinner.

Circular kames and kettles are exposed in Sections 8 and 9, T51N, R18W (Brookston NW Quadrangle). Most other areas of the Culver Moraine are characterized by rolling, hummocky topography with a relief of 10-50 feet.

A small, discontinuous esker can be traced from Section 7 in the
Figure 54. Reproduction of the Albom Quadrangle. Note the esker and fan in the northeast corner (Sections 17 and 20) as well as the flat-topped hills south of Schelin Lake. Scale 1:67,000.
Culver Moraine to Section 17, T52N, R17W (Alborn Quadrangle) where it terminates in a broad, fan-shaped feature (Figure 54). This esker is 20 feet high, 100 feet across, and is represented topographically by segments 500 to 1000 feet long. It has a linear NW-SE trend and extends approximately 2 miles. Paleozoic limestone and Cretaceous shale fragments can be seen in an exposure of the esker sediments north of County road 149 (SE1/4, Section 7, T52N, R17W, Alborn Quadrangle).

The esker grades into a fan in the southeast corner of Section 17, T52N, R17W (Alborn Quadrangle). It has an arcuate shape and extends distally up to one mile where it grades into a low-lying marshy area. To the south of this fan, near Schelin Lake, is a series of conical and flat-topped hills. Figure 55 shows sorted and stratified sand, cut by faults with intruded clastic dike injections, exposed in one of these hills.

These hills originated by deposition of sandy sediment in supraglacial depressions. The margin of the St. Louis Sublobe, based on the position of the Culver Moraine, is located 3 miles to the southeast, beyond the contact between the esker and its fan. This package of landforms represents the stagnation of the glacier and the supraglacial appearance of a subglacial stream. The fan sediments were deposited on top of stagnant ice and, due to the underlying morphology of the Toimi Drumlins, supraglacial water and sediment flowed to the southwest. Depressions present in this stagnant ice were filled by sediment originating from the subglacial stream. As the surrounding ice melted, the basin walls collapsed which inverted the basin sediments and formed
Figure 55. Exposure showing inverted supraglacial lake basin sediments associated with wastage of the St. Louis Sublobe. Located at SE1/4, NW1/4, Section 29, T52N, R17W (Alborn Quadrangle).
a hill. Normal faults were produced and liquefied sand was injected as clastic dikes along the fault planes.

Other geomorphic features located within the margin of the St. Louis Sublobe include palimpsest forms of drumlins and eskers formed by the Rainy Lobe in the St. Croix phase. Drumlinoid forms can be seen on the southern half of the Brookston NW Quadrangle where they have a relief of 10-20 feet. This low relief is due to modification and deposition by the St. Louis Sublobe. Drumlins located to the northwest, which were not affected by this later advance, have a relief of 40 feet or more.

A long, sinuous esker formed by the Rainy Lobe can be seen cutting across the Gowan Quadrangle (Figure 43). This esker is segmented and has a relief of only 10 feet in some areas due to modification and deposition by the St. Louis Sublobe.

Inside of the Culver Moraine, geomorphic features associated with the advance of the St. Louis Sublobe are absent due to modification and deposition of lake sediments by Glacial Lake Upham II.

Origin of Interlayered Till

Most exposures of till associated with the St. Louis Formation which contain the western component show interstratified bands of both the eastern and western components (Figure 41). This stratification can be explained by deformation, detachment, and shearing of Glacial Lake Upham I sediments by the overriding St. Louis Sublobe.

As the St. Louis Sublobe advanced to the southeast from northwest
Minnesota, it spread out in a form similar to a piedmont glacier (Figure 4C). This morphology is directly related to the deformable nature of the sediments, explained below, over which the glacier was moving (Boulton, 1979a; 1979b).

Compressive flow can result near the glacier margin where the ice is frozen to its bed (Moran and Clayton, 1974). Shear dominates the inner zone where the ice is thicker and perhaps separated from its bed by a thin layer of meltwater (Weertman, 1979). If the shear strength of the subglacial sediment is greater than that of the ice, the ice deforms; if the shear strength of the subglacial sediment is less than that of the ice, the sediment deforms (Clayton and others, 1980). Lake clay has a low inherent shear strength. Because it also has a low permeability, the shear strength would be decreased further by an increase in pore pressure (Boulton, 1975; Banham, 1975; Clayton and others, 1980).

Clayton and others (1985), hypothesized that glaciers which advanced across mid-North America were relatively thin and subject to surges. The morphology of the St. Louis Sublobe and associated landforms and deposits support this thin ice hypothesis. As the glacier advanced across the easily deformed lake clay, the ice spread out and thinned considerably. This thinning would result in a decrease in pressure-melting at the glacier bed and possibly a lowered ice temperature. The absence of tunnel valleys associated with this advance is good evidence for a lack of abundant subglacial meltwater.

The St. Louis Sublobe carried with it gray, carbonate-rich till which originated in northwestern Minnesota and the Winnipeg Lowlands.
Exposures of Alborn Till commonly contain interbedded clayey (local) and sandy (transported) till indicating the glacier deformed, eroded, and incorporated fine lake sediments as it advanced across the Lake Upham I basin.

One possible theory is that the low shear strength of the clay and the lack of significant subglacial meltwater allowed the thin ice to freeze onto the subglacial sediment (regelation). This would have allowed the St. Louis Sublobe to "pluck" blocks of clayey lake sediment and incorporate them into subglacial ice. Other workers have discussed how blocks or rafts of non-cohesive subglacial sediment can be deformed, detached, and transported by overriding ice (Ruszczynska-Szenajch, 1987). If there was an increase in water pressure produced by thicker, up glacier ice, melting and flowing into more porous sediment underlying the lake clay, the increase in hydrostatic pressure beneath the frozen layers could push blocks of lake sediment up into the base of the glacier and thus aid the process.

The base of the glacier was likely rich in debris and acted as a deformable bed. The blocks of lake sediment were thinned by shear within this debris-rich sole which interstratified the fine lake sediment with the sandy transported till. When the glacier stagnated, the interbedded subglacial till was melted out and deposited.
Meadowlands Formation

The rock-stratigraphic term "Meadowlands Formation" is here introduced for lake-deposited sediments contained within the Lake Upham basin. These sediments comprise the surface deposits in parts of the Floodwood, McCarty River, Brookston NW, and Prairie Lake Quadrangles. Rhythmites, lake clay, wave-modified till, and beach deposits are included in this formation.

The St. Louis Sublobe reached its maximum position by about 12,000 years ago (Wright and others, 1969). Subsequent to this advance, the ice melted and formed Glacial Lakes Upham II and Aitkin II. These lakes were connected through much of their existence and were at a fairly stable level approximately 10,000 years ago (Hobbs, 1983). Glacial Lake Upham II formed initially as relatively clean glacier ice melted during and after stagnation of the St. Louis Sublobe (Hobbs, 1983). It was dammed on its periphery by topography cored with stagnant ice and sediment associated with this advance. This lake stood at several elevations where wave cut scarps and beaches formed. Sediment associated with Glacial Lake Upham II covers much of the study area.

General Characteristics

The Meadowlands Formation is comprised of a variety of sediment types. Well-sorted and bedded coarse sand and gravel deposits are included in this formation and are exposed in linear ridges.
Homogeneous, well-sorted clay and reworked Alborn Till are exposed in numerous hand auger holes in the lake plain sediments. Rhythmites give evidence of lake bottom deposition and are exposed at low elevations in the lake basin. Other lake bottom sediments include well-sorted deposits of silt and fine sand. The topography of these sediments is expressed as a flat, level, vegetation and peat-covered plain.

Many different processes operate and combine to form a wide variety of sediment types and structures in glacier-fed lakes. A substantial portion of their annual water and sediment budgets are derived from the glacier itself. Ashley (1988) has developed a classification scheme of glaciolacustrine sediments in lakes lying under, on, adjacent to, and separate from ice. The types of sediment within these lakes, among other factors, are dependent on proximity to ice, sediment nature, runoff, and ice cover. The lithofacies groups in this classification scheme include (1) Proximal, represented by subaqueous outwash or deltas, (2) Intermediate, including laminated sands and silts, and (3) Distal, represented by laminated silts and rhythmites (Ashley, 1988).

The majority of the sediment examined in the basin is classified in the Intermediate and Distal categories. Deposits of subaqueous outwash were not found, although some auger holes, generally those at higher elevations, contain coarse sand, possibly deposited in a lacustrine delta, or possibly representing lag deposits from the reworking of glacial sediments. This sediment could represent deposition in the Proximal area.
Site Specific Characteristics

Sand and gravel are exposed in gravel pits developed in wave-cut scarps or strandlines. Exposed in a strandline feature at 1300 feet a.s.l. (Sections 1, 10, 11, T51N, R20W, and Sections 32 and 33, T52N, R19W, McCarty River Quadrangle) is well-bedded, sorted, coarse- to medium-grained sand. Some beds contain abundant iron-oxide, giving the exposure an orange to brown/red color. Gravel pits developed in strandlines at 1275-1280 feet a.s.l. (Sections 23, 24, and 27, T51N, R21W, and Sections 19 and 20, T51N, R20W, Floodwood Quadrangle) contain well-stratified, sorted, horizontally bedded coarse sand with similar iron-oxide staining as that mentioned above.

These lake margin (proximal) sediments were introduced into the lake basin with initial ice wastage. When the ice melted, the stagnant ice and sediment on its periphery melted and was deposited in proximal deltas. This coarse sediment was then transported throughout the lake margin area by wave action which also formed the beach and strandline features.

A nearshore (intermediate) lacustrine facies is represented by homogeneous lake clay and wave-washed till. Numerous soil auger holes revealed clayey to silty, well-sorted sediment and poorly sorted, clayey till with clasts of Paleozoic limestone. This material represents deposition of fine sediment and modification of Alborn Till by currents in the Intermediate lake area.

The deep water (distal) facies of the Meadowlands Formation is
represented by rhythmites (Figure 56) exposed in a tributary of the Whiteface River (SW1/4, SE1/4, SW1/4, Section 6, T53N, R18W, Meadowlands Quadrangle). The bottom of the rhythmite sequence is below the base of the exposure. The exposed rhythmtes are 20 feet thick and are capped by coarse and fine beds of sand. The light and dark layers represent deposition of silt during the summer months and clay during the winter, respectively.

Silt layers range from 1.0-8.0 mm in thickness and have a Munsell color of 5Y 5/1. The clay layers are 4.0-7.0 mm thick and have a Munsell color of 5Y 3/2. A pipette analysis of a rhythmite bulk sample yielded a sand/silt/clay ratio of 0/34/66. Less than 0.5% sand was present.

Pollen analysis of the rhythmtes yielded the following types: Picea (spruce), Pinus (pine), Betula (birch), Salix (willow), Quercus (oak), Corylus (hazel), Cornus (dogwood), Ulmus (elm), Artemisia (wormwood), Chenopodiaceae/Amaranthaceae (goosefoot/amaranth), Ambrosia (ragweed), Gramineae (grass), and Cyperaceae (sedge). Pediasstrum simplex, Pediasstrum Boryanum, and Scenedesmus, all Chlorophycophyta algae, were found, as well as spores of Pteridium-type (bracken fern), and Sphagnum (sphagnum) (Huber and others, 1988). Baker (1964) reported similar pollen types from a postglacial peat deposit located in a drainageway of Glacial Lake Upham II.

The elevation at the top of the rhythmite exposure is 1260 feet a.s.l. A soil sampler was used to check the surrounding area for rhythmtes at this elevation. They were located in a roadside ditch at
Figure 56. Rhythmites of the Meadowlands Formation exposed along the Whiteface River at SW1/4, SE1/4, SW1/4, Section 6, T53N, R18W (Meadowlands Quadrangle).
NW1/4, NW1/4, SW1/4, Section 24, T53N, R19W (Meadowlands Quadrangle) and found to become nonexistent near the margin of the basin. This is evidence for relatively quiet deposition yielding well-sorted, fine-grained material in the inner lake area. Texturally immature sediment was deposited near the margin. Similar relationships have been documented by Francis (1974) and Ashley (1975; 1988).

The presence of rhythmites in the inner, deep part of the basin represents a depositional environment located far from the melting glacier (Ashley, 1988). A wide range of grain sizes is introduced into the lake at the margin, with the finer sediment held in suspension, transported, and deposited far from where it was introduced.

The sedimentation taking place in the deep part of a distal lake is controlled largely by the season. Deposition of clay would dominate during the winter months when the lake surface is frozen, whereas both silt and clay would be deposited during the summer when the lake surface is partially or totally thawed.

Another model to explain the presence of rhythmites in the deep basin and their absence near the margin is with a partially frozen lake surface during the warmer months. With this model, sedimentary material is introduced at the thawed lake margin and the coarser material is deposited nearshore. Silt and clay are transported out into the lake under the frozen summer ice by density currents and deposited there.

Density currents are responsible for carrying sediment from the lake margin area into the deep lake environment (Ashley, 1988). A thin-section of impregnated rhythmites was made and revealed rip-up
clasts of silt present near the contact of silt and clay layers. This is evidence for water current action near the lake floor.

Areal Geology

The Meadowlands Formation boundary in the study area is solely within the St. Louis Formation. This boundary has been traced at an elevation of approximately 1330 feet a.s.l. and represents the boundary between the highest developed lake plain and the up-glacier margin of the Culver Moraine. This moraine acted as a dam at the shore of Glacial Lake Upham II. Several wave-cut scarps exist throughout the lake basin.

Geomorphology

Lake bottom deposited sediments of the Meadowlands Formation are represented topographically by a series of lake plains. These plains are at different elevations and most are associated with wave-cut scarps or strandlines.

The highest lake plain in the study area is at 1330 feet a.s.l. This feature represents a short-lived, non-stable lake level evidenced by the lack of a strandline near this elevation.

A stable lake level occurred at 1300 feet a.s.l. indicated by a well-developed strandline at this elevation. This feature is expressed topographically on the McCarty River Quadrangle (Sections 1, 2, 10, 11, T51N, R20W, and Sections 32 and 33, T52N, R19W) as a linear symmetrical
ridge oriented in a NE-SW direction. It is possible that this is an offshore bar, but the lack of a higher strandline and other workers' research does not support this interpretation (Hobbs, 1983).

The lowest lake level recorded in the study area is at 1275-1280 feet a.s.l. A well-developed wave-cut scarp related to this level is located south of Floodwood, Minnesota (Sections 13, 23, 24, 27, T51N, R21W, Floodwood Quadrangle).

**Summary of Glacial Lake Upham II History**

Hobbs (1983) researched the drainage relationships of the connected Glacial Lakes Upham II and Aitkin II. He hypothesized initial lake formation in the northeast corner of the St. Louis Sublobe, at 1400 feet a.s.l., with outflow leading to the Cloquet and St. Louis Rivers. The first well-developed outlet channel was Hellwig Creek, located in the southwestern Canyon Quadrangle and northwestern Independence Quadrangle, at 1330 feet a.s.l. The elevation of this drainageway supports the highest lake plain discussed above. Meltwater flowed down the Cloquet and St. Louis Rivers, around the Superior Lobe in the Nickerson phase, and eventually to the St. Croix River (Figure 4D).

Glacial Lake Upham II was drained by the Birch and Spider Creek outlets when it stood at 1300 feet a.s.l. Water drained into the lake from the Mississippi River when it stood at 1275-1280 feet a.s.l. Hobbs (1983) suggests the strandline at this elevation, mentioned above, represents a wave cut scarp and associated beach ridge.
The lake was drained to a level of 1250 feet a.s.l. by the Snake River outlet and later separated from Glacial Lake Aitkin II when the Mississippi River outlet opened north of Mille Lacs Lake. Glacial Lake Upham II finally drained down the St. Louis River.

Today the lake plain can be recognized as a flat, featureless plain covered with peat, black spruce, and tamarack. In the study area it is dissected by the Whiteface, St. Louis, and Floodwood Rivers.
LATE-WISCONSIN HISTORY

The study area in northeastern Minnesota contains evidence of three glacial advances and two periods of glacial lake development. The use of modern theories and developments has allowed the re-evaluation and analysis of the sediment associated with each stage of the glacial history.

Conclusions drawn from geomorphic, stratigraphic, and sedimentologic data are presented below in a chronologic outline, from oldest to youngest, of the Late Wisconsin glacial history. Figure 57 represents a composite stratigraphic section of the formations found in the study area.

The glacier model, first introduced by Clayton and Moran (1974), of frozen, erosive, marginal ice, and unfrozen, sliding, inner ice was found to agree well with investigated exposures. The compressive nature of the outer zone and the shear style of deformation in the inner zone was well represented by glaciotectonic features found within the study area. The orientation of many glaciotectonic features, especially fold axes, agrees well with ice motion, as hypothesized by Hicock and Dreimanis (1985).

St. Croix Phase

The earliest ice advance recorded within the study area is represented topographically by eskers, tunnel valleys, and drumlins.
Figure 57. Idealized composite section showing Late-Wisconsin stratigraphy in area of study.
These features were formed by the Rainy Lobe when it advanced approximately 20,500 ± 400 yr BP (Wright, 1973), and subsequently retreated. In this phase, the Rainy Lobe advanced from northeast Minnesota where it eroded granitic, metamorphic, and gabbroic bedrock. The Superior Lobe advanced contemporaneously with the Rainy Lobe in this phase and deposited the Lower Cromwell Formation contemporaneously with the deposition of the Sullivan Lake Formation by the Rainy Lobe. These two lobes advanced from NE-SW and were separated by the North Shore Highland. The Superior Lobe followed the Superior Basin while the Rainy Lobe occupied the upland to the northwest. The study area does not extend into the area glaciated by the Superior Lobe in this phase.

The Sullivan Lake Formation (Gross, 1982) is the name given to brown, stony Independence Till (Wright and others, 1969) and outwash deposited by the Rainy Lobe. In the study area the Independence Till has an average sand/silt/clay ratio of 62/32/6 and clast composition dominated by granite, gabbro, and greenstone.

Geomorphic features formed during this advance include NE-SW trending drumlins of the Toimi Drumlin Field (Wright and others, 1969). An exposure in one of these subglacially formed features yielded a moderately strong N-S fabric within the Independence Till as well as folds and boudinage structures in the underlying sandy outwash. The fabric is problematic not only because it differs from the drumlin axis by 40 degrees but also because the stones dip steeply down-glacier. The folds and boudinage structures have axes which are perpendicular to the drumlin axis and agree well with ice movement. These structures
indicate compressional deformation followed by shear and extension.

Northeast to southwest trending tunnel valleys which contain undersize streams occur in the study area. These features formed during stagnation of the Rainy Lobe and give evidence for abundant subglacial meltwater.

Large eskers related to this advance are located southwest of the tunnel valleys and indicate a decrease in meltwater flow and the deposition of sediment. Numerous gravel pits are developed along these features and contain large boulders and sediment indicative of the glaciers provenance area.

**Automba Phase**

Following the retreat of the Rainy and Superior Lobes in the St. Croix phase, the Superior Lobe readvanced in a more westerly direction in the Automba phase. This advance has been dated at approximately 18,000 yr bp (Wright, 1973).

This advance deposited the red, silty to sandy, Upper Cromwell Formation. Subglacial till of this formation is much siltier in areas near the Superior Basin. In the study area, subglacial till is sandy with a sand/silt/clay ratio of 57/34/9. This is due to incorporation of the underlying Sullivan Lake Formation. Supraglacial till is also rich in sand (sand/silt/clay ratio of 60/31/9) which is due not only to incorporation of the underlying sediment but also to loss of fine material by water during deposition. Clast composition is dominated by
basalt and gabbro.

Geomorphic features related to this advance include the massive Highland Moraine. The Highland Moraine cuts across the southern part of the study area and extends up to 1600 feet a.s.l. It is possible that this feature is a tectonically emplaced body of sediment, modified after ice stagnation by formation into kame and kettle topography. A gravity map of Minnesota shows a gravity high in the area. If this indicates a large mass of bedrock in the area, the Superior Lobe must have flowed up and over. This would allow the erosion of massive amounts of material on the stoss side of the bedrock and the deposition of the sediment on the top and lee side of the bedrock high.

A possible thrust moraine is located along the southern border of the study area with an associated low-lying, swampy area just up-glacier. This asymmetric linear feature is believed to have formed in the subglacial environment. As the Superior Lobe advanced to the west-southwest, the northwest margin was advancing in a SE-NW direction. The frozen outer margin of the glacier eroded a body of sediment, possibly associated with an aquifer system, and deposited it down-glacier as a ridge of sediment. Fold axes and fabric measurements agree well with the local ice motion and thrust moraine morphology.

During and after the Automba phase of the Superior Lobe, red, fine-grained sediment was deposited in proglacial lakes Aitkin I and Upham I. These formed to the northwest of the Highland Moraine (Wright and others, 1969).
Nickerson-Alborn Phase

Approximately 12,000 years ago, after the retreat of the Superior Lobe in the Automba phase, the St. Louis Sublobe advanced out of northwestern Minnesota to within a few miles of the Superior Basin. This glacier was a southeast extension of the much larger Des Moines Lobe, and brought with it clasts of Paleozoic limestone and Cretaceous shale. The Superior Lobe advanced in the Nickerson phase at approximately the same time.

The St. Louis Sublobe deposited till and outwash in northeastern Minnesota, collectively named in this study the St. Louis Formation. The Alborn Till member of this formation contains a western, calcareous component (sand/silt clay ratio of 60/22/18), and an eastern, mixed component (sand/silt/clay ratio of 35/34/31). The eastern component contains evidence of both eastern and western source areas.

As the St. Louis Sublobe advanced, it encountered fine-grained lake sediments deposited earlier in Glacial Lakes Aitkin I and Upham I. As the glacier moved across this basin, it became thin and overextended due to the deformable nature of the glacier bed. Fine-grained (lake) sediments have a low shear strength which decreases further when loaded. When the ice reached the lake sediments, it thinned and became frozen to its bed. The subglacial lake sediment moved by shear along with the glacier and became incorporated into the basal ice. This incorporation allowed blocks of eastern source area sediment to be sheared and mixed with the calcareous sediment within the glacier. When
the ice stagnated, this subglacial sediment melted out as sheared bands of pure, gray (yellow when weathered), western component, and mixed, red, clayey, eastern component.

Geomorphic features associated with this advance include the Culver Moraine and an esker with associated circular, flat-topped hills. The Culver Moraine is a low relief feature which abuts the northwest flank of the Highland Moraine. It was produced when the thin St. Louis Sublobe, already carrying a low sediment load, flowed up onto the Highland Moraine, masking the underlying topography. Palimpsest drumlins of the Toimi Drumlin Field are exposed in the study area and give evidence of this thin, sediment poor ice.

A small discontinuous esker is located in the northeast part of the study area, associated with circular, flat-topped hills. These hills contain beds of well-sorted, stratified sand and are cut by numerous normal faults. It is hypothesized that an esker terminus, located just to the north, represents the supraglacial emergence of a subglacial stream. This stream flowed out on top of the ice where it produced a fan and supplied sediment to supraglacial lake depressions. When the ice melted, the walls of the depressions melted. This inverted the basin sediments from trough shaped to dome shaped, and produced normal faults.

Glacial Lake Upham II

The final activity associated with Late Wisconsin glaciation
culminated with the formation of Glacial Lakes Upham II and Aitkin II from the wasting St. Louis Sublobe. Sediment deposited in Lake Upham II is exposed in the northwest part of the study area. The name Meadowlands Formation has been introduced to include all sediment associated with this glacial lake phase.

This lake stood at several levels where it formed strandlines, modified earlier deposits of till, and deposited nearshore and offshore sediments. The lake plain extends up to 1330 feet a.s.l. Two well developed strandlines exist at 1300 feet and 1275 feet a.s.l.

Rhythmites were located at 1260 feet a.s.l. and represent deposition in (possible) annual cycles within the deep lake basin. In areas closer to the lake margin, the rhythmites are not present. This is due to sediment influx and current activity associated with the near shore environment.

Postglacial processes include peat formation and dissection of the lake plain. The lake basin is completely filled today and contains an abundance of peat and forest vegetation while erosion has proceeded in and along the many streams and river valleys.
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APPENDIX

Guidelines for making thin sections of uncohesive sediment.

DAY 1

1) Obtain 10 sample containers (boxes) approximately 2"x1.5"x.75" and line with aluminum foil.

2) Place sample in sample container.
   a) If sample is cohesive (i.e. a compact till), place a large chunk (one with a cross section large enough to cover a glass slide) in a container.
   b) If sample is uncohesive (loose sand or ?), press sediment into container leaving approximately 0.2" between top of container and sample.

3) Dry samples in oven overnight at approximately 80-90 C.

DAY 2

1) Remove samples and let cool a few minutes.

2) Place all 10 samples in Beuhler Vacuum Impregnator (its best to make sure you’ll be able to check on the samples 6 hours from this point).

3) Take impregnation solution cup and mix solution (I found quantities for HARD set-up, below, worked best. I also mixed up a double batch to be sure I had enough for 10 samples).
Add:

1) 20 gm Vinylcyclohexene Dioxide (VCD)
2) 8 gm DER 736 (Diglyidylether of polypropylene glycol)
3) 52 gm nonenyl succinicanhydride (NSA).
4) 0.8 gm Dimethylaminoethanol (DMAE).

Stir
4) Place cup with solution in vacuum impregnator holder.
5) Place clean dome on top, pressing in place with a turning motion to get a good seal.
6) Attach vacuum hose and gauge, make sure hose clamps are loose.
7) Turn on vacuum pump.
8) Turn off vacuum pump when gauge reads a little more than 30 psi.
9) Tighten hose clamps
10) Pour solution from cup into each sample container making sure each has enough.
11) Recheck in about 6 hours. If vacuum gauge down to 15 or 20 psi, loosen clamps, turn on pump until gauge reads 30 psi, turn off pump, tighten clamps, go home and have a beer.

DAY 3

1) Vacuum should be down to 5-10 psi so jiggle gauge letting air into chamber, and remove clear dome.
2) Remove samples and place in oven to harden (leave them overnight).
DAY 4

1) Remove samples from oven and let cool a few minutes.

2) Remove samples from containers (this is difficult to do sometimes as it is often necessary to destroy the container).

3) Make thin sections.