The late Cenozoic geology of west-central Minnesota from Moorhead to Park Rapids

Roderic L. Perkins

University of North Dakota

Follow this and additional works at: https://commons.und.edu/theses

Part of the Geology Commons

Recommended Citation
https://commons.und.edu/theses/225

This Thesis is brought to you for free and open access by the Theses, Dissertations, and Senior Projects at UND Scholarly Commons. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of UND Scholarly Commons. For more information, please contact zeinebyousif@library.und.edu.
THE LATE CENOZOIC GEOLOGY OF WEST-CENTRAL
MINNESOTA FROM MOORHEAD TO PARK RAPIDS

by

Roderic L. Perkins

Bachelor of Arts, State University of New York College, 1974

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
in partial fulfillment of the requirements
for the degree of
Master of Arts

Grand Forks, North Dakota
August
1977
This thesis submitted by Roderic L. Perkins in partial fulfillment of the requirements for the Degree of Master of Arts from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

Lee Clayton
(Chairman)

Stephen R. More

Alice J. Clark
Dean of the Graduate School
Permission

THE LATE CENOZOIC GEOLOGY OF WEST-CENTRAL MINNESOTA FROM MOORHEAD TO PARK RAPIDS

Title Geology

Degree Master of Arts

In presenting this thesis in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the Library of this University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by the professor who supervised my thesis work or, in his absence, by the Chairman of the Department or the Dean of the Graduate School. It is understood that any copying or publication or other use of this thesis or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota in any scholarly use which may be made of any material in my thesis.

Signature

Date

7/18/77
ACKNOWLEDGMENTS

I am grateful to many individuals and organizations for their assistance and financial support during this study. My graduate committee, Drs. Lee Clayton, Stephen R. Moran, and Walter L. Moore are gratefully acknowledged for their constructive criticisms and suggestions.

I would like to sincerely thank the following people for their helpful suggestions and encouragement they gave throughout the course of the project: John and Anita Himebaugh, Joanne Groenewold, Richard Pilatzke, Thomas Heck, Daniel Daly, and Michael Camara.

This study was supported in part with funds provided by the Minnesota Geological Survey and Sigma Gamma Epsilon Society. The financial support of these institutions made this project possible.
DEDICATION

To my mother.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF PLATES</td>
<td>ix</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>x</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>GEOLOGIC HISTORY</td>
<td>5</td>
</tr>
<tr>
<td>Episode I</td>
<td>42</td>
</tr>
<tr>
<td>Episode II</td>
<td></td>
</tr>
<tr>
<td>Episode III</td>
<td></td>
</tr>
<tr>
<td>Episode IV</td>
<td></td>
</tr>
<tr>
<td>Episode V</td>
<td></td>
</tr>
<tr>
<td>Episode VI</td>
<td></td>
</tr>
<tr>
<td>Episode VII</td>
<td></td>
</tr>
<tr>
<td>APPENDIX A. Methods and Procedures</td>
<td>42</td>
</tr>
<tr>
<td>APPENDIX B. Description of Lithostratigraphic Units</td>
<td></td>
</tr>
<tr>
<td>APPENDIX C. Description of Geomorphic Features</td>
<td>83</td>
</tr>
<tr>
<td>APPENDIX D. Data of Near Surface Samples</td>
<td>87</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>96</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Correlation of Stratigraphic Units Present in the Study Area with</td>
<td>9</td>
</tr>
<tr>
<td>Stratigraphic Units in Other Areas</td>
<td></td>
</tr>
<tr>
<td>2. List of Aerial Photographs in this Study</td>
<td>45</td>
</tr>
<tr>
<td>3. Temperature and Corresponding Setting Time Required to Determine</td>
<td>48</td>
</tr>
<tr>
<td>the Amount of Clay in Suspension Using a Hydrometer</td>
<td></td>
</tr>
<tr>
<td>4. Summary of the Laboratory Analysis of the Pebble-Loam in the</td>
<td>55</td>
</tr>
<tr>
<td>Lithostratigraphic Units, Showing the Means and Standard Deviations</td>
<td></td>
</tr>
<tr>
<td>5. Data of the Pebble-Loam Analysis for Each Sample</td>
<td>90</td>
</tr>
</tbody>
</table>
### LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Location of the Study Area in West-Central Minnesota</td>
<td>3</td>
</tr>
<tr>
<td>2.</td>
<td>Time-Distance Diagram Showing Periods of Deposition of Formations Present in the Study Area</td>
<td>7</td>
</tr>
<tr>
<td>3.</td>
<td>Early Wisconsinan Advance of Glacial Ice from the Northeast</td>
<td>15</td>
</tr>
<tr>
<td>4.</td>
<td>First Late Wisconsinan Glacial Advance from the Northwest</td>
<td>21</td>
</tr>
<tr>
<td>5.</td>
<td>Second Late Wisconsinan Glacial Advance from the Northwest</td>
<td>25</td>
</tr>
<tr>
<td>6.</td>
<td>Third Late Wisconsinan Glacial Advance from the Northwest</td>
<td>29</td>
</tr>
<tr>
<td>7.</td>
<td>Phases of Lake Agassiz During Late Wisconsinan to Holocene Time</td>
<td>35</td>
</tr>
<tr>
<td>8.</td>
<td>Graph of the Compositional Variation of Pebble-Loam of Lithostratigraphically Correlated Units in West-Central Minnesota and North-Central Minnesota</td>
<td>58</td>
</tr>
<tr>
<td>9.</td>
<td>East-West Cross Section of the Type Sections for the Hawley and Downer Formations</td>
<td>71</td>
</tr>
<tr>
<td>10.</td>
<td>East-West Cross Section of the Reference Section for the Hawley Formation</td>
<td>73</td>
</tr>
</tbody>
</table>
## LIST OF PLATES

<table>
<thead>
<tr>
<th>Plate</th>
<th>Page</th>
</tr>
</thead>
</table>
| 1. Geology of the Moorhead to Park Rapids Area  
West-Central Minnesota | (in pocket) |
| 2. Isopach Map of the Sand and Gravel Lithology  
New York Mills Formation, Park Rapids Area | (in pocket) |
ABSTRACT

Based on lithostratigraphic and geomorphic information, the
Quaternary history of an area bounded by the Red River of the North,
95°00' west longitude, 47°00' and 46°45' north latitude in west­
central Minnesota, includes seven geologic episodes.

Glacial advances and retreats over all or part of the study
area occurred during the first six geologic episodes. The glaciers
advanced either southward across northern Minnesota, entering the
study area from the northeast; or across eastern North Dakota and
southwestern Manitoba, entering the study area from the northwest.
As a result of these glacial events the sediment of Unit A, Sebeka
Formation, New York Mills Formation, Dunvilla Formation, Barnesville
Formation, and Hawley Formation (new) was deposited in the study area.

The creation and drainage of Lake Agassiz occurred during the
seventh episode, between 13 000 years B. P. to 9 500 years B. P. The
sediment deposited as a result of this event is contained in the
Sherack Formation, Downer Formation, Argusville Formation, and Poplar
River Formation. During this episode, starting about 12 300 years
B. P., the present-day streams, bogs, and sloughs were created. The
sediment deposited during this event is contained in the Walsh Forma­
tion.
INTRODUCTION

The area between Moorhead and Park Rapids in west-central Minnesota (Figure 1) is underlain by 30 to as much as 200 metres of Quaternary sediment of which only the upper few tens of metres is exposed in outcrops in the area. Sparse subsurface information suggests that scattered patches of pre-Cretaceous pisolithic conglomerates and clay deposits and Cretaceous shale and sandstone lie between the Quaternary deposits and the Precambrian igneous and metamorphic rock (Bingham, 1960 and Anderson, 1957). The overlying Quaternary deposits, the subject of this study, consists largely of glacial sediment and associated fluvial and lacustrine sediment. The surface sediment in the Red River Valley, the western quarter of the study area, was for the most part deposited in Lake Agassiz at the end of the last Wisconsinan glaciation. The eastern three-quarters of the study area is characterized by glacial collapse topography, fluvial plains, and melt-water channels created during several pre-Wisconsinan and Wisconsinan glacial advances.

This thesis is presented in an unconventional format. The conclusions of the study, the geologic history of west-central Minnesota, are presented as the major part of the text. Much of the detail has been omitted and only the evidence which is essential to support the conclusions is given. It is hoped that the text will be more readable by not belaboring the reader with data, numbers, and definitions which can be better presented in appendix form.
Fig. 1. Location of the Study Area in West-Central Minnesota. Showing adjacent study areas of Sackreiter (1975) and Anderson (1976). Size of study area is 3850 kilometres.
The map on Plate 1 shows the distribution of surficial sediments and geomorphic features in the area and is a visual summary of the study. The map units are briefly described and their genetic origins are given in the map legend. A more detailed description of the sediments is presented in Appendix B. The diagram, Age of the Stratigraphic Units, on Plate 1, presents the stratigraphic order of deposition and the estimated or known ages of the formations exposed in the study area. Description of the geomorphic features is presented in Appendix C.

Those persons interested in the methods are referred to Appendix A. Composition, regional correlation, and other detailed description of the surficial sediments are included in Appendix B. The origin and description of the topography in the study area is given in text section entitled Geologic History and in Appendix C. Basic laboratory data from the analysis of the glacial sediment is given in Appendix D.
GEOLOGIC HISTORY

The late Cenozoic history of the study area is here presented in seven episodes. An episode is a happening or occurrence of geologic importance. In this report, each episode is first described, and then the evidence to support the geologic history is presented. The geologic history is reconstructed from the study of nine lithostratigraphic units found within the study area (Figure 2). Seven of these units have been described in previous studies in eastern North Dakota and western Minnesota; the Downer and Hawley Formations are defined in this study. All of the units are pre-Wisconsinan, Wisconsinan, or Holocene in age.

Episode I

Episode I, probably occurring during pre-Wisconsinan time, is the first late Cenozoic event for which there is any evidence. During that time, a glacier advanced from the northeast probably over all of the study area. Glacier ice deposited in the pebble-loam of Unit A, and melt water deposited the sand and gravel of Unit A. The ice advance is thought to have occurred in northwestern Minnesota because Unit A is correlated with Unit 2 (Sackreiter, 1975), and it is thought to have occurred in northeastern North Dakota because Unit A is correlated with the Tiber Formation (Sackreiter, 1975) (Table 1).

The maximum observed thickness of Unit A is 2.5 metres. Nowhere in the study area has the lower contact been observed, and the upper
Fig. 2. Time-Distance Diagram Showing Periods of Deposition of Formations in West-Central Minnesota.
Table 1. Correlation of Stratigraphic Units Present in the Study Area with Stratigraphic Units in Other Areas.
|---------------------------|--------------|--------------------|------------------------|--------------------------|------------|------------------------|------------------------|

<table>
<thead>
<tr>
<th>Unit D</th>
<th>Hawley Pm.</th>
<th>Barnesville Pm.</th>
<th>New Ulm Till</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.33-0.39-0.28</td>
<td>0.34-0.42-0.24</td>
<td>0.31-0.43-0.26</td>
<td></td>
</tr>
<tr>
<td>0.53-0.30-0.17</td>
<td>0.53-0.42-0.05</td>
<td>0.27-0.33-0.45</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dahlen Pm.</th>
<th>Dahlen Pm.</th>
<th>Red Lake Falls Pm.</th>
<th>Red Lake Falls Pm.</th>
<th>Dunvilla Pm.</th>
<th>Dunvilla Pm.</th>
<th>New York Mills Pm.</th>
<th>Granite Falls Till</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.32-0.33-0.33</td>
<td>0.31-0.42-0.27</td>
<td>0.35-0.41-0.24</td>
<td>0.28-0.45-0.27</td>
<td>0.36-0.39-0.25</td>
<td>0.40-0.35-0.25</td>
<td>0.31-0.43-0.26</td>
<td>0.38-0.43-0.20</td>
</tr>
<tr>
<td>0.25-0.15-0.60</td>
<td>0.31-0.24-0.43</td>
<td>0.51-0.34-0.13</td>
<td>0.60-0.27-0.13</td>
<td>0.41-0.24-0.35</td>
<td>0.40-0.25-0.35</td>
<td>0.27-0.23-0.45</td>
<td>0.49-0.43-0.02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>New York Mills Pm.</th>
<th>Granite Falls Till</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44-0.36-0.20</td>
<td>0.45-0.39-0.16</td>
</tr>
<tr>
<td>0.57-0.37-0.05</td>
<td>0.82-0.17-0.01</td>
</tr>
<tr>
<td>0.71-0.27-0.02</td>
<td>0.64-0.32-0.04</td>
</tr>
<tr>
<td>0.49-0.43-0.02</td>
<td>0.38-0.43-0.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Marcoux Pm.</th>
<th>Sebeka Pm.</th>
<th>Hawk Creek Till</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.36-0.40-0.24</td>
<td>0.54-0.33-0.13</td>
<td>0.47-0.26-0.13</td>
</tr>
<tr>
<td>0.78-0.19-0.05</td>
<td>0.85-0.13-0.01</td>
<td>0.80-0.20-0.00</td>
</tr>
<tr>
<td>0.93-0.07-0.00</td>
<td>0.79-0.12-0.01</td>
<td>0.31-0.38-0.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit A</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.37-0.36-0.29</td>
</tr>
<tr>
<td>0.69-0.28-0.03</td>
</tr>
</tbody>
</table>
contact of Unit A with the overlying Sebeka Formation has been observed in only one outcrop in the study area (for description of Unit A, see Appendix B).

The sand and gravel lithology of Unit A was observed in the study area, and probably has an associated pebble-loam that was not observed. The pebble-loam is probably the same as the pebble-loam of Unit 2. Unit 2 is found below the Marcoux Formation in two testholes in Sackreiter's (1975) study area to the north. In Sackreiter's study area, the pebble-loam matrix (finer-than-gravel fraction) averages 0.37 sand, 0.34 silt, and 0.29 clay. The very-coarse sand (1 to 2 mm) of the pebble-loam averages 0.69 igneous and metamorphic rock, 0.28 limestone and dolomite, and 0.03 shale.

The large amount of igneous and metamorphic rock indicates the pebble-loam was derived from an area to the northeast on the Canadian Shield of northern Minnesota and southwestern Ontario. The location of the source area implies a glacial advance to the southwest.

Although the pebble-loam of Unit A was not observed in the study area, it is predicted that Unit A pebble-loam in the study area will be sandier, have less shale, and have a higher proportion of limestone and dolomite relative to the amount of igneous and metamorphic rock than in Sackreiter's area. The prediction is based on the compositional variation of the pebble-loam lithologies with distance down glacier (see Appendix B).

The sand and gravel of Unit A was probably deposited by braided streams because the sediment is very poorly sorted, has a large amount of gravel, and lacks silt and clay. The sediment is generally an
interbedding of fine to coarse sand, sandy gravel, and gravelly sand that is cross bedded or horizontal bedded.

The topography created by the glacier of Episode I has been covered or destroyed by the geologic processes of subsequent geologic episodes. The melt water of the glacier created fluvial channels in which the sand and gravel of Unit A was deposited. These channels can be seen partly buried beneath the Sebeka Formation (Plate 1). They appear on air photographs as a chain of depressions or as trough-shape depressions containing wetlands.

The age of this episode is tentatively dated as pre-Wisconsinan. This conclusion is based on the stratigraphic position of Unit A below the Sebeka Formation.

**Episode II**

Episode II occurred during pre-Wisconsinan or Early Wisconsinan time. At that time, a glacier advanced from the northeast, probably over all of the study area, across eastern North Dakota, southwestern Minnesota, and northwestern Minnesota. The glacier eroded the sediment of Unit A, forming the drumlins of the Wadena Drumlin Field, which the glacier later covered with a layer of pebble-loam of the Sebeka Formation (Plate 1).

The layer of pebble-loam has a maximum observed thickness of 3 metres. Correlation of the Sebeka Formation with the Hawk Creek Till in southwestern Minnesota (Matsch, 1971), the Marcoux Formation of northwestern Minnesota (Sackreiter, 1975, Harris and others, 1974, and Harris, 1975), and the Cando Formation in eastern North Dakota (Hobbs, 1975) indicates the extent of this advance (Table 1).
The pebble-loam of the Sebeka Formation has a matrix with a mean composition of 0.61 sand, 0.26 silt, and 0.13 clay. The very-coarse sand (1 to 2 mm) in the matrix has a mean composition of 0.80 igneous and metamorphic rock, 0.20 limestone and dolomite, and 0.00 shale. The large amount of igneous and metamorphic rock in the very-coarse sand indicates that the pebble-loam was derived from the Canadian Shield to the northeast of the study area. Typically, the pebble-loam of the Sebeka Formation is overlain by numerous boulders and cobbles scattered on uncleared pastureland and in enormous boulder piles on cleared cropland.

The Sebeka Formation overlies Unit A; the contact between these units is abrupt and unconformable. The Sebeka Formation is overlain by the New York Mills Formation; the contact between these two formations has not been observed in outcrop. It can be inferred that the New York Mills Formation overlies the Sebeka Formation because fluvial sediment which appears to be derived from the pebble-loam of the New York Mills Formation has partly buried the drumlins that are covered with pebble-loam of the Sebeka Formation. This fluvial sediment is assumed to have been deposited from the melt water of the glacier that deposited the pebble-loam of the New York Mills Formation.

The drumlins are 10 to 20 metres high and about a kilometre long. South of Wolf Lake, the long axis of the drumlins is oriented east-west. To the east, the orientation of the drumlins gradually changes, and beyond the eastern boundary of the study area the drumlins are oriented northeast-southwest. The drumlins found beyond the eastern boundary are partly buried beneath fluvial sediment of the New York Mills Formation.

The burial of the drumlins beneath the fluvial sediment can be explained in the following manner. First, melt-water channels were cut
around the base of the drumlins. Then, a cycle consisting of the collection of water behind ice dams within the channels, the freezing of the dammed water, and the deposition of an insulating layer of sand and gravel over the ice. This cycle probably occurred several times until the channels were filled with sand and ice. Eventually, the drumlins were buried beneath the sediment of the fluvial plain. Finally, after several hundred years of warmer climate, the ice melted, causing the sediment overlying the channels to collapse. As a result of the collapsing of the sediment, the sand and gravel is draped over the drumlins.

**Episode III**

During Early Wisconsinan time, a glacier advanced from the northeast and covered the western part of the study area (Figure 3). The glacier deposited the pebble-loam in the New York Mills Formation, having a maximum observed thickness of 8 metres, and the melt water deposited the fluvial sand and gravel in the New York Mills Formation, having a maximum recorded thickness of 39 metres. Where observed, the sand and gravel facies overlies the pebble-loam facies. The extent of the New York Mills Formation exposed in the study area is shown in Plate 1. Plate 2 shows the thickness of the sand and gravel lithology in the Park Rapids Fluvial Plain. Correlation of the New York Mills Formation with the lower part of the Red Lake Falls Formation in northwestern Minnesota (Sackreiter, 1975, Harris and others, 1974), and the Granite Falls Till in southwestern Minnesota (Matsch, 1971) indicates the total known extent of this ice advance (Table 1).

The distinguishing characteristics of the pebble-loam are the large amount of sand (0.51) in the matrix, the large amount of igneous
Fig. 3. Early Wisconsinan Advance of Glacial Ice from the Northeast. Deposition of New York Mills Formation (west-central Minnesota), lower part of the Red Lake Falls Formation (northwestern Minnesota), and Granite Falls Till (southwestern Minnesota).
and metamorphic rock (0.71), and the small amount of shale (0.02) (many samples contain no shale in the very-coarse sand). The composition of the pebble-loam of the New York Mills Formation is similar to the composition of the pebble-loam of the Sebeka Formation, but the pebble-loam of the Sebeka Formation is sandier (averaging 0.61 as compared to 0.51) contains more igneous and metamorphic rock (averaging 0.80 as compared to 0.71), and consistently contains no shale. The large amount of igneous and metamorphic rock in the very-coarse sand of the pebble-loam of the New York Mills Formation indicates the pebble-loam was derived from the Canadian Shield, northeast of the study area. Occurrences of boulder-size inclusions of sand and gravel are fairly common and are more common in the New York Mills Formation than in the other formations within the study area.

The sand and gravel is known to have been deposited in braided streams because the channels of the streams are visible on aerial photographs. The fluvial sediment contains interbedded sand, gravelly sand, and gravel, with the sand having ripple and dune cross bedding as well as horizontal bedding and the gravel having mostly horizontal bedding with some dune cross bedding. The stones in the gravel consist of igneous and metamorphic rock, limestone, and dolomite. In the western part of the study area, no shale has been observed in the sand and gravel of the New York Mills Formation, and in the eastern part of the study area, a minute amount of shale has been observed. Folding and faulting in the sand and gravel, evidence for the collapse of the sediment as the underlying glacial ice melted out, are more prevalent in the New York Mills Formation than in the fluvial sediment than in other formations (see Appendix B for description of New York Mills Formation).
The topography created during this episode contrasts with the topography created during Episode II. The topography of Episode III is hummocky terrain with high relief (generally more than 10 and less than 20 metres difference in elevation of adjacent high and low areas) mostly underlain by pebble-loam. Numerous small scattered patches of sand and gravel deposited from supraglacial melt water overlie the pebble-loam of the New York Mills Formation. The topography formed during Episode III consists mostly of collapse glacial features such as linear and circular disentraction ridges, circular depressions, and conical hummocks. These features have an irregular surface, resulting in angular contours. The collapse features that are composed of pebble-loam of the New York Mills Formation have steeper slopes than collapse features composed of pebble-loam of the other formations. This is because the pebble-loam of the New York Mills Formation had a higher shear strength when it was deposited than the other glacial sediment deposited in the study area. The higher shear strength of the New York Mills pebble-loam probably results from its lower clay and much more sand content than the other glacial sediment in the study area. The steeper slopes may also be caused by the thickness of the glacial sediment. Assuming that the grain-size distribution and the clay mineralogy are the same for all the pebble-loam lithologies of the study area, the thinner the supraglacial sediment, the steeper are the slopes of the collapse features (Clayton and Moran, 1974). It is not known whether the pebble-loam of the New York Mills Formation is thinner than the other pebble-loam units of the study area.

Local glacial flow to the south and southeast are indicated by the numerous tranverse compressional lineations and subglacial
longitudinal shear marks (defined in Appendix C) overlain by pebble-loam of the New York Mills Formation. For example, 20 kilometres northeast of Detroit Lakes, around Height of Land Lake, the local glacial-flow direction to the southeast represents a small diversion of the overall glacial flow direction to the southwest probably as a result of a regional slope to the south and southeast. The diversion may also have been caused by a central spreading center to the northwest. The formation of the spreading area may have been the result of a local thickening of the glacial ice, caused by increased accumulation.

Most of the sand and gravel was deposited in proglacial fluvial plains and melt-water channels. Eskers on the western and northwestern margin of many of the fluvial plains suggests that the margins of the fluvial plains represent temporary standstills of a retreating glacial margin and that the fluvial plains are proglacial (for an example, the fluvial plain 8 kilometres south of Height of Land Lake). Sediment of the fluvial plains was deposited by braided streams, the anastomosing channels are visible on aerial photographs.

Many of the braided streams are truncated by linear pits in the fluvial plains, which are partly buried fluvial channels. The buried channels are many times wider and deeper than the braided stream channels on the surface of the plains. Apparently, these channels existed before the formation of the fluvial plains and were created before Episode III or during an early retreat phase of Episode III. During this early retreat phase, the melt water was free of sediment and was able to cut narrow channels. As the sediment load became greater, the streams aggraded, as a result, and the narrow channels became choked with sediment and were eventually buried.
The orientation of the melt-water channels created during the later phases of Episode III showed that water flowed to the south and southeast away from the ice margin. Some of the channels originate on the terrain covered with glacial sediment and feed into fluvial plains. Other melt water channels that formed later cross both the glacial sediment and fluvial plains.

**Episode IV**

During Episode IV, in Late Wisconsinan time, glacier ice of the Des Moines Lobe advanced from the northwest, over the western part of the study area (Figure 4). The eastward advance of this glacier was blocked by dead ice in central Minnesota left behind by the glacier of Episode III. Clayton (1966) points out that the Streeter ice margin in North Dakota and the Burnstad ice margin in North Dakota and South Dakota were contemporaneous with the Des Moines Lobe in central Minnesota. The Streeter and Burnstad ice margins are several hundred metres higher than the Des Moines Lobe in central Minnesota. Clayton suggested that the Des Moines Lobe should have spread eastward into the relatively low land (at 455 metres elevation or less) in the area of central Minnesota but that the ice advance into the area could have been prevented by a band of dead ice moraine from a glacier from the northeast (Episode III of this report).

This western glacier deposited the pebble-loam of the Dunvilla Formation. The extent of the Dunvilla Formation is not fully known. However, correlation of the Dunvilla Formation with the upper part of the Red Lake Falls Formation, immediately north of the study area (Sackreiter, 1975, Harris and others, 1974), and the Dahlen Formation,
Fig. 4. First Late Wisconsinan Glacial Advance from the Northwest. Deposition of Dunvilla Formation (west-central Minnesota), upper part of the Red Lake Falls Formation (northwestern Minnesota), and Dahlen Formation (western North Dakota).
of western North Dakota (Hobbs, 1975, Camara, in preparation), (Table 1) indicates the known extent of this ice advance. The extent of the Dunvilla Formation exposed in the study area is shown in Plate I.

The Dunvilla Formation contains pebble-loam having a maximum observed thickness of 2.5 metres. The pebble-loam of the Dunvilla contains more shale (averaging 0.35 as compared to 0.02) and less sand (averaging 0.36 as compared to 0.51) than the pebble-loam of the underlying New York Mills Formation (see Appendix B for detailed description of Dunvilla Formation).

The large amount of shale in the pebble-loam of the Dunvilla was in part derived from eastern North Dakota, evidence that the glacier entered the study area from the northwest.

The topography created by Episode IV is hummocky terrain of medium relief (8 to more than 15 metres) underlain with the pebble-loam of the Dunvilla Formation. This terrain is similar in appearance to the terrain underlain by the pebble-loam of the New York Mills Formation. The terrain of this episode, however, has lower relief, fewer small depressions, and does not have transverse-compressional lineations. As stated previously in the discussion of Episode III, the difference in relief of collapsed glacial terrain underlain by pebble-loam may result from the thickness of the sediment or the amount of clay in the pebble-loam. The amount and type of subglacial erosion may also cause the difference in relief. Glacial thrusting caused the numerous tranverse compressional ridges found in the terrain underlain by pebble-loam of the New York Mills Formation. No evidence of this form of subglacial erosion was seen associated with
the Dunvilla Formation and on this basis it is assumed that large-scale subglacial thrusting was absent or minor during the deposition of the pebble-loam of the Dunvilla Formation.

**Episode V**

During Episode V, in Late Wisconsinan time, the eastern margin of the Des Moines Lobe fluctuated, causing the glacier to readvance into the study area from the northwest (Figure 5). It is speculated that the readvance was on the order of 100 kilometres. The glacier deposited the pebble-loam of the Barnesville Formation, and the melt water produced by the glacier deposited the sand and gravel of the Barnesville Formation. The extent of the Barnesville Formation exposed in the study area is shown in Plate I. Outside the study area, the known extent of the ice advance is limited to Anderson's (1976) study area in west-central Minnesota. No correlative of the Barnesville Formation has been recognized elsewhere (Table 1).

Within the study area, the Barnesville Formation contains pebble-loam as thick as 6.5 metres and sand and gravel as thick as 3.5 metres. Where observed, the sand and gravel generally overlies the pebble-loam.

The distinguishing characteristics of the pebble-loam are the small amount of sand (0.16) in the pebble-loam and the large amount of shale (0.16) in the very-coarse sand fraction. The comparatively large amount of shale is evidence that the rock was in part derived from the Pierre Shale outcropping in eastern North Dakota. The glacier that deposited the pebble-loam therefore entered the study area from the northwest. Compared to the pebble-loam of the underlying Dunvilla
Fig. 5. Second Late Wisconsinan Glacial Advance from the Northwest. Deposition of Barnesville Formation (west-central Minnesota).
Formation, the pebble-loam of the Barnesville Formation is less sandy (0.16 as compared to 0.36) and has less shale in the very-coarse sand (0.16 as compared to 0.35).

The fluvial sand and gravel of the Barnesville Formation is similar to the stratified fluvial sand and gravel of the New York Mills Formation. The Barnesville Formation, however, contains a small amount of shale whereas the New York Mills Formation has none. (In one outcrop in the western part of the study area a minute amount of shale was observed in what is believed to be fluvial sediment of the New York Mills Formation). (See Appendix B for detailed description of the Barnesville Formation).

Probably the ice advance of Episode V is a local fluctuation of a relatively short distance, for the following reasons. There is no evidence, such as a soil horizon, a weathered zone between the Barnesville and Dunvilla Formation, or radiocarbon dates that would indicate as long an interglacial period as would be expected prior to a major glacial fluctuation. There is no change in the flow direction of the ice from Episode IV to Episode V, suggesting the two ice advances are related to the same ice lobe. The pebble-loam of the Barnesville Formation is limited to east-central Minnesota, suggesting that the readvance of the ice margin was a local occurrence.

The pebble-loam of the Barnesville Formation is associated with two different types of topography. The first type consists of broad hills with hummocks superimposed on them with a total average relief of 12 to 20 metres (25 metres maximum). This type of topography is found east of Detroit Lakes around Big Cormorant Lake. The broad hills are
probably the pre-advance topography that was modified by glacial erosion. The small hummocks of pebble-loam were later deposited on top. The second type of topography consists of hummocks having an average relief of 8 to 15 metres (20 metres maximum). These hummocks of pebble-loam obscure the pre-advance surface so that it does not readily show through.

Compared with the topography underlain by the pebble-loam of either the New York Mills or the Dunvilla Formations, the topography underlain by the Barnesville Formation has smoother, more regular contours, and broader hummocks.

The pitted fluvial plains created during this episode are either proglacial, as is the fluvial plain in the Detroit Lakes area, or are supraglacial, as are the two fluvial plains west of Detroit Lakes. The supraglacial fluvial plains have high relief similar to the relief of adjacent areas underlain by pebble-loam. In the large supraglacial fluvial plain west of Detroit Lakes, fault grabens created as the sediment collapsed can be observed on aerial photographs (section 17, T. 138N, R. 43W). The proglacial fluvial plain in the Detroit Lakes area contains many large lakes that were formed by the melting of large blocks of ice that stuck out above the level of the plain.

**Episode VI**

During Episode VI, in Late Wisconsinan time, the ice margin readvanced a short distance, perhaps 100 kilometres, to the southeast from a position to the north (Figure 6). This readvance probably represents a small fluctuation of the ice margin of the Des Moines Lobe because the direction of the ice movement is the same as direction of the ice movement in the two previous episodes suggesting the three ice advances from
Fig. 6. Third Late Wisconsinan Glacial Advance from the Northwest. Deposition of Hawley Formation (west-central Minnesota) and Unit D (southwestern North Dakota).
the northwest are related to the same ice lobe. The initial advance of this ice was halted by stagnant ice of Episode V, which persisted in the Big Cormorant Lake area (description of this area given in Episode IV).

The glacier of this advance deposited the pebble-loam of the Hawley Formation, which has a maximum observed thickness of 3.5 metres; the melt water produced from the glacier deposited the fluvial sand and gravel of the Hawley Formation, which has a maximum observed thickness of 4.5 metres. Where observed, the sand and gravel overlies the pebble-loam. The extent of the Hawley Formation exposed in the study area is shown on Plate 1. The Hawley Formation (new) is tentatively correlated with Unit D in southeastern North Dakota (Camara, in preparation) (Table 1).

Distinguishing characteristics of the pebble-loam of the Hawley Formation are the moderate amount of sand (0.35) in the pebble-loam matrix and a large amount of igneous and metamorphic rock (0.53), as well as a small amount of shale (0.05) in the very-coarse sand (1 to 2mm). Compared to the pebble-loam of the Barnesville Formation, the pebble-loam of the Hawley Formation contains less shale (averaging 0.05 as compared to 0.16) and more sand (averaging 0.35 as compared to 0.16). The relatively large amount of limestone and dolomite plus the presence of shale in the very-coarse sand in the pebble-loam is evidence that the rocks in the pebble-loam were derived from outcrops in eastern North Dakota and south-central Manitoba and that the glacial sediment was deposited by a glacier coming from the northwest.

Two lines of evidence suggests stagnant ice in the Big Cormorant Lake area (covered with pebble-loam of the Barnesville Formation, Plate 1)
halted the ice of Episode VI. First, the ice advance of Episode VI should have maintained an ice margin at 440 metres elevation along its entire length. In the eastern part of the study area, south of Hawley, the ice margin of Episode VI is 30 to 50 metres lower than it is in the central part of the study area by Detroit Lakes (440 metres elevation). The difference in the elevation of this ice margin suggests that part of the ice margin was against dead ice. Second, ice should have flowed into the low land of the Big Cormorant Lake area but evidently failed to do so because of the occupation of this area by dead ice. The average elevation of the Big Cormorant Lake area is 30 to 50 metres lower than the ice margin of Episode VI.

After the initial glacial advance of Episode VI, the ice margin retreated to a position somewhere just west of the Buffalo River melt water channel. The melt water from the glacier margin when it was in the northern part of the study area and north of the study area flowed southward in the Buffalo River channel and its tributary channels. These channels cross the area that is covered by pebble-loam of the Hawley Formation (Plate 1). Originally, the Buffalo River flowed past Hawley, and into the fluvial plain to the south. From there, the water continued southward and out of the study area. During this time, the ice margin in the central part of the study area was located a few kilometres west of Hawley. The melt water from this section of the ice margin flowed to the southeast and into the same fluvial plain as the Buffalo River. As the ice margin continued to retreat, production of melt water from the ice margin west of Hawley ceased. The water flowing down the Buffalo River then incised its channel below the level of the
fluvial plain. This caused the water in the channel to be diverted westward into Lake Agassiz.

At about this time, the section of the Buffalo River melt-water channel east of the Clay-Becker County boundary, was covered by a glacial readvance and was buried by a layer of pebble-loam. The part of the Buffalo River melt-water channel not covered by the readvance, west of the Clay-Becker County boundary, has steep sides, and fluvial sand and gravel is found at the bottom of the channel. The part of the Buffalo River melt-water channel covered by the readvance, east of the county boundary, has much gentler slopes and is poorly defined, and pebble-loam is found at the bottom of these channels. Upon retreat of the ice margin, several transverse depositional ridges were produced north of Lake Park (Plate 1). These ridges are less than 3 metres high and are concave to the northwest. The ridges trace the successive ice margin positions of the glacier as it retreated northwesterly out of the study area.

Supraglacial-lake sediment is found in the pebble-loam of the Hawley Formation south of Hawley and buried lake deposits are exposed in a gravel pit outside of Muskota. The buried lake deposits consist of lenses of laminated clayey silt. The concave upward lenses are less than 0.1 metre thick and 2 to 4 metres long. Within the laminated clayey silt are gravel-size fragments of pebble-loam and clayey silt. The presence of supraglacial-lake deposits at these two locations suggests that the glacial sediment was underlain by dead ice. The dead ice eventually melted, causing the overlying pebble-loam to collapse and form small depressions. Some of the depressions were filled with
surface run-off water, creating small supraglacial lakes. As the clayey silt was deposited, continued melting of the underlying ice caused the lake basin to gradually sink. Fragments of pebble-loam from along the margin of the lake and clayey silt from the outer margin of the lake broke off and were deposited in the lake basins by small debris flows. Continued melting of the ice resulted in the filling of the depressions with pebble-loam deposited by debris flows. Many of the depressions were only partly filled and some remain as small lakes and sloughs on top of the pebble-loam of the Hawley Formation.

**Episode VII**

During Episode VII (from 13,000 to 9,500 B.P.), Lake Agassiz existed in the western part of the study area (Ashworth and others, 1972) (Figure 7). Sediment deposited during the Emerson Phase of Lake Agassiz include deep-water clayey silt of the Sherack Formation. Near-shore silty, very-fine sand of the Downer Formation was deposited during the Emerson Phase and the beach sand and gravel of the Downer Formation was deposited during the Lockhart and Emerson Phases. Present-day streams, bogs, and sloughs throughout the study area came into existence about 12,300 years B.P. (McAndrews, 1966), after the last glacial advance retreated from the study area. The streams continue to deposit the silt, sand, and gravel of the Walsh Formation, and the bogs and sloughs continue to deposit the peat and organic clay of the Walsh Formation (Plate 1).

The Downer Formation (new) is composed of silty, very-fine sand, having a maximum observed thickness of 2 metres, and sand and gravel, having a maximum observed thickness of 2.3 metres. The Downer Formation
Fig. 7. Phases of Lake Agassiz During Late Wisconsinan to Holocene Time. Major rivers in the study area are shown.
has not been lithostratigraphically correlated with any other previously recognized lithostratigraphic unit (Table 1).

The sand and gravel of the Downer Formation differs from the sand and gravel of other formations previously mentioned in several ways. Where observed, the sediment of the Downer Formation is excellently sorted between bedding planes; in the gravel the stones have a well developed imbrication with the stones dipping down the regional slope, and the sediment has low-angle cross bedding. In the sand and gravel of the other formations in the study area, the sediment is poorly sorted, the stones in the gravel have a poorly developed imbrication with the stones dipping up the regional slope, and the sediment has high-angle cross bedding.

In the study area, the sand and gravel of the Downer Formation is found in a narrow belt oriented north-south. Within this narrow belt, the sediment is deposited in north-south ridges and in a veneer covering a bevelled slope that slopes gently to the west.

The silty, very-fine sand of the Downer Formation has horizontal bedding and low-angle cross bedding having a thickness of less than 0.002 metres. The sand is white (5Y 8/2) with light, yellowish (2.5Y 6/4) mottles. The silty, very-fine sand is found immediately west of the sand and gravel of the Downer Formation in a narrow north-south belt. On the surface, the silty, very-fine sand deposited in a near-shore environment, has a nearly flat surface sloping to the west, having a gradient of about 2 metres per kilometre.

The Sherack Formation is composed mostly of clayey silt, with silty clay and silt, having a maximum observed thickness of 3 metres.
The sediment is horizontally bedded, with individual laminae having a maximum thickness less than 0.0025 metre. The Sherack Formation is dark olive gray (10YR 3/1) or light olive gray (5Y 6/2) when moist. The Sherack Formation, which outcrops west of the Downer Formation, has a flat surface interrupted only by some very low undulations and ridges.

In the study area, the Walsh Formation is composed of peat and organic clay having a maximum observed thickness of 1 metre and silt, sand, and gravel having a maximum observed thickness of 2 metres.

The peat and organic clay is composed primarily of partly decayed organic material with some sand and silt deposited in sloughs and ponds. The bedding may be vague or absent. The silt, sand, and gravel is sediment deposited in stream channels and stream flood plains. The sediment is poorly sorted fine to coarse sand, sandy gravel, and gravel where found in stream channels; as overbank sediment, it is primarily sandy silt with some silty sand. The overbank sediment has poorly developed horizontal bedding; the bedding of the channel sediment has not been observed.

The presence of organic material within the fluvial sediment of the Walsh Formation separates this unit from the fluvial sediment of the other formations found in the study area. (See Appendix B for complete description of the above formations).

Several events occurred during Episode VII. The first of these is the Lockhart Phase of the Lake Agassiz history. From about 13 500 to 11 000 years B.P., the Des Moines Lobe occupying the Lake Agassiz basin retreated northward into southern Manitoba. The melt water from this glacier refilled the Lake Agassiz basin, and the water from the
lake flowed through the southern outlet at Browns Valley. While the lake drained through Browns Valley, the lake level slowly fell and then temporarily stabilized at the Campbell Level.

North of the study area, below the Campbell level, Ashworth and others (1972) reported a local unconformity overlain by a layer of peat. Johnson (1921), Brophy (1967), and several other investigators also have recognized this unconformity in other areas throughout the Lake Agassiz basin. The unconformity is evidence that Lake Agassiz was temporarily drained. Johnson (1921) reasoned that the lake was drained when the glacier that was occupying the basin retreated to the northeast and opened lower outlets. Before the lake receded from the study area, however, beach sediment of the Downer Formation was deposited along the Campbell and higher shorelines, along with the offshore sediment of the Argusville Formation, which was not observed in this study.

The Lockhart Phase was followed by the Moorhead Phase, from 11 000 to 9 900 years B.P. During the Moorhead Phase, the plain of the drained Lake Agassiz was a swamp (Brophy, 1967, Ashworth and others, 1972). Streams flowed across the lake plain, depositing the fluvial sediment of the Poplar River Formation (Harris and others, 1974), which were not observed in this study.

About 9 900 years B.P., the Emerson Phase began when the ice sheet north of the study area readvanced and closed the eastern drainage outlets of Lake Agassiz. This caused the water of Lake Agassiz to rise until the outlet at Browns Valley was reactivated (Ashworth and others, 1972). The deep-water sediment of the Sherack Formation was deposited during this period, as was the near-shore sediment and beach
sediment of the Downer Formation. Once again, the glacier north of the study area retreated northward and reopened the eastern drainage outlets, causing the lake to drain rapidly. About 9 300 years B. P., the lake receded from the study area for the last time (Ashworth and others, 1972). During the Emerson Phase, the lower shorelines were produced in the study area.

At the time Lake Agassiz existed, the present-day bogs, sloughs, and streams were forming on the glaciated upland. Prior to 12 300 years B. P. and after the final retreat of the glacial ice, a boreal forest predominately of spruce and aspen trees developed on the glaciated upland (McAndrews, 1966). About 11 000 years B. P., the boreal forest was replaced by a pine forest in west-central Minnesota and by a prairie grassland in North Dakota. On the glaciated upland were numerous water-filled depressions created by the slow melting of buried ice over a period of several thousand years (Florin and Wright, 1969). Peat and organic clay of the Walsh Formation was probably being deposited in the abandoned melt-water channels prior to the deposition of peat and organic clay in the forming ice-melt depressions.

Due to the short time it has had to develop, the drainage within the study area is largely non-integrated. However, the drainage is more integrated along the Lake Agassiz beach slope where the strandlines have a U shape or cuspatel form. The points of the cusps are about 2 to 4 kilometres apart. Between the cusps, down slope of the strandline, there is a shallow basin cut into the slope. Numerous drainage channels have developed within each of these basins. These channels converge at the bottom of the basin to form a single channel which
breeches the next lower strandline. The collection and concentration of water into a single channel within the basins has accelerated the development of integrated drainage. When the water flows out onto the lake plain from the beach slope, the slope decreases rapidly. At the point where the slope changes, the drainage lines spread out, creating alluvial fans. Several of these alluvial fans occur along the western edge of the Lake Agassiz beach slope. An example of this type of drainage is in sections 33, 34, and 35, T. 139N, R. 46W, about 6 kilometres north of Downer (Plate 1).

Several very low isolated ridges can be seen on the Lake Agassiz plain (Plate 1). One particularly large ridge is found near Sabin and is referred to as the Sabin Ridge or King's Trail. The name King's Trail apparently originated in the early 19th century when the Hudson Bay Company operated in the area. Along this ridge are the Moorhead municipal water wells, which are drawing water from a major sand and gravel aquifer below the ridge, and several gravel pits. At one of the sand and gravel pits on the ridge, the sand and gravel is being dredged from below the Sherack Formation to a depth of 40 metres. At other sand and gravel pits a few kilometres south of the dredging operation, the sand and gravel is being excavated along with the fluvial sand and gravel outcropping on the surface. The presence of sand and gravel below the Sabin Ridge suggests that the Sabin Ridge and the other isolated ridges on the lake plain are compaction ridges. These ridges formed as a result of the compression of the Sherack Formation around underlying largely incompressible fluvial sand and gravel bodies (Bluemle, 1967).
The fluvial sand and gravel exposed in the gravel pits along the Sabin Ridge indicates a southward flow direction. The sediment is highly faulted in many places, evidence that the sediment collapsed during the melting of underlying ice. This evidence suggests that the Sabin Ridge is probably a partly buried esker left behind after the last glacial advance into the study area.
APPENDIX A

METHODS AND PROCEDURES
Field work began May, 1975, and was completed October, 1976. Using aerial photographs (see Table 2 for list of photographs) and soils maps (Nikiforoff and others, 1939, Arneman and others, 1969) as a source of supplementary lithologic information, the surface sediment of the study area was mapped at a scale of 1:250 000. Field techniques included the examination of outcrops to determine the lithologic character and stratigraphic position of the surface sediment and the collection of pebble-loam samples for laboratory analysis to help characterize different stratigraphic units.

Almost every passable road in the study area was driven. Seventy-two pebble-loam samples were collected at suitable outcrops. At each sample locality one sample was collected from each stratigraphic unit believed to be present.

Laboratory analysis was performed to determine the proportion of sand, silt, and clay in the pebble-loam and to determine the petrography of the very-coarse sand. The petrographic categories determined were igneous and metamorphic rock, limestone and dolomite, and shale.

**Determination of Sand, Silt, and Clay Content**

1. Air dry the samples for 48 hours.

2. Weight out approximately 30.0 to 35.0 g of sample and physically disaggregate.

3. Weigh to the nearest 0.001 g.

4. Place the sample in a beaker and add $1.25 \times 10^{-4} \text{m}^3$ of Calgon (Na$_3$PO$_4$)$_6$ stock solution. The stock solution is made up to a concentration of 40 g/m$^3$ (56.5 mol/m$^3$) with distilled water.
Table 2. List of the Aerial Photographs Used in This Study.
Army Map Service
Corp of Engineers
Washington, D. C.

Minnesota, 1952
nos. 366 to 377
nos. 904 to 916
nos. 83 to 94

Mark Hurd Aerial Surveys, Inc.
Minneapolis, Minnesota

Minnesota, 1969
BRA-324 to BRA-333
BRA-324 to BRA-346
BRA-138 to BRA-150
BRA-1119 to BRA-1125
5. After the sample has soaked for 24 hours, mix the disaggregated sample and solution in a blender for 1 minute. Wash the mixed suspension into $10^{-3}$ m$^3$ graduate cylinder or hydrometer jar using distilled water. Fill the cylinder to $10^{-3}$ m$^3$ mark with distilled water.

6. Make up a standard in a $10^{-3}$ m$^3$ graduate cylinder by mixing $1.25 \times 10^{-4}$ m$^3$ of the Calgon stock solution and $8.50 \times 10^{-4}$ m$^3$ of distilled water.

7. Place a thermometer in the standard cylinder and record the temperature in degrees Celsius.

8. Mix the sample in suspension with a plunger to get all the clay-size particles in suspension. Insert the plunger to the bottom of the cylinder and vertically agitate through a distance of 0.1 m until all material is in suspension. Then withdraw the plunger to the top of the fluid column and return to the base. After 5 stirring strokes, remove the plunger.

9. After mixing each sample suspension record the time. Set the cylinder aside for the prescribed time shown in Table 3.

10. At the end of the specified time, insert a standard Bouyoucos H 9569 hydrometer into the sample suspension and the standard cylinder and record the readings.

11. Wet sieve the sample suspension using a number 230 U. S. Standard Sieve (0.0625 mm). This removes the silt and clay, leaving only the gravel and sand.

12. Put the gravel and sand in a beaker and place in a drying oven for 12 hours at 105° Celsius.
Table 3. Temperature and Corresponding Settling Time Required to Determine the Amount of Clay in Suspension Using a Hydrometer.
<table>
<thead>
<tr>
<th>Temperature</th>
<th>Settling Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>18°C</td>
<td>168.5 min.</td>
</tr>
<tr>
<td>19°C</td>
<td>164.5 min.</td>
</tr>
<tr>
<td>20°C</td>
<td>160.5 min.</td>
</tr>
<tr>
<td>21°C</td>
<td>156.5 min.</td>
</tr>
<tr>
<td>22°C</td>
<td>152.8 min.</td>
</tr>
<tr>
<td>23°C</td>
<td>149.4 min.</td>
</tr>
<tr>
<td>24°C</td>
<td>145.8 min.</td>
</tr>
</tbody>
</table>
13. Sieve the oven-dried samples in a RoTap machine for 10 minutes, using number 10 (2mm), 18 (1mm), and 230 (0.0625 mm) U. S. Standard sieves. This separates the gravel, very-coarse sand, and fine to medium sand.

14. Mark and weigh an envelope for the gravel and weigh the envelopes for the very-coarse sand and the fine to medium sand together.

15. Place the sieved material in the appropriate envelope. Weigh and record the gravel envelope and weigh both sand envelopes together.

16. Calculate:

A. (Gravel and envelope weight)-(envelope weight)= (weight of gravel).

B. (Sand and envelope weight)-(envelope weight)= (weight of sand).

C. (Sample weight)-(gravel weight)= (corrected sample weight).

D. (Hydrometer reading of sample in solution)-(hydrometer reading of standard cylinder)= (weight of clay).

E. (Corrected sample weight)-(weight of sand and clay)= (weight of silt).

F. \[\frac{(Weight \ of \ sand, \ silt, \ or \ clay)}{(Corrected \ sample \ weight)}\] = proportion of the matrix comprised of that constituent.

The procedure outlined above determines an arbitrarily defined "clay" content. Because the sand, silt, and clay data are intended for use as an index property for stratigraphic correlations rather than as a measure of the actual amount of sand, silt, and clay, the only requirement of the procedure is that it be reproducible. This procedure has been selected because it minimizes the time and labor needed to analyze and calculate the matrix parameters and it is reproducible.
At the time this procedure was adopted, examination of existing clay analyses, which has been determined with a pipette procedure, indicated that tills in eastern North Dakota and northwestern Minnesota most commonly contained a proportion of 0.20 clay in matrix. Values from 0.05 to 0.50 occur but values differed from the central tendency of 0.20 to 0.25 were rare. Thirty samples that were run as a comparison of the standard pipette and standard hydrometer (curve) procedures gave a mean $4 \times 10^{-6}$ m clay content of 0.23 with a standard deviation of about 0.06.

Because the depths at which the hydrometer reads is a function of the density of the fluid and therefore the amount of clay present, determination of clay content using a hydrometer requires a series of readings of time, depth, and density from which to plot a curve. It is not possible to know beforehand the time at which the particle size of interest will be the size being measured by the hydrometer as it is with the pipette method. Additional operation time is required to obtain the multiple readings and to make the calculations of actual clay content, which involves the use of a series of temperature and density dependent constants.

In view of the consideration outlined above Dr. S. R. Moran streamlined the procedure to use only a single hydrometer reading. From the test comparison of the thirty samples and the review of existing analysis, a proportion of 0.23 was selected as the amount of clay to standardize. A series of time-versus-temperature values were calculated for this amount of clay (Table 3) and used to determine when to take hydrometer readings. This procedure differs from the procedure used by the Quaternary laboratory of the Illinois State
Geological Survey (Moran, personal communication, May, 1977) only in that this procedure permitted temperature to vary, for which corrections were applied, whereas the Illinois laboratory uses a water bath to maintain constant temperature.

The procedure used for this study produces reproducible results, which deviate from actual amount to clay by an increasing amount the greater the values are from the standard proportion of 0.23. In samples that contain very little clay, the hydrometer will sink deeper and therefore read a large particle size giving an amount of clay that is greater than the actual amount of clay. In a very clayey sample, the hydrometer will ride higher and therefore read a smaller particle size. This will result in a reading less than the actual amount of clay (Moran, personal communication, May, 1977).

Determination of Petrography of the Very-Coarse Sand

1. Separate the very-coarse (1 to 2mm) sand that was isolated during the sand-silt-clay analysis into the four categories previously mentioned using a low-power binocular microscope.
   A. Place sand grains on watch glass.
   B. Separate the rock types using a knife onto separate watch glasses.
   C. Count grains.

2. Calculate:

\[
\frac{\text{Number of grains in a group}}{\text{Total number of grains}} = \text{Proportion for that petrographic class.}
\]
APPENDIX B

DESCRIPTION OF LITHOSTRATIGRAPHIC UNITS
The lithostratigraphic units of the study area consist of unconsolidated sediment. Criteria for recognizing the units are lithology and stratigraphic position. Boundaries of the lithostratigraphic units are defined in the following manner. Where a layer of glacial pebble-loam is overlain by a layer of fluvial sand and gravel, the two layers are considered to be facies of the same formation. Discontinuous inclusions of sand and gravel and clayey silt within the pebble-loam are considered part of that facies.

Descriptions of the lithostratigraphic units in Appendix B are given from the oldest to the youngest formation. From the laboratory analysis and field evidence, it has been determined that there are at least five distinctive formations in the study area that contain pebble-loam. Regional correlation of the lithostratigraphic units is presented in Table 1. The grain size and petrography of the very-coarse sand of the pebble-loam samples from each unit are listed in Appendix D. The means and standard deviations of the samples from each formation have been calculated for each formation and are presented in Table 4.

**Glacial Flow Direction and Compositional Variation in the Pebble-Loam in the Study Area**

Most of the pebble-loam in the study area is interpreted to be collapsed supraglacial debris-flow deposits derived from the melting out of englacial sediment. The composition of the sediment reflects the composition of the materials over which an eroding glacier advanced (Dremanis and Vagners, 1971). Based on the apparent source of the very-coarse sand in the pebble-loam found in the five formations, the general glacier flow directions are determined for each of the glacial advances.
Table 4. Summary of the Laboratory Analysis of the Pebble-Loam from the Lithostratigraphic Units, Showing the Means and Standard Deviations.
<table>
<thead>
<tr>
<th>Lithostratigraphic Unit</th>
<th>Number of Samples</th>
<th>Grain Size Proportions in the matrix</th>
<th>Very-Coarse Sand (1 to 2 mm) Petrography Proportions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sand</td>
<td>Silt</td>
</tr>
<tr>
<td>Hawley Fm.</td>
<td>18</td>
<td>0.34 ± 0.08</td>
<td>0.42 ± 0.06</td>
</tr>
<tr>
<td>Barnesville Fm.</td>
<td>14</td>
<td>0.16 ± 0.04</td>
<td>0.45 ± 0.07</td>
</tr>
<tr>
<td>Dunvilla Fm.</td>
<td>8</td>
<td>0.36 ± 0.08</td>
<td>0.39 ± 0.04</td>
</tr>
<tr>
<td>New York Mills Fm.</td>
<td>24</td>
<td>0.50 ± 0.08</td>
<td>0.31 ± 0.07</td>
</tr>
<tr>
<td>Sebeka Fm.</td>
<td>8</td>
<td>0.61 ± 0.03</td>
<td>0.26 ± 0.03</td>
</tr>
</tbody>
</table>
This assumes that one glacial advance deposits a single characteristic pebble-loam. The glacial flow directions are given in the discussion of the geologic history of the study area.

The source of the igneous- and metamorphic-rock fragments is the Precambrian Shield of Ontario, Manitoba, and northern Minnesota, north and northeast of the study area (Sims, 1970). The closest probable source of the Paleozoic limestone and dolomite detritus in the pebble-loam is eastern North Dakota and south-central Manitoba, northwest of the study area. The source of the shale detritus is west of the limestone and dolomite source area in eastern North Dakota and southwestern Manitoba (Matsch, 1971).

Analysis of the pebble-loam in northwestern and west-central Minnesota indicates that within this study area, Sackreiter's (1975) study area, and Anderson's (1976) study area, the formations can be distinguished on the basis of the proportion of igneous and metamorphic rock excluding the content of shale of the very-coarse sand relative to the amount of sand in the pebble-loam matrix (smaller-than-gravel-fraction of the pebble-loam) (Figure 8). The graph in Figure 8 also indicates that the lithostratigraphically correlated units have similar pebble-loam composition, but the composition changes with distance southward.

The amount of limestone, dolomite, and sand in the pebble-loam deposited by glaciers from the northwest (Barnesville, Dunvilla, and part of the Upper Red Lake Falls) increases down glacier. Presumably, the source of the limestone and dolomite is eastern North Dakota and south-central Manitoba. The change in composition may be due to one or both
Fig. 8. Graph of the Compositional Variation of Pebble-Loam of Lithostratigraphically Correlated Units in West-Central Minnesota and North-Central Minnesota.
Numbers beside the symbols represent average proportion of shale in the very-coarse-sand fraction.

(Sand in matrix)/(Sand + Silt + Clay in matrix)

**PEBBLE-LOAM LITHOLOGIES**

<table>
<thead>
<tr>
<th>Sackreiter (1975)</th>
<th>This Study</th>
<th>Anderson (1976)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawley Fm.</td>
<td>+</td>
<td>Barnesville Fm.</td>
</tr>
<tr>
<td>Barnesville Fm.</td>
<td>□</td>
<td>Barnesville Fm.</td>
</tr>
<tr>
<td>upper Red Lake Falls Fm.</td>
<td>△</td>
<td>Dunvilla Fm.</td>
</tr>
<tr>
<td>lower Red Lake Falls Fm.</td>
<td>□</td>
<td>New York Mills Fm.</td>
</tr>
<tr>
<td>Marcoux Fm.</td>
<td>○</td>
<td>Sebeka Fm.</td>
</tr>
</tbody>
</table>
of the following situations. Either the glacier eroded scattered patches of Paleozoic limestone and dolomite beneath the study area in western and west-central Minnesota, or the crushing of the limestone and dolomite to produce very-coarse sand occurred at a much faster rate than the crushing of the igneous and metamorphic rock. The first interpretation is unlikely since there is little or no evidence of limestone and dolomite in the Paleozoic section in west-central Minnesota (Austin, 1972, Anderson, 1957). The second interpretation would require that the limestone and dolomite be less resistant to crushing than igneous and metamorphic rock while being transported in glacier ice. The second interpretation is consistent with the conclusion of Dremanis and Vagner (1971) that during glacier transport, materials such as granite and gneiss that are more resistant to crushing and abrasion comminuted at a slower rate than less resistant materials such as limestone and dolomite.

The pebble-loam of the Sebeka, Marcoux, lower part of the Red Lake Falls, and New York Mills Formations display a less orderly change in the amounts of sand, limestone, and dolomite with increased distance down glacier than does the pebble-loam deposited by the western glaciers. This less orderly change is due to a shift from a bedrock source to a pebble-loam source; to the northwest for the limestone and dolomite. The distribution of the limestone and dolomite is erratic due to the varying areal distribution of the pebble-loam units, and to the varying distribution of the limestone and dolomite within each of the pebble-loam units. The erratic distribution of the source of the limestone and dolomite could result in limestone and dolomite being incorporated into the pebble-loam at different concentrations with each successive glacial advance.
Unit A

In the study area, Unit A consists of sand and gravel having a maximum observed thickness of 2.5 metres. The extent of Unit A is not fully known, but it has been observed in Anderson's (1976) study area to the south.

Unit A is overlain by the Sebeka Formation; an abrupt and unconformable contact between the two lithostratigraphic units is exposed in a 4-metre-deep gravel pit in the SE_{1/4}NE_{1/4} sec.11, T. 138 N, R. 36W. Below the contact is 2.5 metres of sand and gravel of Unit A. Above the contact is 1 metre of pebble-loam of the Sebeka Formation, which is overlain by 0.5 metre of wind-blown silty, very-fine sand. At this location, the pebble-loam of the Sebeka has a matrix (smaller-than-gravel-fraction) of 0.58 sand, 0.31 silt, and 0.11 clay and very-coarse sand (1 to 2 mm) composed of 0.79 igneous and metamorphic rock, 0.22 limestone and dolomite, and 0.00 shale. Unit A is moderately to poorly sorted, fine to coarse sand, gravelly sand, and sandy gravel. Unit A is generally lacking silt or clay. The stones are composed of nearly equal proportions of metamorphic and igneous rock, with a smaller amount of limestone and dolomite. The sediment has cross bedding as well as horizontal bedding. The sand is pale yellow (2.5Y 7/4; Munsell Soil Color Chart).

The sand and gravel of Unit A lies in fluvial channels, sections of which are partially or completely buried beneath pebble-loam of the Sebeka Formation (Plate 1). Because the channels are too deep to be braided channels found on a fluvial plain, it is assumed that the channels are cut into the pebble-loam of Unit 2 of Sackreiter
Unit 2 is the pebble-loam underlying the Marcoux Formation, which is correlated with the Sebeka Formation. The age of Unit A is unknown. However, its stratigraphic position suggests that it was deposited during pre-Wisconsinan time.

Sebeka Formation

The Sebeka Formation has been previously defined and named by Anderson (1976). The Sebeka Formation consists of pebble-loam, having an observed maximum thickness of 3.0 metres in the study area. The lateral extent of the formation is not known. The Sebeka Formation probably lithostratigraphically correlates with the Marcoux Formation immediately north of the study area (Sackreiter, 1975, Harris and others, 1974), with the Hawk Creek Till in southwestern Minnesota (Matsch, 1971), and with the Vang Formation in northeastern North Dakota (Hobbs, 1975) (Table 1). The stratigraphic position, the sandiness of the pebble-loam, and the large amount of igneous and metamorphic rock in the very-coarse sand (1 to 2 mm) of the pebble-loam are the bases for the correlation of the units. The distribution of exposures of the Sebeka Formation in the study area is shown in Plate 1.

The Sebeka Formation overlies Unit A. The contact between the two lithostratigraphic units is exposed in a 4-metre-deep gravel pit located SE

NE

sec.11, T. 138N, R. 36W (see Unit A section for description of outcrop). The contact is abrupt and unconformable.

Pebble-Loam Lithology

The pebble-loam of the Sebeka Formation is an unsorted and unstratified homogeneous mixture of clay-size to boulder-size
material. The pebble-loam of the Sebeka has a matrix (smaller-than-gravel fraction) averaging 0.61 sand, 0.26 silt, and 0.13 clay; the very-coarse sand (1 to 2 mm) averages 0.80 igneous and metamorphic rock, 0.20 limestone and dolomite, and 0.00 shale (Table 4). Oxidized pebble-loam of the Sebeka Formation is generally pale olive (5Y 6/3) or pale yellow (5Y 7/3) when dry.

The large amount of igneous and metamorphic rock and the absence of shale in the very-coarse sand (1 to 2 mm) indicates that the pebble-loam is probably derived from the Canadian Shield to the northeast.

The age of the Sebeka Formation is unknown, but its stratigraphic position suggests that it was deposited during pre-Wisconsinan or Early Wisconsinan time (Anderson, 1976).

New York Mills Formation

The New York Mills Formation has been previously defined and named by Anderson (1976). The formation contains pebble-loam having a maximum observed thickness of 8 metres and sand and gravel having a maximum thickness of 39 metres (Plate 2).

Plate 2 shows the thickness of this sand and gravel in the Park Rapids area in the study area (Glockzin, 1976). Where observed, the sand and gravel generally overlies the pebble-loam. The extent of the New York Mills Formation is not fully known. The New York Mills Formation lithostratigraphically correlates with the lower part of the Red Lake Falls Formation immediately north of the study area (Sackreiter, 1975, Harris and others, 1971) and the Granite Falls Till in southwestern Minnesota (Matsch, 1971). The stratigraphic position, the
small amount of shale, and the large amount of igneous and metamorphic rock in the very-coarse sand (1 to 2 mm) of the pebble-loam, and the relative sandiness of the pebble-loam matrix are the bases for the lithostratigraphic correlation of the units (Table 1). The exposed extent of the formation in the study area is shown in Plate 1. Plate 2 shows the approximate extent of the pebble-loam of this formation under the sand and gravel in the western part of the study area.

The New York Mills Formation overlies the Sebeka Formation. The contact between the two formations can be demonstrated from geomorphic evidence (described in the section on Episode II).

Pebble-Loam

The pebble-loam of the New York Mills Formation has a matrix averaging 0.50 sand, 0.32 silt, and 0.18 clay, and the very-coarse sand (1 to 2 mm) averages 0.71 igneous and metamorphic rock, 0.27 limestone and dolomite, and 0.02 shale (Table 4). Oxidized pebble-loam of the New York Mills Formation in the eastern part of the study area is pale yellow (5Y 7/3) when dry and light grey (2.5Y 7/2) in the western part of the study area when dry. The unoxidized pebble-loam is dark grey (10YR 4/1) when dry. Some inclusions of sand and gravel are commonly observed in the pebble loam. More inclusions were observed in the New York Mills Formation than in other formations located within the study area. The sand and gravel inclusions are less than 0.3 metres in length and less than 0.075 metres thick; generally they are small stringers of sand only 0.01 to 0.03 metre long and less than 0.01 metre wide.
The large amount of igneous and metamorphic rock indicates that the pebble-loam was probably derived from the Canadian Shield in northern Minnesota. The shale, limestone, and dolomite were probably derived from previously deposited glacial sediment.

Sand and Gravel

The sand and gravel of the New York Mills Formation was deposited by braided stream channels. The sediment is either poorly to moderately-well sorted, fine to coarse sand, gravelly sand, sandy gravel, and gravel, or unstratified gravelly sand. The sediment is generally lacking silt or clay. The gravel is composed of igneous and metamorphic rock fragments with an equal or smaller amount of limestone and dolomite. Very few boulder-size inclusions of pebble-loam from the New York Mills Formation have been observed in the sand and gravel. The stratified sediment has ripple and dune cross bedding and horizontal bedding. In many of the outcrops, the stratification is folded and faulted. The sand is a pale yellow (2.5Y 7/4).

The New York Mills Formation was probably deposited during Late Wisconsinan time. The age is based on a radiocarbon date of 33 000 years B. P. from wood found in an overlying sand and gravel deposit near Muskota, Minnesota (see description of Hawley Formation for details).

Dunvilla Formation

The Dunvilla Formation has been previously defined by Anderson (1976). The Dunvilla Formation consists of pebble-loam having a maximum observed thickness of 2.5 metres. The extent of the Dunvilla
Formation is not fully known. The Dunvilla Formation probably litho-
stratigraphically correlates with the upper part of the Red Lake Falls
Formation immediately north of the study area (Sackreiter, 1975), the
New Ulm Till in southwestern Minnesota (Matsch, 1971), and the Dahlen
Formation in northeastern North Dakota (Hobbs, 1975). The bases for
correlation is the stratigraphic position of the units and the rela-
tive abundance of shale in the very-coarse sand of the pebble-loam
(Table 1).

The Dunvilla Formation overlies the New York Mills Formation.
The contact between the two formations is exposed in a 1.5 metre out-
crop located at NE^4SE^4NE^4 sec. 28, T. 140N, R. 48W. The contact is
abrupt and unconformable and is located about 1 metre below the top
of the outcrop. At this location, the pebble-loam of the Dunvilla
Formation has a matrix composed of 0.32 sand, 0.36 silt, and 0.32
clay. The very-coarse sand contains 0.33 igneous and metamorphic
rock, 0.25 limestone and dolomite, and 0.42 shale. The pebble-loam
of the New York Mills Formation has a matrix composed of 0.50 sand,
0.32 silt, and 0.18 clay; the very-coarse sand is composed of 0.70
igneous and metamorphic rock, 0.23 limestone and dolomite, and 0.07
shale.

Pebble-Loam

The pebble-loam of the Dunvilla Formation is a homogeneous
mixture of unsorted and unstratified clay-size to boulder-size mate-
rial with rare inclusions of gravelly sand. The pebble-loam of the
Dunvilla Formation has a matrix averaging 0.36 sand, 0.39 silt, and
0.25 clay. The very-coarse sand (1 to 2 mm) averages 0.41 igneous
and metamorphic rock, 0.24 limestone and dolomite, and 0.35 shale. Oxidized pebble-loam of the Dunvilla Formation is yellowish gray (2.5Y 7/2) when dry.

The large amount of shale in the pebble-loam indicates that the pebble-loam was in part derived from the Pierre Formation in eastern North Dakota.

The Dunvilla Formation was probably deposited during Late Wisconsinan time. The age is obtained from a radiocarbon date of 14,000 years B.P. at the base of the Cary Drift in Iowa (Ruhe, 1969) which is correlated with the New Ulm Till (Matsch, 1971). Glacial sediment in Iowa associated with this advance dated tenuously as 20,000 years B.P., may represent the southwest margin of this advance (Matsch, 1972). The radiocarbon date indicates the earliest date at which the glacier may have covered southwestern Minnesota and central Iowa and deposited the pebble-loam of the New Ulm Till. The pebble-loam of the Dunvilla was probably deposited after the deposition of the New Ulm Till (14,000 years B.P.) because the glacier that deposited the layer of pebble-loam melted first in southwestern Minnesota and then melted progressively northward into the study area (Anderson, 1976).

Barnesville Formation

The Barnesville Formation has been previously defined and named by Anderson (1976). The Barnesville Formation consists of pebble-loam that has a maximum observed thickness of 8 metres and sand and gravel having a maximum observed thickness of 2 metres. The extent of the Barnesville Formation is not known. The
Barnesville Formation has been observed only in west-central Minnesota. The exposed extent of the formation in the study area is shown in Plate I.

The Barnesville Formation overlies the Dunvilla Formation. The contact between the two formations is exposed in a 5-metre high outcrop at Sec. 35, T. 140 N., R. 45 W. on the east side of County Highway 37. The contact dips about 20° to the north and intersects the top of the cut-away section of the hill. The contact is abrupt and unconformable. Below the contact is 5 metres of pebble-loam of the Dunvilla Formation. A lens of gravelly sand 2 metres thick and 3 metres long lies at the upper contact of the Dunvilla Formation along part of the contact. Above the contact are 2 to 3 metres of pebble-loam of the Barnesville Formation.

At this location, the pebble-loam of the Dunvilla has a matrix composed of 0.24 sand, 0.40 silt, and 0.36 clay; the very-coarse sand is composed of 0.13 igneous and metamorphic rock, 0.09 limestone and dolomite, and 0.78 shale. The pebble-loam of the Barnesville has a matrix composed of 0.14 sand, 0.47 silt, and 0.39 clay; and it has very-coarse sand (1 to 2 mm) composed of 0.41 igneous and metamorphic rock, 0.29 limestone and dolomite, and 0.30 shale.

Pebble-Loam

The pebble-loam of the Barnesville Formation consists of a homogeneous mixture of an unsorted and unstratified, clay-size to boulder-size material. The pebble-loam of the Barnesville Formation has a matrix averaging 0.16 sand, 0.45 silt, and 0.39 clay; and it has a very-coarse sand (1 to 2 mm) averaging 0.43 igneous and
metamorphic rock, 0.41 limestone and dolomite, and 0.16 shale (Table 4). Oxidized pebble-loam of the Barnesville Formation is pale yellow (5Y 7/3 or 2.5Y 7/4) when dry.

The relatively large amount of shale in the very-coarse sand of the pebble-loam indicates that the source of the rock was in part the Pierre Formation outcropping in eastern North Dakota.

Sand and Gravel

The sand and gravel is interpreted to have been deposited by braided streams. It is very-poorly to well sorted fine to coarse sand, gravelly sand, sandy gravel, and gravel. The sediment is generally lacking silt and clay. The gravel is mostly igneous and metamorphic rock with an equal or lesser amount of limestone and dolomite and a very small amount of shale. The sediment has cross bedding and horizontal bedding.

The Barnesville Formation was deposited during Late Wisconsinan time. The age is based of the stratigraphic position of the Barnesville Formation above the Dunvilla Formation (Anderson, 1976).

Hawley Formation (new)

The name Hawley Formation is proposed here for the lithostratigraphic unit overlying the Barnesville Formation. The source of the name is the town of Hawley in Clay County, Minnesota.

The formation includes a pebble-loam containing lentils of clayey silt, sand, and gravel. Where observed, the sand and gravel overlies the pebble-loam. Maximum observed thickness of the formation is 8 metres, consisting of 3.5 metres of pebble-loam and 4.5 metres of
sand and gravel. The extent of the Hawley Formation is not known, and it has not yet been recognized beyond the study area. The exposed extent of the Hawley Formation in the study area is shown in Plate 1.

The type section of the Hawley Formation is in a gravel pit located ¼ mile south of Muskoda, Minnesota, NE\textsuperscript{3}NE\textsuperscript{3}SW\textsuperscript{3} sec. 18, T. 140, R. 45W. The outcrop is about 16 metres high (Figure 9). At the type section, the sand and gravel unit of the Hawley Formation is absent. A reference section for this sand and gravel unit is located at SE\textsuperscript{3}SE\textsuperscript{3}SE\textsuperscript{3} sec. 26, T. 139, R. 45W (Figure 10). A more suitable type section that would include both the pebble-loam and the sand and gravel units of the Hawley Formation was not found because of the lack of outcrops in the study area.

The contact between the New York Mills and Hawley Formations is abrupt and unconformable. The contact can be observed at the northeast corner of the gravel pit, about 5 metres down from the rim of the excavation. Below the contact are about 9.4 metres of contorted fluvial sand and gravel, probably belonging to the New York Mills Formation.

The bedding in the sand and gravel (previously described in the section on the New York Mills Formation) is mostly folded with some reverse faulting. Some of the folds are overturned, with the axes-oriented northeast-southwest. The sediment is cross bedded and horizontally bedded. The cross bedding indicates a southward flow direction.

Within the sand and gravel of the New York Mills Formation is a layer of medium sand containing conifer wood. The wood was age dated at the Isotope Geochemistry Laboratory, Waterloo University, Waterloo, Ontario. Preliminary reports gives the wood a radiocarbon date of 33 000 years B. P.
Fig. 9. East-West Cross Section of the Type Sections for the Hawley and Downer Formations. Location: NE4NE4SW4 sec. 18, T. 140N, R. 45W.
LITHOLOGIES

- Glacial Pebble-Loam
- Beach Sand and Gravel
- Fluvial Sand and Gravel
- Lacustrine Clayey Silt
Fig. 10. East-West Cross Section of the Reference Section for the Hawley Formation. Location SE\(\frac{1}{4}\)SE\(\frac{1}{4}\) SE\(\frac{1}{4}\) sec. 26, T. 139N, R. 45W.
LITHOLOGIES

- Sandy gravel
- Sand
- Gravel
- Gravelly sand
Below the sand and gravel of the New York Mills Formation is 1.6 metres of pebble-loam of the New York Mills Formation extending to an unknown depth. At this location, a sample of pebble-loam of this formation has a matrix composed of 0.44 sand, 0.31 silt, and 0.25 clay; the very-coarse sand (1 to 2 mm) is composed of 0.64 igneous and metamorphic rock, 0.31 limestone and dolomite, and 0.05 shale.

The unoxidized pebble-loam of the New York Mills Formation is dark gray (10YR 4/1).

Above the contact between the New York Mills and Hawley Formations are 0.3 and 2.5 metres of pebble-loam of the Hawley Formation. The pebble-loam contains clayey silt inclusions. At the base of the pebble-loam is a boulder pavement.

The boulders of the boulder pavement are pressed into the underlying sand and gravel of the New York Mills Formation. The bedding in the underlying sand and gravel is contorted and is molded around the surface of the boulders. On the northwest side of the boulders is a streamlined tail of extremely sandy pebble-loam. The maximum length and width of the tails is no greater than the maximum diameter of the boulders. The tops of the boulders are beveled and striaed. The striae have an orientation of N24°W.

The inclusions of clayey silt occur as lens from 2 to 4 metres long and 0.01 to 1 metre thick. The clayey silt has laminated bedding about 0.0025 to 0.007 metres thick and has intraformational gravel composed of pebble-loam and clayey silt. The inclusions are concave upward, and some of these inclusions are contorted. One of the inclusions of clayey silt lies at the base of the unit and rests on the boulder pavement.
At this location, the pebble-loam of the Hawley Formation ranges in thickness from 0.01 to 2.5 metres. The pebble-loam has a matrix composed of 0.34 sand, 0.50 silt, and 0.16 clay; the very-coarse sand (1 to 2 mm) is composed of 0.57 igneous and metamorphic rock, 0.37 limestone and dolomite, and 0.06 shale.

Above the Hawley Formation are about 2.5 metres of sand and gravel of the Downer Formation. The contact between the Downer and Hawley Formations is abrupt, irregular, and unconformable. The Downer Formation consists of well-sorted to very-well sorted, sand, sandy, gravel, gravel, and gravelly sand. Most of the sand and gravel is nearly horizontally bedded, with some large scale low-angle cross bedding. At the top of this unit a fine sand displays small scale high-angle cross bedding.

The reference section of the sand and gravel of the Hawley Formation is exposed at the north side of a gravel pit that is 3 metres deep (Figure 10). At this location, the sediment is coarse to fine sand, sandy gravel, gravelly sand, and gravel. The sand and gravel has cross and horizontal bedding. The gravel is composed mostly of igneous and metamorphic rock, with a smaller amount of limestone and dolomite, plus a small amount of shale. The sand is pale yellow (2.5Y 8/4).

Pebble-Loam

The pebble-loam of the Hawley Formation has a matrix averaging 0.34 sand, 0.42 silt, and 0.24 clay; the very-coarse sand (1 to 2 mm) averages 0.53 igneous and metamorphic rock, 0.42 limestone and dolomite, and 0.05 shale. The pebble-loam contains some inclusions of clayey
silt. These inclusions have been observed at two locations. The inclu-
sions of clayey silt at the Muskoda gravel pit are described above.
Oxidized pebble-loam of the Hawley is light gray (5Y 4/1) when dry.

The relatively large amount of limestone and dolomite and the
presence of shale in the very-coarse sand indicates that the source
of these rocks was probably eastern North Dakota and south-central
Manitoba.

Sand and Gravel

The sand and gravel of the Hawley Formation was deposited in
braided streams. Where observed, the sand and gravel of the Hawley
and Barnesville Formations is indistinguishable on the bases of lith-
ologic characteristics, but were distinguished on the bases of strati-
graphic position.

The sand and gravel of the Hawley Formation is coarse to very-
fine sand, sandy gravel, gravelly sand, and gravel; the sediment has a
minor amount of silt. The sediment has cross and horizontal bedding.
The gravel is primarily composed of igneous and metamorphic rock, with
a smaller amount of limestone, dolomite, and shale. The sand is pale
yellow (2.5Y 8/4 or 5Y 7/3) when dry.

The Hawley Formation was deposited during Late Wisconsinan time.
This is based on the stratigraphic position of the Hawley above the
Barnesville Formation.

Downer Formation (new)

The name Downer Formation is proposed here for the sediment over-
lying of the Hawley Formation in the study area. The source of the name
is the town of Downer in Clay County, Minnesota.
The formation includes sand and gravel having a maximum observed thickness of 2.3 metres, and silty very-fine sand having a maximum observed thickness of about 2.5 metres. The extent of the Downer Formation is limited to the Lake Agassiz basin of North Dakota, South Dakota, Minnesota, and Manitoba. The extent of the Downer Formation exposed in the study area is shown in Plate 1.

The type section of the Downer Formation is exposed in a gravel pit located ¾ mile south of Muskoda, Minnesota, NE\textsuperscript{1/4}NE\textsuperscript{1/4}SW\textsuperscript{1/4} sec. 18, T. 140N, R. 45W. The outcrop is about 16 metres high (Figure 10). The contact between the Downer Formation and the underlying Hawley Formation is located about 2.5 metres below the northeast rim of the excavation. This contact is abrupt, irregular, and unconformable.

The Downer Formation contains sand, sandy gravel, gravelly sand and gravel, which are well to very-well sorted within individual beds. The sediment has mostly horizontal bedding and very-low-angle cross bedding.

At the type section for the Downer Formation, the silty very-fine sand is absent. However, a reference section for this sediment is designated at NE\textsuperscript{1/4}SW\textsuperscript{1/4}SW\textsuperscript{1/4} sec. 35, T. 140, R. 47W.

At the reference section, the silty very-fine sand is exposed in an outcrop about 2.5 metres high. Below the soil layer is nearly 2.5 metres of silty very-fine sand. The silty very-fine sand has low angle cross bedding and horizontal bedding; bedding thicknesses are less than 0.005 metres. The silty very-fine sand has interbedded layers of clayey silt. The clayey silt has horizontal bedding; the bedding thicknesses are less than 0.010 metre. The silty very-fine sand is white (5Y 8/2)
with light, yellowish brown mottles (2.5Y 6/4) when dry. The clayey silt is olive gray (5Y 4/2) when dry.

Sand and Gravel

The sand and gravel is interpreted to be lacustrine beach and near-shore sediment. The sand and gravel is moderately-well sorted to very-well sorted within individual beds; overall, the sediment is poorly sorted. The sand and gravel sediment consists of fine to coarse sand, gravelly sand, sandy gravel, and gravel. The sediment has horizontal and low-angle cross bedding where observed. The gravel is imbricated, with the dip of the stones to the west, down the regional slope. The gravel is primarily composed of igneous and metamorphic rock; with a smaller amount of limestone and dolomite, plus a small amount of shale. The sand is pale yellow (2.5Y 7/4) when dry.

The sand and gravel of the Downer Formation is differentiated from the older sand and gravel deposits in the study area on the bases of sorting, orientation of stones in the gravel, bedding of the sediment, and the stratigraphic position. The Downer Formation is much better sorted within individual beds than the older fluvial sand and gravel. The stones in the Downer Formation are strongly imbricated, dipping to the west down regional slope. In comparison, the stones in the sand and gravel of the older fluvial sediment are poorly imbricated and the dip of the stones is upstream, up the regional slope at the time of deposition. The bedding of the Downer Formation has been observed to have low-angle cross bedding and horizontal bedding. In comparison, the bedding planes of the older fluvial sand and gravel are mostly high-angle cross bedding with some horizontal bedding.
Silty, Very-Fine Sand

The silty, very-fine sand is interpreted to be primarily lacustrine deep-nearshore sediment. This sediment contains primarily silty, very-fine sand, with some interbedded clayey silt.

The silty, very-fine sand is very well sorted and has horizontal bedding and low-angle ripple cross bedding. The bedding thicknesses are less than 0.002 metres. The sediment is white (5Y 8/2) and may have light, yellowish brown (2.5Y 6/4) mottles when dry at some localities.

The interbedded clayey silt is very well sorted. It has horizontal bedding less than 0.010 metres thick. The sediment is olive gray (5Y 4/2) when dry.

The silty, very-fine sand is differentiated from the sediment of the Sherack Formation by the differences in color, grain size, and bedding. The Sherack Formation (described below) is composed primarily of clayey silt, with smaller amounts of silt and clay. The Sherack Formation is very dark olive gray (10YR 3/1) or light olive gray (5Y 6/2) when moist and has horizontal bedding.

At the reference section of the Downer Formation, the lower contact has not been observed. It is thought that the interbedded clayey silt may represent the deep-water-lacustrine sediment. This may indicate that the Sherack Formation interfingers with the Downer Formation.

The Downer Formation was deposited during the Late Wisconsinan to Early Holocene time, 13 000 to 9 500 years B. P. (Ashworth and others, 1972).
Sherack Formation

The Sherack Formation has been previously named and defined by Harris and others (1974). The Sherack Formation contains primarily clayey silt deposited in deep lacustrine water.

The maximum observed thickness of the Sherack Formation within the study area is 3 metres. The Sherack Formation is limited to the Lake Agassiz basin in North Dakota, South Dakota, Minnesota, and Manitoba. The extent of the formation exposed within the study area is shown in Plate 1.

The bottom of the Sherack Formation has not been observed in the study area. The exact stratigraphic relationship of the Sherack Formation to the Downer Formation is not fully known at this time. It is possible that the Sherack Formation interfingers with the Downer Formation (see definition of Downer Formation in Appendix B), and therefore it is thought that the Sherack and Downer Formations represent a regressive sequence of lacustrine facies. The Downer Formation represents the beach, nearshore, and deep-nearshore facies, and the Sherack Formation represents the deep-water facies of Lake Agassiz.

Clayey Silt

The Sherack Formation contains mostly clayey silt with interbedded silty clay and silt. The sediment is very thinly bedded. The bedding is less than 0.0025 metres thick, or the bedding is absent. The bedding is horizontal and continuous. The sediment is very dark olive gray (10YR 3/1), or light olive gray (5Y 6/2) when moist.
The Sherack Formation was deposited during Late Wisconsinan and Early Holocene time, 11,000 to 9,500 years B. P. (Harris and others, 1974).

Walsh Formation

The Walsh Formation has been previously named and defined by Arndt (1972). The Walsh Formation contains two types of sediment within the study area, a peat and organic clay sediment, having a maximum observed thickness of about 1 metre; and a silt, sand, and gravel sediment having a maximum observed thickness of 2 metres. The extent of the Walsh Formation is not fully known. The Walsh Formation is found throughout North Dakota (Bluemle, 1977). The extent of the Walsh Formation exposed in the study area is shown in Plate 1.

Peat and Organic Clay

The peat and organic clay is interpreted as being slough and bog sediment. The sediment contains mostly peat (a mat of partially decayed plants), organic clay, and some minor amounts of sand and silt. Bedding is generally absent or vague. The sediment is dark brown (7.5YR 3/2), or dark olive gray (5Y 3/2) when moist.

Silt, Sand, and Gravel

The silt, sand, and gravel is interpreted as being channel and overbank sediment. The channel sediment is generally poorly sorted fine to coarse sand, sandy gravel, and gravel. The overbank sediment is mostly very-fine sandy silt with some silty, very-fine sand at the margins of the channels. The very-fine sandy silt and silty, very-fine
sand has poorly developed horizontal bedding; the bedding of the channel sediment has not been observed.

The gravel in this formation is derived from the erosion of glacial, beach, and fluvial sediment and is therefore composed primarily of igneous and metamorphic rock, dolomite, limestone, and shale. This sediment has varying amounts of organic material. The very-fine sandy silt and silty, very-fine sand is dark olive (5Y 3/2) when moist. The beds of very-fine to coarse sand are light gray (5Y 7/2) when wet.

As reported by Bluemle (1973), sediment contained in the Walsh Formation was first deposited about 10,000 years B. P. when organic material first appeared in the postglacial sediment. This date corresponds to the time when the vegetation in North Dakota and the rest of the Great Plains changed from a spruce forest (tundra-type climate) to a prairie grassland. In west-central Minnesota, the Walsh Formation started being deposited at an earlier date. McAndrews (1966) reported organic sediment at the bottom of a slough in west-central Minnesota as being first deposited about 12,300 years B. P. The Walsh Formation continues to be deposited today.
APPENDIX C

DESCRIPTION OF GEOMORPHIC FEATURES
This section describes the geomorphic features given in Plate 1.

Transverse compressional ridges. Transverse compressional ridges are nearly parallel, sharp, well defined ridges which are 3 to 12 metres high and commonly less than 200 metres across. In map view, these features are concave up-glacier, and on the up-glacier side of the ridges there is usually a depression.

Transverse compressional ridges were created by vertical displacement of subglacial material along glacial ice shear planes. These ridges formed in the marginal part of an actively flowing glacier when the ice margin was frozen to the underlying sediment and excess groundwater pressure was present. The excess groundwater pressure reduces the shear strength of the underlying rock and provides an additional vertical force that aids the glacier in the upward movement of sediment. The individual ridges are folds and thrust masses and the up-glacier depression near the ridges are left by the down-glacier displacement of subglacial material (Clayton and Moran, 1974).

Transverse depositional ridges. Transverse depositional ridges generally are less than 3 metres high, are as wide as 1000 metres, and are several thousand metres long. In map view these ridges are gently concave up-glacier. In comparison to transverse compressional ridges, transverse depositional ridges are less well defined.

Transverse depositional ridges form as a result of greater thickness of englacial sediment deposited along periodically spaced transverse zones of shearing (Clayton and Moran, 1974).

Longitudinal shear lineations. Longitudinal shear lineations are streamlined ridges and elongate troughs which are less than 3 to
12 metres high and are 300 to 2000 metres long. These features are streamlined parallel to the direction of ice movement.

Longitudinal shear lineations form as a result of subglacial erosion of unfrozen material as the glacier slides over its bed (Clayton and Moran, 1974).

**Esker.** An esker is a long, narrow, and sinuous steep-sided ridge or several connected ridges. These features generally are 2 to 10 metres high and 100 to 1700 metres long. Eskers commonly have a thin veneer of glacial sediment but mostly are composed of stratified sand and gravel.

Eskers were deposited by a subglacial or englacial stream flowing between ice walls or in an ice tunnel of a retreating glacier and was left behind when the ice melted.

**Compaction ridge.** A compaction ridge is a ridge of lacustrine sediment found on the Lake Agassiz plain. This feature is less than 3 metres high and can be several thousand metres long.

Compaction ridges were created from the differential compaction of buried sand and gravel bodies and overlying lacustrine clay and silt (Bluemle, 1967).

**Strandline.** A strandline is a lineation marking the former position of the edge of a standing body of water. In the study area, strandlines are marked by beach ridges that are less than 6 metres high and wave-cut scarps that are 3 to 12 metres high.

**Partly buried fluvial channel.** A partly buried fluvial channel is a trench with irregular and poorly defined sides and the bottom of which contains glacial sediment.
A partly buried fluvial channel is a river channel that has been overrun by glacier ice and covered with glacial sediment.

Melt-water channel. A melt-water channel is a trench that has regular and well defined sides.

A melt-water channel is created by flowing glacial melt water. Within the channels sand and gravel was deposited which is free of organic material. Commonly, either an underfit stream, a slough, or both an underfit stream occupies the bottom of the channel, at the present time.
APPENDIX D

DATA ON NEAR SURFACE SAMPLES
"Matrix" refers to the finer-than-gravel fraction in the pebble-loam. The proportion of sand, silt, and clay was determined for each sample (Appendix A).

"Very-Coarse Sand" (1-2mm) refers to that fraction found in the pebble-loam. The proportion of igneous and metamorphic rock, limestone and dolomite, and shale was determined for each sample (Appendix A).

"Count" refers to the total number of grains of very-coarse sand counted to determine the proportion. Miscellaneous grains in the very-coarse sand were ignored.

The depth of the sample below the original land surface is given where known. A blank space in the "Depth" column indicates that the depth of the sample is not known because an unknown thickness of sediment had been removed.

The location of each sample is given. The letters A, B, C, and D refer to the northwest, northeast, southwest, and southeast quarters respectively. The last three numbers refer to section number, township, and range, respectively.

"N-number" refers to the number of the sample in the North Dakota Geological Survey core library.
Table 5. Data of the Pebble-Loam Analysis for Each Sample.
### SEBEKA FORMATION

<table>
<thead>
<tr>
<th>N Number</th>
<th>Location</th>
<th>Elevation (in metres)</th>
<th>Matrix Sand</th>
<th>Matrix Silt</th>
<th>Matrix Clay</th>
<th>Very-Coarse Sand Igneous, Metamorphic</th>
<th>Very-Coarse Sand Limestone, Dolomite</th>
<th>Shale Count</th>
<th>Depth (in metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3645</td>
<td>CAA18,141,34</td>
<td>442</td>
<td>0.57</td>
<td>0.30</td>
<td>0.13</td>
<td>0.84</td>
<td>0.16</td>
<td>0.00</td>
<td>285</td>
</tr>
<tr>
<td>3646</td>
<td>CCC15,139,35</td>
<td>445</td>
<td>0.63</td>
<td>0.24</td>
<td>0.13</td>
<td>0.88</td>
<td>0.12</td>
<td>0.00</td>
<td>229</td>
</tr>
<tr>
<td>3647</td>
<td>DAA11,138,36</td>
<td>438</td>
<td>0.58</td>
<td>0.31</td>
<td>0.11</td>
<td>0.78</td>
<td>0.22</td>
<td>0.00</td>
<td>227</td>
</tr>
<tr>
<td>3648</td>
<td>AAA34,139,36</td>
<td>454</td>
<td>0.63</td>
<td>0.24</td>
<td>0.13</td>
<td>0.73</td>
<td>0.27</td>
<td>0.00</td>
<td>244</td>
</tr>
<tr>
<td>3649</td>
<td>BBC5,139,36</td>
<td>483</td>
<td>0.64</td>
<td>0.23</td>
<td>0.13</td>
<td>0.73</td>
<td>0.27</td>
<td>0.00</td>
<td>244</td>
</tr>
<tr>
<td>3650-1</td>
<td>ACC25,141,36</td>
<td>457</td>
<td>0.63</td>
<td>0.25</td>
<td>0.12</td>
<td>0.78</td>
<td>0.22</td>
<td>0.00</td>
<td>207</td>
</tr>
<tr>
<td>-2</td>
<td></td>
<td>456</td>
<td>0.62</td>
<td>0.24</td>
<td>0.14</td>
<td>0.85</td>
<td>0.15</td>
<td>0.00</td>
<td>220</td>
</tr>
<tr>
<td>3651</td>
<td>CCC23,139,37</td>
<td>489</td>
<td>0.59</td>
<td>0.26</td>
<td>0.15</td>
<td>0.80</td>
<td>0.20</td>
<td>0.00</td>
<td>212</td>
</tr>
<tr>
<td>N Number</td>
<td>Location</td>
<td>Sample Elevation (in metres)</td>
<td>Matrix</td>
<td>Very-Coarse Sand</td>
<td>Depth (in metres)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>----------------</td>
<td>------------------------------</td>
<td>--------</td>
<td>------------------</td>
<td>------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sand</td>
<td>Igneous, Limestone, Metamorphic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Silt</td>
<td>Dolomite</td>
<td>Shale</td>
<td>Count</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3628</td>
<td>AAB1,138,37</td>
<td>466</td>
<td>0.58</td>
<td>0.30</td>
<td>0.12</td>
<td>0.68</td>
<td>0.32</td>
<td>0.00</td>
<td>182</td>
</tr>
<tr>
<td>3629</td>
<td>AAA5,138,37</td>
<td>472</td>
<td>0.61</td>
<td>0.27</td>
<td>0.12</td>
<td>0.73</td>
<td>0.27</td>
<td>0.00</td>
<td>204</td>
</tr>
<tr>
<td>3630-1</td>
<td>BAD33,140,37</td>
<td>494</td>
<td>0.52</td>
<td>0.34</td>
<td>0.14</td>
<td>0.68</td>
<td>0.32</td>
<td>0.00</td>
<td>163</td>
</tr>
<tr>
<td></td>
<td>BAD33,140,37</td>
<td>491</td>
<td>0.44</td>
<td>0.15</td>
<td>0.41</td>
<td>0.72</td>
<td>0.28</td>
<td>0.00</td>
<td>188</td>
</tr>
<tr>
<td>3631</td>
<td>BCC13,138,38</td>
<td>468</td>
<td>0.57</td>
<td>0.28</td>
<td>0.15</td>
<td>0.69</td>
<td>0.29</td>
<td>0.02</td>
<td>190</td>
</tr>
<tr>
<td>3632</td>
<td>BBA13,139,38</td>
<td>487</td>
<td>0.59</td>
<td>0.26</td>
<td>0.15</td>
<td>0.72</td>
<td>0.28</td>
<td>0.00</td>
<td>197</td>
</tr>
<tr>
<td>3633</td>
<td>AAB19,138,39</td>
<td>440</td>
<td>0.51</td>
<td>0.30</td>
<td>0.19</td>
<td>0.72</td>
<td>0.28</td>
<td>0.00</td>
<td>180</td>
</tr>
<tr>
<td>3634</td>
<td>BBD13,139,39</td>
<td>443</td>
<td>0.51</td>
<td>0.28</td>
<td>0.21</td>
<td>0.69</td>
<td>0.22</td>
<td>0.09</td>
<td>177</td>
</tr>
<tr>
<td>3635-1</td>
<td>ACA11,139,39</td>
<td>453</td>
<td>0.55</td>
<td>0.33</td>
<td>0.12</td>
<td>0.73</td>
<td>0.23</td>
<td>0.04</td>
<td>284</td>
</tr>
<tr>
<td></td>
<td>ACA11,139,39</td>
<td>452</td>
<td>0.53</td>
<td>0.38</td>
<td>0.09</td>
<td>0.77</td>
<td>0.23</td>
<td>0.00</td>
<td>177</td>
</tr>
<tr>
<td>3636</td>
<td>ADA,29,139,39</td>
<td>453</td>
<td>0.51</td>
<td>0.35</td>
<td>0.14</td>
<td>0.78</td>
<td>0.21</td>
<td>0.00</td>
<td>180</td>
</tr>
<tr>
<td>3637</td>
<td>CDD29,140,39</td>
<td>454</td>
<td>0.48</td>
<td>0.32</td>
<td>0.20</td>
<td>0.67</td>
<td>0.25</td>
<td>0.18</td>
<td>179</td>
</tr>
<tr>
<td>3638</td>
<td>ACA7,140,39</td>
<td>451</td>
<td>0.40</td>
<td>0.50</td>
<td>0.10</td>
<td>0.77</td>
<td>0.23</td>
<td>0.00</td>
<td>146</td>
</tr>
<tr>
<td>3624-2</td>
<td>ADA28,140,49</td>
<td>445</td>
<td>0.47</td>
<td>0.34</td>
<td>0.19</td>
<td>0.70</td>
<td>0.23</td>
<td>0.07</td>
<td>194</td>
</tr>
<tr>
<td>3639</td>
<td>ABD18,138,40</td>
<td>445</td>
<td>0.59</td>
<td>0.24</td>
<td>0.17</td>
<td>0.71</td>
<td>0.28</td>
<td>0.01</td>
<td>190</td>
</tr>
<tr>
<td>3640</td>
<td>AAC36,140,40</td>
<td>437</td>
<td>0.68</td>
<td>0.23</td>
<td>0.09</td>
<td>0.69</td>
<td>0.31</td>
<td>0.00</td>
<td>334</td>
</tr>
<tr>
<td>N Number</td>
<td>Location</td>
<td>Sample Elevation (in metres)</td>
<td>Matrix Sand</td>
<td>Silt</td>
<td>Clay</td>
<td>Very-Coarse Sand Igneous, Metamorphic</td>
<td>Limestone, Dolomite</td>
<td>Shale</td>
<td>Count (in metres)</td>
</tr>
<tr>
<td>----------</td>
<td>----------</td>
<td>-----------------------------</td>
<td>-------------</td>
<td>------</td>
<td>------</td>
<td>-------------------------------------</td>
<td>--------------------</td>
<td>-------</td>
<td>-----------------</td>
</tr>
<tr>
<td>3641</td>
<td>BCA32,140,44</td>
<td>361</td>
<td>0.42</td>
<td>0.33</td>
<td>0.25</td>
<td>0.70</td>
<td>0.30</td>
<td>0.00</td>
<td>251</td>
</tr>
<tr>
<td>3627-2</td>
<td>BAA1,140,45</td>
<td>329</td>
<td>0.53</td>
<td>0.37</td>
<td>0.10</td>
<td>0.77</td>
<td>0.23</td>
<td>0.00</td>
<td>229</td>
</tr>
<tr>
<td>3642-1</td>
<td>CAA3,139,46</td>
<td>293</td>
<td>0.50</td>
<td>0.40</td>
<td>0.10</td>
<td>0.77</td>
<td>0.23</td>
<td>0.00</td>
<td>309</td>
</tr>
<tr>
<td>-2</td>
<td></td>
<td>289</td>
<td>0.50</td>
<td>0.42</td>
<td>0.08</td>
<td>0.72</td>
<td>0.28</td>
<td>0.00</td>
<td>423</td>
</tr>
<tr>
<td>3643</td>
<td>CCD3,138,45</td>
<td>350</td>
<td>0.45</td>
<td>0.34</td>
<td>0.31</td>
<td>0.68</td>
<td>0.29</td>
<td>0.03</td>
<td>146</td>
</tr>
<tr>
<td>3644-1</td>
<td>ACC12,138,46</td>
<td>316</td>
<td>0.47</td>
<td>0.29</td>
<td>0.24</td>
<td>0.70</td>
<td>0.24</td>
<td>0.06</td>
<td>140</td>
</tr>
<tr>
<td>-2</td>
<td></td>
<td>315</td>
<td>0.58</td>
<td>0.21</td>
<td>0.21</td>
<td>0.68</td>
<td>0.24</td>
<td>0.08</td>
<td>295</td>
</tr>
<tr>
<td>3609-12</td>
<td>AAC18,139,45</td>
<td>318</td>
<td>0.44</td>
<td>0.31</td>
<td>0.25</td>
<td>0.64</td>
<td>0.31</td>
<td>0.05</td>
<td>295</td>
</tr>
<tr>
<td>N Number</td>
<td>Location</td>
<td>Sample Elevation (in metres)</td>
<td>Matrix Sand</td>
<td>Silt</td>
<td>Clay</td>
<td>Very-Coarse Sand</td>
<td>Depth (in metres)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>---------------</td>
<td>-----------------------------</td>
<td>-------------</td>
<td>------</td>
<td>------</td>
<td>------------------</td>
<td>------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3524-1</td>
<td>ADA28,140,40</td>
<td>446</td>
<td>0.32</td>
<td>0.36</td>
<td>0.32</td>
<td>0.33</td>
<td>187</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>3625</td>
<td>CDAl,140,40</td>
<td>449</td>
<td>0.40</td>
<td>0.43</td>
<td>0.17</td>
<td>0.74</td>
<td>182</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>3617-2</td>
<td>CCA11,138,42</td>
<td>426</td>
<td>0.28</td>
<td>0.43</td>
<td>0.29</td>
<td>0.23</td>
<td>176</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3626-1</td>
<td>ADA19,138,42</td>
<td>418</td>
<td>0.37</td>
<td>0.39</td>
<td>0.24</td>
<td>0.45</td>
<td>218</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>-2</td>
<td></td>
<td>415</td>
<td>0.37</td>
<td>0.38</td>
<td>0.25</td>
<td>0.45</td>
<td>247</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>3622-2</td>
<td>ADD11,140,43</td>
<td>367</td>
<td>0.46</td>
<td>0.39</td>
<td>0.15</td>
<td>0.46</td>
<td>308</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>3623-2</td>
<td>DBB35,140,45</td>
<td>418</td>
<td>0.24</td>
<td>0.40</td>
<td>0.36</td>
<td>0.13</td>
<td>388</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>3627-1</td>
<td>BAA1,140,45</td>
<td>329</td>
<td>0.46</td>
<td>0.31</td>
<td>0.23</td>
<td>0.48</td>
<td>333</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>Location</td>
<td>Sample Elevation (in metres)</td>
<td>Sand</td>
<td>Silt</td>
<td>Clay</td>
<td>Very-Coarse Sand Elevation Matrix Igneous, Limestone, Depth (in metres)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>---------------</td>
<td>------------------------------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>---------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3615</td>
<td>CCC28,141,41</td>
<td>424</td>
<td>0.17</td>
<td>0.34</td>
<td>0.39</td>
<td>0.44 0.43 0.13 64 1.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3602-2</td>
<td>CDD7,140,41</td>
<td>418</td>
<td>0.13</td>
<td>0.41</td>
<td>0.46</td>
<td>0.42 0.45 0.13 67 1.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3616</td>
<td>CCA7,139,41</td>
<td>429</td>
<td>0.11</td>
<td>0.43</td>
<td>0.46</td>
<td>0.52 0.42 0.06 69 1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>427</td>
<td>0.14</td>
<td>0.45</td>
<td>0.41</td>
<td>0.52 0.37 0.11 84 2.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3617-1</td>
<td>CCA11,138,42</td>
<td>427</td>
<td>0.23</td>
<td>0.48</td>
<td>0.29</td>
<td>0.48 0.37 0.15 129</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3618</td>
<td>CCB24,139,42</td>
<td>426</td>
<td>0.20</td>
<td>0.46</td>
<td>0.34</td>
<td>0.33 0.58 0.09 92 3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3619</td>
<td>DCB28,140,42</td>
<td>381</td>
<td>0.19</td>
<td>0.44</td>
<td>0.37</td>
<td>0.55 0.36 0.09 102 0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3620-1</td>
<td>DCB2,138,43</td>
<td>430</td>
<td>0.16</td>
<td>0.42</td>
<td>0.42</td>
<td>0.44 0.41 0.15 102 0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2</td>
<td></td>
<td>428</td>
<td>0.16</td>
<td>0.46</td>
<td>0.38</td>
<td>0.29 0.55 0.16 87 2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3621</td>
<td>DDD3,140,43</td>
<td>396</td>
<td>0.11</td>
<td>0.38</td>
<td>0.51</td>
<td>0.45 0.37 0.18 82</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3622-1</td>
<td>ADD11,140,43</td>
<td>368</td>
<td>0.24</td>
<td>0.42</td>
<td>0.34</td>
<td>0.37 0.45 0.18 168 1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3623-1</td>
<td>DBB35,138,44</td>
<td>418</td>
<td>0.14</td>
<td>0.47</td>
<td>0.39</td>
<td>0.41 0.29 0.30 91 2.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3606-2</td>
<td>CCA11,139,44</td>
<td>414</td>
<td>0.17</td>
<td>0.41</td>
<td>0.42</td>
<td>0.36 0.48 0.16 108 2.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3603-2</td>
<td>BBC26,140,44</td>
<td>368</td>
<td>0.12</td>
<td>0.64</td>
<td>0.24</td>
<td>0.46 0.26 0.28 43 4.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## HAMLEY FORMATION

<table>
<thead>
<tr>
<th>Number</th>
<th>Location</th>
<th>Sample Elevation (in metres)</th>
<th>Matrix Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Very-Coarse Sand</th>
<th>Igneous</th>
<th>Limestone, Metamorphic</th>
<th>Dolomite</th>
<th>Shale</th>
<th>Count (in metres)</th>
<th>Depth (in metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3600</td>
<td>DCC19,139,42</td>
<td>429</td>
<td>0.40</td>
<td>0.33</td>
<td>0.27</td>
<td>0.60</td>
<td>0.34</td>
<td>0.06</td>
<td>300</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3601</td>
<td>CDD9,140,43</td>
<td>365</td>
<td>0.23</td>
<td>0.51</td>
<td>0.26</td>
<td>0.48</td>
<td>0.45</td>
<td>0.07</td>
<td>111</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3602-1</td>
<td>CDD7,140,41</td>
<td>429</td>
<td>0.26</td>
<td>0.41</td>
<td>0.33</td>
<td>0.44</td>
<td>0.53</td>
<td>0.03</td>
<td>141</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3603-1</td>
<td>BCC26,140,44</td>
<td>369</td>
<td>0.25</td>
<td>0.54</td>
<td>0.21</td>
<td>0.63</td>
<td>0.29</td>
<td>0.08</td>
<td>112</td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3604-</td>
<td>CDD14,138,44</td>
<td>426</td>
<td>0.29</td>
<td>0.49</td>
<td>0.22</td>
<td>0.48</td>
<td>0.44</td>
<td>0.08</td>
<td>160</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3605</td>
<td>BBD30,139,44</td>
<td>362</td>
<td>0.31</td>
<td>0.49</td>
<td>0.20</td>
<td>0.47</td>
<td>0.49</td>
<td>0.04</td>
<td>174</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3606-1</td>
<td>CCA11,139,44</td>
<td>415</td>
<td>0.27</td>
<td>0.43</td>
<td>0.30</td>
<td>0.52</td>
<td>0.41</td>
<td>0.07</td>
<td>130</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3607</td>
<td>CAA24,139,44</td>
<td>427</td>
<td>0.36</td>
<td>0.38</td>
<td>0.26</td>
<td>0.53</td>
<td>0.42</td>
<td>0.05</td>
<td>173</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3608-1</td>
<td>ABC7,139,44</td>
<td>379</td>
<td>0.36</td>
<td>0.42</td>
<td>0.22</td>
<td>0.49</td>
<td>0.48</td>
<td>0.03</td>
<td>200</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3609-1</td>
<td>AAC18,139,45</td>
<td>330</td>
<td>0.33</td>
<td>0.44</td>
<td>0.23</td>
<td>0.51</td>
<td>0.44</td>
<td>0.05</td>
<td>204</td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3610</td>
<td>DCD20,139,44</td>
<td>362</td>
<td>0.32</td>
<td>0.42</td>
<td>0.26</td>
<td>0.61</td>
<td>0.33</td>
<td>0.06</td>
<td>176</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3611</td>
<td>AA2,140,45</td>
<td>369</td>
<td>0.41</td>
<td>0.38</td>
<td>0.21</td>
<td>0.53</td>
<td>0.46</td>
<td>0.01</td>
<td>179</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3612</td>
<td>ADC32,140,45</td>
<td>340</td>
<td>0.58</td>
<td>0.28</td>
<td>0.14</td>
<td>0.59</td>
<td>0.41</td>
<td>0.00</td>
<td>206</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3613-1</td>
<td>CCC6,139,44</td>
<td>372</td>
<td>0.39</td>
<td>0.38</td>
<td>0.23</td>
<td>0.61</td>
<td>0.34</td>
<td>0.05</td>
<td>200</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3613-2</td>
<td>CCC6,139,44</td>
<td>371</td>
<td>0.40</td>
<td>0.40</td>
<td>0.20</td>
<td>0.52</td>
<td>0.41</td>
<td>0.07</td>
<td>254</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3614</td>
<td>ADD5,139,41</td>
<td>423</td>
<td>0.24</td>
<td>0.42</td>
<td>0.34</td>
<td>0.58</td>
<td>0.33</td>
<td>0.09</td>
<td>279</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
REFERENCES
REFERENCES


GEOLOGY OF THE MOORHEAD TO PARK RAPIDS AREA
WEST-CENTRAL MINNESOTA

AGE OF STRATIGRAPHIC UNITS

- Interbedded silt, sand and gravel with some organic material; crossed and horizontal bedding; well to poorly sorted. Origin: modern fluvial and overbank fluvial sediment.
- Mud and organic clay; wavy bedding. Origin: bog and algal sediment.
- Interbedded sand and gravel; crossed and horizontal bedding; well to poorly sorted. Origin: lacustrine deep nearshore sediment.
- Pebble-loam; unbedded homogeneous mixture. Origin: glacial sediment.
- Clayey silt; thin laminated bedding; well sorted. Origin: supraglacial lacustrine sediment.

MAP UNITS

- Silty, very fine sand; planar and low angle cross bedding; well sorted. Origin: lacustrine deep nearshore sediment.
- Interbedded sand and gravel; crossed and horizontal bedding; moderately well to excellently sorted. Origin: lacustrine beach sediment.
- Less than 1 metre of beach sediment over pebble-loam of the New York Mills or the Dunvilla Formations and fluvial sediment of unknown stratigraphic position.

LINE SYMBOLS

- Transverse compressional ridges (spike ridges).
- Transverse depositional ridges.
- Longitudinal shear lineations.
- Esker.
- Composite ridge.
- Glacial meltwater channel.
- Pockmarked fluvial channel.

SPECIAL LEGEND

- Includes beach ridges and beach scarps.
- Lithologic contact (dashed where position may be in error by as much as 1 kilometre).

R. L. PERKINS 1977
ISOPACH MAP OF
SAND AND GRAVEL LITHOLOGY-
NEW YORK MILLS FM.,
PARK RAPIDS AREA

CONTOUR INTERVAL- 5 METRE

PEBBLE-LOAM

APPROXIMATE ICE MARGIN POSITION OF
EPISODE III BENEATH SAND AND GRAVEL