1976

Pleistocene geology of the Comstock-Sebeka area, west-central Minnesota

Curtis A. Anderson

University of North Dakota

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PLEISTOCENE GEOLOGY OF THE COMSTOCK-SEBEKA AREA,

WEST-CENTRAL MINNESOTA

by

Curtis A. Anderson

Bachelor of Arts, University of Minnesota, Duluth, 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

May
1976
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1976
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Date 4-20-76
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<td>1. Surficial Sediment of the Comstock-Sebeka Area, West-Central Minnesota</td>
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This study is a reconnaissance of the surficial geology and a reconstruction of the late Cenozoic history of an area in west-central Minnesota. The study area extends eastward from the Comstock area (14 miles south of Moorhead, Minnesota) in the Red River Valley to the Sebeka area (13 miles north of Wadena, Minnesota). The area is about 27 kilometres wide and 140 kilometres long.

Surface materials include Pleistocene glacial sediment and Pleistocene and Holocene fluvial, lacustrine, eolian, and bog sediment.

Four geomorphic districts are recognized. The flat Lake-Plain District is underlain by sand, silt, and clay that was deposited as offshore sediment in the Lake Agassiz basin in Early Holocene time. The flat to rolling Shoreline-Complex District is underlain largely by lacustrine shoreline sand and gravel. The district includes the complex network of beach ridges and wave-cut scarps that were developed at the margin of Lake Agassiz in Late Wisconsinan and Early Holocene time. The gently undulating to strongly rolling Glacial-Upland District is underlain by glacial and fluvial sediment that varies in age from pre-Wisconsinan to Late Wisconsinan. Topography characteristic of subglacial smoothing and the collapse of englacial and superglacial debris, as well as meltwater channels, eskers, and esker complexes are characteristic types of morphology present in the dis-
The Outwash District is underlain largely by sand and gravel that was deposited by rivers that flowed on top of and from melting glacier ice. The characteristic morphology of the district includes collapsed outwash topography and pitted outwash plains.

The deposits of four glacial events form four lithostratigraphic units that are recognized at the surface in the study area. The units, which are characterized by distinctive texture and lithology of the very-coarse-sand fraction of the glacial pebble-loam, are readily recognized in the field by differences in color, structure, and texture.

The pre-Wisconsinan or Early Wisconsinan Sebeka Formation, Early Wisconsinan New York Mills Formation, Late Wisconsinan Dunvilla Formation, and Late Wisconsinan Barnesville Formation were deposited by advances of glacial ice that came from the northeast, due north, northwest, and northwest respectively. All but the Barnesville Formation correlate with other lithostratigraphic units in northwestern Minnesota and northeastern North Dakota.
INTRODUCTION

Purpose of Study

This study is a reconnaissance of the surficial geology of an area in west-central Minnesota. Information obtained through the field and laboratory investigations in this and similar studies contribute to the development of the late Cenozoic history of Minnesota and the Upper Midwest in general.

Area of Study

The area of study is located in west-central Minnesota and consists of 3,864 square kilometres (1,492 square miles) (Figure 1).

The geomorphology of the area is varied. The Lake Agassiz plain and shoreline complex at the west end of the area give way to glacial and outwash topography that extends to the east.

The pre-agriculture vegetation that covered the area was prairie in the west part, deciduous forest in the central part, and mixed conifer and deciduous forest in the east part.

Previous Work

Previous to now, no integrated geological study of the sediment within this area had been completed.

Warren Upham and Frank Leverett studied parts of the area. Upham (1896) completed a regional study of Lake Agassiz. Leverett's study of the surficial landforms of Minnesota was conducted from 1906 to 1912 (Leverett, 1932).
Fig. 1. Location of the Comstock-Sebeka Area, showing county boundaries.
In 1939 C. C. Nikiforoff, a United States Department of Agriculture pedologist, published reconnaissance soil maps of western Minnesota counties adjacent to the Red River of the North. His geological contribution was an alternate to Upham's interpretation of the history of Lake Agassiz (Nikiforoff, 1947).

The glacial history of Minnesota is summarized by Wright and Ruhe (1965) and Wright (1972).

Numerous stratigraphic studies on Pleistocene sediments have been conducted in the region. C. L. Matsch (1971) has developed the Quaternary stratigraphy in southwestern Minnesota using the extensive exposures along the Minnesota River valley. A similar study was done by K. L. Harris (1973) on exposures along the Red Lake River in northwestern Minnesota. K. L. Harris (1975) and D. K. Sackreiter (1975) conducted surface and subsurface stratigraphic studies in northwestern Minnesota. A similar study was done by Howard Hobbs (1975) in northeastern North Dakota. A detailed stratigraphic study of the offshore sediments of Lake Agassiz in eastern North Dakota was done by B. Michael Arndt (1975).

Concurrent with this study, a similar study is being conducted immediately north of this area by Roderic L. Perkins (in preparation). A detailed surface and subsurface stratigraphic study of Pleistocene sediments is being conducted by Michael Camara (in preparation) in southeastern North Dakota.

Field Methods

Field mapping began in May, 1975, and was completed in October, 1975. County highway maps, scale 1:125,000 (about 1 inch: 2 miles),
were used as field base maps. The information was then compiled onto a United States Geological Survey topographic map, scale 1:250 000 (about 1 inch : 4 miles).

The most useful tools used in the mapping procedure were stereoscopic aerial photographs. Army Map Service photos, scale 1:59 000 (about 1 inch : 1 mile), flown in July, 1952, were used for the western half of the area. Photos used in the eastern half were flown in March, 1969, by Mark Hurd Aerial Survey, Inc., scale 1:90 000 (about 1 inch : 1.4 miles).

Soils maps were available for the entire area. Reconnaissance soils maps by C. C. Nikiforoff were used to map the Lake Agassiz plain and shoreline complex (Nikiforoff, 1939). The Minnesota Soils Atlas (Arneman and others, 1969) was used to map the remaining part of the study area.

The procedure followed in mapping the surficial sediment had two parts. An office map was prepared using aerial photographs and soils maps. The office map was then field checked by driving most of the passable roads. Study of the lithologic, textural, and bedding characteristics of the sediment in surface exposures provided the most useful information. A 1.5-metre hand auger was used in areas such as the Lake Agassiz plain where exposures were scarce.

Laboratory Methods

Sixty-three samples of glacial sediment (till) were collected from surface exposures. The samples were analyzed for their texture and the lithology of the very-coarse-sand fraction. The data is tabulated in the Appendix. This information was used to distinguish the
lithostratigraphic units present in the study area. Means and standard deviations were calculated for each of these lithostratigraphic units.

Texture

The samples were analyzed for content of sand (2 mm to 1/16 mm), silt (1/16 mm to 1/256), and clay (less than 1/256 mm). Air-dried samples were disaggregated in a prescribed solution of Calgon and distilled water. The sample was then poured into a 1-litre graduated cylinder, and distilled water was added to attain a total volume of 1 litre. The content of the cylinder was thoroughly stirred and allowed to stand for a length of time based on the settling rate of clay-sized particles in a water medium. At the end of the prescribed length of time, a hydrometer was used to measure the density of the suspension. The weight of the clay component of the sample was then calculated as the difference between the hydrometer reading of the suspension and the hydrometer reading of a standard (Calgon and distilled water). The clay, silt, and Calgon were then removed from the sample by a wet-sieve process. The sand and gravel that remained was dried. The dried sand and gravel was separated into 1/16 mm to 1 mm, 1 mm to 2 mm, and greater than 2 mm fractions by a dry-sieve process. The sand (1/16 mm to 2 mm) component and the gravel (greater than 2 mm) component were each determined by weighing on a scale, and the weight of the silt component of the sample was calculated as the difference between the weight of the clay, sand, and gravel and the total weight of the sample.

Contents of sand, silt, and clay are expressed as percentages of the total sample weight less the weight of the gravel (pebble) component. The content of gravel is usually so small that it is not
considered useful as a distinguishing characteristic of the glacial sediment.

The analysis was carried out in the North Dakota Geological Survey sediment laboratory.

Very-Coarse-Sand Lithology

The 1 to 2 mm sand fraction was separated from the samples during the textural analysis. The sand grains were counted under a binocular microscope (average count about 200 grains for each sample). Percentages of igneous-rock and metamorphic-rock fragments, carbonate-rock fragments, and shale fragments were calculated. Other rock fragments present in minor quantities were brown chert, red chert, unidentified black-rock, red sandstone, tan sandstone, limonite, and hematite.
SURFACE GEOLOGY

Surface Map

The surface map (Plate 1) shows the distribution of materials within the study area at a reconnaissance scale of 1:250,000. Each map unit is defined on the basis of two characteristics. The first characteristic is descriptive lithologic, and the second characteristic is the interpreted genesis of the material making up the unit. The map units vary in thickness but are more than a metre thick.

Map Units

Unit 1. Fluvial Sand, Silt, and Clay

This unit shows the distribution of poorly to moderately well sorted sand, silt, clay, and organic debris. The material is variably interbedded and obscurely laminated. It was deposited by present river systems as fluvial channel and overbank sediment.

Unit 2. Eolian Sand

This map unit shows the distribution of very well sorted, very-fine-grained to fine-grained sand. The material is obscurely bedded and contains a moderate amount of organic debris. It is a blanket-like deposit that conforms to the pre-deposition topography. The material is generally distributed in patches throughout the map area, however, one deposit, extensive enough to appear on the map, is located about 10 kilometres southeast of Barnesville.
Unit 3. Bog Peat, Muck, and Organic Clay

This map unit shows the distribution of peat, muck, or organic clay. The unit consists of bog, marsh, and slough sediment that is found in low poorly drained areas.

Unit 4. Lacustrine Shoreline Sand

This map unit shows the distribution of well sorted medium-grained to coarse-grained sand. The material is ripple crossbedded to horizontally bedded and contains little or no organic debris. The sand was deposited in lacustrine shoreline or nearshore environments.

Unit 5. Lacustrine Shoreline Sand and Gravel

This map unit shows the distribution of medium-grained to coarse-grained sand, gravelly sand, sandy gravel, gravel, and cobbles. Little or no organic debris is present in the sediment. The sediment is ripple crossbedded to horizontally bedded. Individual beds are moderately well sorted, often bimodally, and the pebbles and cobbles are commonly imbricated. The material was deposited in a beach environment as forebeach, topbeach, and backbeach sediment.

Unit 6. Lacustrine Shoreline Sand over Pebble-Loam

This map unit shows the distribution of less than a metre of sand overlying pebble-loam. The overlying sand and the underlying pebble-loam have the same descriptive and genetic characteristics as the materials of Unit 4 and Unit 11 respectively. The sand is exposed in at least 50 percent of the map unit area. Pebble-loam is exposed in the remaining part.
Unit 7. Lacustrine Offshore Silt and Clay

This map unit shows the distribution of very well sorted silt, clayey silt, silty clay, and clay. The material is variably interbedded and laminated. It was deposited in a lacustrine offshore deep-water environment.

Unit 8. Lacustrine Offshore Sand, Silt and Clay

This map unit shows the distribution of the same material that Unit 7 is composed of with the addition of some beds of very-fine-grained to fine-grained sand. This sediment was deposited in a slightly shallower lacustrine offshore environment than the sediment of Unit 7.

Unit 9. Fluvial Sand

This map unit shows the distribution of well sorted medium-grained to coarse-grained sand. The material is variably interbedded with dune crossbedded, ripple crossbedded, and trough-shaped beds. Little or no organic debris is present in the sediment. It is fluvial channel sediment that was deposited by rivers that flowed from melting glacier ice.

Unit 10. Fluvial Sand and Gravel

This map unit shows the distribution of medium-grained to coarse-grained sand, gravelly sand, sandy gravel, and gravel. Little or no organic debris is present in the sediment. The material is variably interbedded with trough-shaped, dune and ripple crossbedded, and horizontal beds. Individual beds are poorly-sorted to moderately well-sorted and some are faintly imbricated. It was deposited as
upper-flow-regime and lower-flow-regime fluvial channel sediment by rivers that flowed from melting glacier ice.

Unit 11. Glacial Pebble-Loam

This map unit shows the distribution of a mixture of clay, silt, sand, pebbles, cobbles, and boulders in varying proportions. The material is unbedded and unsorted.

The pebble-loam was deposited as superglacial-collapse, englacial-collapse, and subglacial melt-out sediment.

Melting caused the accumulation of debris on the glacial ice surface. The debris was moved about the ice surface by mass movement (mud flows) until, upon complete melting, the superglacial-collapse sediment (ablation till) rested on the ground surface. Where the debris was coarse enough to let porewater escape, little mass movement occurred and the debris was let down directly onto the ground surface (Clayton and Moran, 1974). Variable amounts of meltwater-deposited sand are associated with superglacial-collapse sediment. Superglacial-collapse pebble-loam that is clayey (such as that of the Dunvilla Formation) has a greater number of the sand deposits associated with it than does pebble-loam that is sandier (such as that of the New York Mills Formation). The sand deposits are usually lenticular in shape and quite small (see the discussion of the Dunvilla Formation). However, deposits of sand and gravel as large as 0.2 square kilometres in area occur within the area of exposed pebble-loam of the Dunvilla Formation. These deposits are not large enough to appear on the surface map. No such sand and gravel was found in association with the superglacial-collapse sediment of the New York Mills Formation.
Englacial-collapse sediment also resulted from collapse due to melting; however, in this case debris was in short supply, very little mass wasting occurred, and the resulting sediment was relatively thin (Clayton and Moran, 1974). Very little englacial-collapse sediment was observed in the study area. The recognition of englacial-collapse sediment is based entirely upon the recognition of englacial-collapse morphology (washboard moraine). One small area of englacial-collapse morphology was observed (see the discussion of the Glacial-Upland District). The sediment that underlies this morphology is part of the Barnesville Formation. There is probably more englacial-collapse sediment present in the study area, but its characteristic morphology is probably masked by the more dominating characteristics of the pre-advance elements of the topography.

Deposition of subglacial melt-out sediment (lodgement till) occurred at the base of the glacier. Deposition at the base of active ice occurred when the englacial debris near the base was released by thawing. Deposition at the base of inactive ice occurred where a slice of ice was trapped in an irregularity in the bed of an active glacier, where the basal zone had become so choked with debris that movement was no longer possible, or where the glacier had stagnated (Clayton and Moran, 1974). Subglacial melt-out sediment present in the study area is texturally variable. The bulk of the pebble-loam of the Barnesville Formation is interpreted to be subglacial. This sediment contains a considerable proportion of clay-sized particles. It probably originated as englacial debris that was released at the base of active ice by thawing. The pebble-loam of the Sebeka Forma-
tion is thought to be entirely subglacial. This pebble-loam is very sandy. The sediment is thought to have been deposited as a result of thawing at the base of the active glacier and at the same time was moulded into a very well developed drumlin morphology. This origin does not fit the Clayton and Moran (1974) model because in that study drumlins are considered to be erosional in origin.

The texture of glacial pebble-loam seems to be governed by the types of lithologies present in the areas from which the sediment was derived. Pebble-loam that contains a large proportion of clay-sized particles (Dunvilla Formation and Barnesville Formation) has a source area to the northwest where extensive outcrops of shale occur. Pebble-loam that contains a large proportion of sand-sized particles (New York Mills Formation and Sebeka Formation) has a source area to the north or northeast where extensive outcrops of crystalline rock occur.

The glacial pebble-loam exposed in the study area is described in more detail in the "Lithostratigraphic Units" section of this report.

Geomorphology

Four geomorphic districts have been recognized in the study area (Figure 2). The Lake-Plain District is located at the extreme west end of the area. The Shoreline-Complex District is near the west end of the area. The Glacial-Upland District is in the central part and at east end of the area. The Outwash District is in the central part of the area.
Fig. 2. Geomorphic districts of the Comstock-Sebeka Area.
1. Lake-Plain District
2. Shoreline-Complex District
3. Glacial-Upland District
4. Outwash District
Lake-Plain District

The Lake-Plain District is the bed of glacier-dammed Lake Agassiz. The dominant sediment type that underlies the district is the lacustrine offshore silt and clay of Unit 7. The district is characterized by its flat surface. Intersecting lineations and compaction ridges are two subtle types of geomorphic features that disturb the flatness of the lake plain.

The intersecting lineations are very subtle and difficult to see at ground level. The intersecting lineations consist of ridges and grooves that generally trend northwest-southeast and have less than 1 metre of relief. They show up best on aerial photographs. An example is provided of the area 2 kilometres southwest of Comstock (Figure 3). Although they are not prominent features on the landscape, they do control the drainage of the flat lake plain.

An interesting cultural note was obtained during a conversation with a farmer who lives in the Comstock area. His description of a landscape feature, which is thought to be a pioneer oxcart trail, corresponds to the location and trend of the lineation located 1.5 kilometres southwest of Comstock (Figure 3). Perhaps the pioneer activity along this lineation was responsible for making it more visible on the aerial photograph than the other intersecting lineations that are present.

The intersecting lineations are interpreted by Clayton and others (1965) as ice-drag marks produced by large chunks of ice floating on Lake Agassiz during a low-water stage. The trend was controlled by prevailing winds from the northwest.
Fig. 3. Intersecting lineations, Lake-Plain District. Photography by U. S. Army Map Service. vv BE M2 195 and 196.
Compaction ridges are broad low-relief ridges. They are 0.5 to 2 kilometres wide and extend across the Lake-Plain District from the north boundary to the south boundary of the study area. The sand and gravel that is found in the cores of these ridges does not compact as much as the surrounding silt and clay thus forming ridges on the landscape.

There are two compaction ridges present in the study area. The smaller of the two rises up to 2 metres above the surrounding lake plain and can be seen at ground level 4 kilometres east of Comstock. The surficial sediment of this ridge consists of lacustrine silt and clay (Unit 7). The sand and gravel in its core is thought to be fluvial channel sediment that was deposited by a river that flowed over the exposed Lake Agassiz bed during a period when the lake had withdrawn. The larger ridge has slightly more relief and can be seen 8 kilometres east of Comstock. The core of this ridge is exposed at the surface and is being mined. The sediment of the core is thought to be that of an esker because no organic debris or fossils are present in the sediment.

Shoreline-Complex District

The Shoreline-Complex District is located along the margin of Lake Agassiz.

The district consists of north-south trending beach ridges that rise up to 6 metres above the surrounding flat to undulating landscape. The ridges are underlain by shoreline sand and gravel (Unit 5). The area surrounding the ridges is underlain by shoreline sand (Unit 4), shoreline sand over pebble-loam (Unit 6), or glacial
pebble-loam (Unit 11). An example of a spit that developed along a beach is 10 kilometres south of Barnesville along Minnesota Highway Number 9 (Figure 4). Wave-cut scarps of similar relief and trend developed where wave energy was too great for the deposition of beach sediments. An example is located 8 kilometres north of Barnesville (Figures 5 and 6).

Glacial-Upland District

The Glacial-Upland District is the largest and most diverse geomorphic district in the study area. Characteristic types of morphology found in the district are subglacial-sheared, subglacial-thrust, englacial-collapse, superglacial-collapse, meltwater channels, eskers, and esker complexes.

The subglacial-sheared topography present within the study area consists of drumlins and glacial flutings that are produced by shearing at the base of the glacier and are oriented parallel to the direction of ice movement. One area where drumlins and glacial flutings are present is located about 10 kilometres northeast of Barnesville. Here the drumlins are of low relief, up to 3 kilometres in length, and trend northwest-southeast. They are underlain by glacial pebble-loam (Unit 11). Several miles to the south the lineations become superimposed upon superglacial-collapse topography providing evidence for at least two advances of glacial ice in the immediate vicinity.

A more extensively developed drumlin field near Sebeka contains a large number of moderate-relief drumlins (Figures 7 and 8). These drumlins are underlain by sandy glacial sediment and crest up
Fig. 4. Spit developed along a beach, Shoreline-Complex District. Photography by U. S. Army Map Service. vv BE M2 217 and 218.
Fig. 5. Wave-cut scarp, aerial view, Shoreline-Complex District. Photography by U. S. Army Map Service. vv BE M1 72 and 73.
Fig. 6. Wave-cut scarp, surface view, Shoreline-Complex District. Road in foreground is boundary between sections 24 and 25 of T. 138 N., R. 46 W. Photograph by Curtis A. Anderson.
Fig. 7. Drumlin Field near Sebeka, aerial view, Glacial-Upland District. Photography by Mark Hurd Aerial Survey, Inc. Photograph Numbers BRA-220 and BRA-221.
Fig. 8. Drumlín topography near Sebeka, surface view, Glacial-Upland District. View is to the north across SE², Sec. 7, T. 135 N., R. 34 W. Photograph by Curtis A. Anderson.
to 20 metres above the intervening peat bogs. The drumlins trend northeast-southwest in the east part of the drumlin field and fan to an east-west trend farther west.

The subglacial-thrust topography present within the study area consists of push-ridges that are sub-parallel arcuate ridges of moderate relief. They are produced at the margin of the glacier where the ice is frozen to the underlying ground surface. Masses of material are thrust into the ice along sub-parallel shear planes within the glacier producing a broad arcuate pattern on the landscape that is concave up-glacier (Clayton and Moran, 1974). An example of push-ridge morphology is in an area about 4 kilometres west of Vergas (Figure 9). Here the morphology is largely underlain by glacial sediment with isolated areas of sand and gravel.

Englacial-collapse morphology (washboard moraine) is typified by low-relief surface lineations that are perpendicular to the direction of ice movement. They are produced by the collapsing of thin englacial debris (Clayton and Moran, 1974). The only englacial-collapse morphology present in the study area is located about 11 kilometres northeast of Barnesville.

Superglacial-collapse topography is the most wide-spread type of topography within the Glacial-Upland District. The undulating to hummocky surface (Figures 10 and 11) is underlain largely by collapsed glacial sediment. The local relief varies from nearly flat to about 50 metres. Prominent scarps are present at the boundary between this topography and outwash plains of the Outwash District.

Meltwater channels are common geomorphic features in the Glacial-Upland District. They are meandering channels that have been
Fig. 9. Push-ridges, Glacial-Upland District. Photography by U. S. Army Map Service. vv BE M2 206 and 207.
Fig. 10. Superglacial-collapse topography, aerial view, Glacial-Upland District. Photography by U. S. Army Map Service.
vv BE M2 213 and 214.
Fig. 11. Superglacial-collapse topography, surface view, Glacial-Upland District. View is to the north across SE₁, Sec. 25, T. 136 N., R. 44 W. Photograph by Curtis A. Anderson.
cut into the glacial sediment by rivers that flowed from melting glacier ice. The channels are usually bounded on either side by a prominent scarp. The sediment underlying the channels is largely fluvial sand and gravel (Unit 10) except where it has been overridden by glacial ice and blanketed with glacial sediment. Lower-flow-regime fluvial sand and gravel in a terrace of a meltwater channel is shown in Figure 12. Some of the channels are now occupied by small rivers such as the Red Eye River, which flows in an extensive meltwater channel that cuts through the northeast part of the map area (Figure 13). Others are occupied by lakes or support extensive agricultural activity.

Eskers and esker complexes are common in the Glacial-Upland District. They usually occur in association with meltwater channels, such as 8 kilometres northwest of Dunvilla (Figures 14 and 15). They are underlain by upper-flow-regime and lower-flow-regime fluvial sand and gravel that was deposited by waning rivers that flowed through tunnels within glacial ice. Upon complete melting of the ice, the esker sediment was collapsed to form curved ridges on the landscape. Normal and reverse faulting occurred within the sediment as it was collapsed. Reverse faulting is most common and can be observed in the upper-flow-regime fluvial sand and gravel that is found in an esker 2.5 kilometres south of Perham (Figures 16 and 17).

Outwash District

The Outwash District is the second largest geomorphic district in the study area. Characteristic types of morphology found in the district are collapsed outwash and pitted outwash plains.
Fig. 12. Lower-flow-regime sand and gravel in a terrace of a meltwater channel, Glacial-Upland District. SE\textfrac{1}{4}, NE\textfrac{1}{4}, SE\textfrac{1}{4} Sec. 19, T. 136 N., R. 34 W. Photograph by Curtis A. Anderson
Fig. 13. Meltwater channel, Glacial-Upland District. Photography by Mark Hurd Aerial Survey, Inc. Photograph Numbers BRA-357 and BRA-358.
Fig. 14. Esker complex and meltwater channel, aerial view, Glacial-Upland District. Photography by U. S. Army Map Service. vv BE Ml 76 and 77.
Fig. 15. Esker complex, surface view, Glacial-Upland District. View is to the west. The road passes over the esker complex and down the center of Sec. 17, T. 137 N., R. 43 W. Photograph by Curtis A. Anderson.
Fig. 16. Esker near Perham, Glacial-Upland District. Photography by Mark Hurd Aerial Survey, Inc. Photograph Numbers BRA-224 and BRA-225.
Fig. 17. Esker sediment of esker near Perham, Glacial-Upland District.  NW\(\frac{1}{4}\), NW\(\frac{1}{4}\), NW\(\frac{1}{4}\) Sec. 34, T. 136 N., R. 39 W.  Photograph by Curtis A. Anderson.
The rolling to hummocky surface of collapsed outwash topography is underlain by fluvial sand and gravel (Unit 10). The sand and gravel was deposited by water that flowed on the surface of glacial ice. The morphology of the ice surface governed the distribution of the sediment. Thick sediment accumulated in depressions, and it thinned towards the depressions margins. Upon complete melting of the ice, the thick sediment collapsed to produce hummocks. Exposures often exhibit a draped-over appearance and the sediment is commonly faulted.

Collapsed outwash topography is similar to the hummocky surface that is underlain by glacial sediment. However, when visualized in cross-section, there is generally a smaller radius of curvature of the hummocks underlain by sand and gravel than that of glacial sediment.

Pitted outwash plains are generally flat lowlands dotted with ice-block depressions. They are large fluvial fans that developed at the mouths of large rivers that flowed from melting glacier ice. As the water flowed onto the fan, velocities decreased and allowed the sediment load to be deposited. Complex distributary networks developed on the fan and their abandoned channels disturb the flatness of the plain.

One well developed outwash plain is present in the study area. Figure 18 shows the morphology of this plain about 8 kilometres north of Perham. The river that supplied the sediment for this outwash plain flowed from the north and had its mouth near Frazee. The fluvial sand and gravel (Unit 10) that underlies the plain becomes generally finer-grained and thinner away from the mouth.
Fig. 18. Pitted outwash plain morphology, Outwash District. Photography by Mark Hurd Aerial Survey, Inc. Photograph Numbers BRA-355 and BRA-356.
LITHOSTRATIGRAPHIC UNITS

General Statement

Five lithostratigraphic units are presently recognized in the study area (Figure 19).

The Sebeka, New York Mills, Dunvilla, and Barnesville Formations are being defined and named for the first time in this report. The Sebeka and Dunvilla Formations contain glacial and fluvial sediment. The fluvial sediment parts of these two units were included in an effort to maintain stratigraphic consistency and are not considered distinguishing parts of the units. The New York Mills and Barnesville Formations contain glacial sediment. The main objective of the lithostratigraphic study was to distinguish the Sebeka, New York Mills, Dunvilla, and Barnesville Formations by using the characteristics of the glacial pebble-loam that they contain.

The term "pebble-loam" is used throughout the discussion of the lithostratigraphic units to refer to the homogeneous sediment of mixed sizes (boulders to clay). The term "pebble-loam" is preferred over "till" because "pebble-loam" is a descriptive term, whereas "till" is a descriptive and genetic term. Modifiers of the term pebble-loam, such as "sandy" and "clayey", are used loosely to reflect the relative abundance of particles of those sizes in the sediment.

The Sebeka, New York Mills, Dunvilla, and Barnesville Formations are distinguished largely by the texture and the lithology of
Fig. 19. Surface exposure of lithostratigraphic units in the Comstock-Sebeka Area.
Surficial sediment not defined as part of any lithostratigraphic unit.

Sherack Formation.

New York Mills Formation, Dunvilla Formation, and Barnesville Formation.

Dunvilla Formation.

New York Mills Formation and Dunvilla Formation.

New York Mills Formation.

Sebeka Formation.
the very-coarse-sand fraction of the glacial pebble-loam contained in the units. Methods of sampling and sample analysis are presented in the "Laboratory Methods" section of this report. Data on the texture and lithology of the very-coarse-sand fraction is tabulated for each unit in the Appendix. Means and standard deviations have been calculated for each unit and are presented in Table 1. Other distinguishing characteristics, such as the relative presence of jointing and the structure of the pebble-loam, were also used and are described in the discussions of the units. The colors of the pebble-loam contained in the units were not particularly useful in distinguishing the units. Color should not be considered a distinguishing characteristic of the pebble-loam unless otherwise stated. Color designations used for pebble-loam are from the Munsell Soil Color Chart.

The exact distributions of the New York Mills, Dunvilla, and Barnesville Formations were not mapped in the west-central part of the study area (Figure 19). Generally, exposures in that area contain one of the formations and in some cases two in their respective stratigraphic positions.

The Sherack Formation has been previously defined and named (Harris and others, 1974). It contains interbedded silt and clay of lacustrine origin. The Sherack Formation is easily traced from areas where it has been mapped north of the study area, and for that reason has been included in the lithostratigraphic study of this report.

The lacustrine shoreline sediment exposed in the Shoreline-Complex District, the interbedded sand, silt, and clay exposed in the
Table 1. Summary of textural and very-coarse-sand lithology data of pebble-loam of lithostratigraphic units.
<table>
<thead>
<tr>
<th>Lithostratigraphic Unit</th>
<th>Mean or Standard Deviation</th>
<th>Texture (%)</th>
<th>Very-Coarse-Sand Lithology (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sd</td>
<td>Silt</td>
</tr>
<tr>
<td>Barnesville Fm. n = 9</td>
<td>Mean</td>
<td>21</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>3.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Dunvilla Fm. n = 11</td>
<td>Mean</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>8.1</td>
<td>2.9</td>
</tr>
<tr>
<td>New York Mills Fm. n = 26</td>
<td>Mean</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>11.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Sebeka Fm. n = 17</td>
<td>Mean</td>
<td>66</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>4.1</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Lake-Plain District, and the fluvial sediment of the large compaction ridge located in the Lake-Plain District were not defined in any lithostratigraphic unit in this report because the emphasis of the stratigraphic study was placed on glacial sediment. The relationships between the above types of sediment and sediment of defined lithostratigraphic units are presented in the discussion of the Sherack Formation. The eolian sand that is exposed in the Glacial-Upland District was not included in any defined unit for the same reason. The fluvial sediment that is exposed in the extreme northeastern corner of the study area is not included in any defined lithostratigraphic unit for the same reason, and the relationships between this sediment and defined lithostratigraphic units are presented in the discussion of the Sebeka Formation.

Scattered deposits of bog sediment and fluvial sediment occur at the surface throughout the area. These deposits are the result of surface processes occurring today. They are not included in any lithostratigraphic unit because of their minor occurrence, incomplete history, and the reconnaissance scale of this study.

The lithostratigraphic units are discussed from oldest to youngest. The discussion includes distinguishing characteristics, source area, regional correlation, and age.

**Sebeka Formation**

The Sebeka Formation is exposed in the eastern fifth of the study area (Figure 19). The source of its name is the village of Sebeka in Wadena County, Minnesota. Sebeka is located on the Sebeka 7.5 minute quadrangle.
The Sebeka Formation consists of glacial and fluvial sediment. The oxidized glacial pebble-loam of the Sebeka Formation has a pale yellow color (5Y 7/3) when dry and an olive color (5Y 5/3) when wet. The colors grade to slightly-more-reddish colors towards the top of the outcrops (see the type section description). This color change is thought to be the result of soil-forming processes occurring in the present surface and near-surface environment. The glacial pebble-loam of the Sebeka Formation is composed of an average of 66% sand, 21% silt, and 13% clay (Table 1). Pebbles are abundant but relatively insignificant when compared to the proportions of the other components present. The very-coarse-sand fraction of the pebble-loam contains an average of 93% igneous-rock and metamorphic-rock fragments, 7% carbonate-rock fragments, and no shale fragments (Table 1). The pebble-loam is unbedded, unjointed, and very friable.

Near-vertical outcrops of the pebble-loam part of the Sebeka Formation tend to hold that attitude very well. This is probably due to its sandy texture, which allows rain water to infiltrate through the material rather than to run off the exposed surface of the material.

Fluvial sand and gravel inclusions were not observed in the pebble-loam part of the Sebeka Formation. However, deep cuts found in gravel pits in the area northwest of Sebeka expose underlying fluvial sand and gravel that is in sharp contact with the overlying pebble-loam. This fluvial sediment is included in the Sebeka Formation in an effort to maintain stratigraphic consistency. It is not considered a distinguishing part of the formation. The location of an example
section is NE%, NE%, SE% Sec. 33, T. 138 N., R. 35 W. Here the pebble-loam is 2.5 metres thick and has the typical colors of the Sebeka Formation. The pebble-loam is unbedded, unjointed, and very friable. The pebble-loam at this location is composed of 67% sand, 21% silt, and 12% clay. The very-coarse-sand fraction contains 90% igneous-rock and metamorphic-rock fragments, 10% carbonate-rock fragments, and no shale fragments (analysis of 1 sample taken at a depth of 1.5 metres). One metre of upper-flow-regime and lower-flow-regime fluvial sand and gravel is exposed beneath the pebble-loam and extends to an unknown depth. The fluvial sediment is moderately sorted medium-grained to coarse-grained sand, gravelly sand, sandy gravel, and gravel. The fluvial sediment is variably interbedded from dune crossbedded to horizontally bedded. The pebble fraction contains about a third carbonate-rock fragments and two-thirds igneous-rock and metamorphic-rock fragments. When viewed in direct sunlight, the general color of the fluvial sediment is light tan.

A larger exposure of fluvial sediment that is laterally equivalent to that of the above discussion is located in a gravel pit at NE%, NE%, NE% Sec. 31, T. 138 N., R. 35 W. At this location the sediment has been folded into overturned folds that have their axial planes nearly horizontal. The folding was probably produced as a result of forces that were exerted on the fluvial sediment as glacial ice flowed over it. It is thought that this advance of glacial ice deposited the pebble-loam part of the Sebeka Formation.

The type area of the Sebeka Formation is the Sebeka area. The location of the type section of the Sebeka Formation is NE%, NE%,
NW¼ Sec. 15, T. 136 N., R. 35 W. To reach the type section proceed one and one-half miles south of Sebeka on highway number 71, then one-third mile east on road number 132 (gravel). The type section consists of 5 metres of exposed pebble-loam in the railroad cut on the south side of the road. The material of the upper 1.5 metres of the type section has a slightly-more-reddish color when viewed in sunlight than the lower 3.5 metres. The color of the lower part is pale yellow (5Y 7/3) when dry and olive (5Y 5/3) when wet. The boundary between the two colors is gradational and mottled. Two samples were collected from the exposure at depths of 1 metre and 3 metres. The samples were analyzed for their texture and the lithology of the very-coarse-sand fraction. The first sample contained 70% sand, 18% silt, and 12% clay, and the lithology of the very-coarse-sand fraction was 99% igneous-rock and metamorphic-rock fragments, 1% carbonate-rock fragments, and no shale fragments. The second sample contained 70% sand, 20% silt, and 10% clay, and the lithology of the very-coarse-sand fraction was 93% igneous-rock and metamorphic-rock fragments, 7% carbonate-rock fragments, and no shale fragments. The pebble-loam of the type section is unbedded, unjointed, and very friable.

The Sebeka Formation is the lowermost lithostratigraphic unit observed in the study area. The considerably sandier texture of the pebble-loam of the Sebeka Formation distinguishes it from that of the New York Mills Formation. The characteristics most useful in the identification of the Sebeka Formation are the large number of igneous-rock and metamorphic-rock fragments and lower number of carbonate-
rock fragments in the very-coarse-sand fraction of the pebble-loam. It contains an average of 93% igneous-rock and metamorphic-rock fragments and 7% carbonate-rock fragments, whereas the New York Mills Formation contains an average of 65% and 31% respectively (Table 1).

The contact between the Sebeka Formation and the overlying New York Mills Formation was not present in any of the outcrops that were studied within the study area. The age relationship between these two lithostratigraphic units was arrived at through the use of geomorphologic information. The contact between the Sebeka Formation and the New York Mills Formation, as it appears on the Figure 19, is also a geomorphic contact. Drumlin morphology exists to the immediate east of the contact and superglacial-collapse morphology exists to the immediate west of the contact. The drumlin morphology is underlain by the sediment of the Sebeka Formation and the superglacial-collapse morphology is underlain by the sediment of the New York Mills Formation. Evidence that the drumlin morphology is older than the superglacial-collapse is observed near the village of New York Mills. In that area the superglacial-collapse morphology is superimposed on the drumlin morphology and elements of both are present. Therefore, the Sebeka Formation is older than the New York Mills Formation. The evidence presented in the above discussion does leave a small element of doubt as to the relative ages of the two formations. To prove or disprove the argument presented above requires additional information from the subsurface or from surface exposures outside of the study area.

The Sebeka Formation is overlain by well sorted medium-grained to coarse-grained sand of fluvial origin in the extreme northeastern
corner of the study area. Stratigraphic evidence for this relationship was not observed. However, the drumlin morphology that is underlain by glacial sediment of the Sebeka Formation is clearly visible in that area. The fluvial sediment is thought to have been deposited by rivers that flowed from melting glacier ice which had its margin about 32 kilometres east of the study area. The soils map reveals that this fluvial sediment is part of a large body of fluvial sediment that blankets the drumlin morphology in a broad area east of and adjacent to the study area.

The pebble-loam part of the Sebeka Formation is thought to have a northeastern source area because the very-coarse-sand fraction contains a very large proportion of Canadian Shield rock. It was deposited by an advance of glacial ice which came from the northeast. All that can be said about the origin of the fluvial sediment in the Sebeka Formation is that it was deposited by a river that flowed from melting glacier ice before the overlying pebble-loam was deposited.

The stratigraphic position, sandy texture of the pebble-loam, and large proportion of igneous-rock and metamorphic-rock fragments in the very-coarse-sand fraction of the pebble-loam suggest that the Sebeka Formation correlates with the Marcoux Formation in northwestern Minnesota (Harris and others, 1974; Harris, 1975; Sackreiter, 1975) and possibly correlates with the "Hawk Creek Till" of southwestern Minnesota (Matsch, 1971) (Table 2). The Sebeka Formation may also correlate with the Vang Formation in northeastern North Dakota (Hobbs, 1975) because of their similar stratigraphic positions (Table 2).
Table 2. Correlation of lithostratigraphic units present in the Comstock-Sebeka area with stratigraphic units in other areas.
<table>
<thead>
<tr>
<th>RED LAKE FALLS AREA</th>
<th>GRAND FORKS-BEMIDJI AREA</th>
<th>GRAND FORKS-BEMIDJI AREA</th>
<th>STUDY AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td>NORTHEASTERN MINNESOTA</td>
<td>NORTHWESTERN MINNESOTA</td>
<td>NORTHWESTERN MINNESOTA</td>
<td>SOUTHWESTERN MINNESOTA</td>
</tr>
<tr>
<td>SD-SLT-CLY</td>
<td>SD-SLT-CLY</td>
<td>SD-SLT-CLY</td>
<td>SD-SLT-CLY</td>
</tr>
<tr>
<td>XTAL-CO$_3$-SH</td>
<td>XTAL-CO$_3$-SH</td>
<td>XTAL-CO$_3$-SH</td>
<td>XTAL-CO$_3$-SH</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sherack Fm.</th>
<th>Sherack Fm.</th>
<th>Sherack Fm.</th>
<th>Sherack Fm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barnesville Fm.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-42-38</td>
<td>42-44-14</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Dahlen Fm. | U.Red Lake Falls Fm. | | | | New Ulm Till |
|------------|---------------------|--------------------------|-------------|----------------|

**Red Lake Falls Fm.**

<table>
<thead>
<tr>
<th>37-42-21</th>
<th>56-37-5</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>L.Red Lake Falls Fm.</th>
<th></th>
<th>New York Mills Fm.</th>
<th>Granite Falls Till</th>
</tr>
</thead>
<tbody>
<tr>
<td>44-36-20</td>
<td></td>
<td>49-30-21</td>
<td>38-43-20</td>
</tr>
<tr>
<td>57-37-5</td>
<td></td>
<td>64-32-4</td>
<td>49-43-3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vang Fm.</th>
<th>Marcoux Fm.</th>
<th>Marcoux Fm.</th>
<th>Marcoux Fm.</th>
<th>Sebeka Fm.</th>
<th>Hawk Creek Till</th>
</tr>
</thead>
<tbody>
<tr>
<td>39-21-40</td>
<td>78-19-5</td>
<td>82-16-2</td>
<td>85-13-1</td>
<td>93-7-0</td>
<td>79-12-1</td>
</tr>
</tbody>
</table>
The age of the Sebeka Formation is unknown, but its stratigraphic position under the New York Mills Formation suggests that it is pre-Wisconsinan or Early Wisconsinan in age.

New York Mills Formation

The New York Mills Formation is the most extensively exposed lithostratigraphic unit in the study area (Figure 19). The source of its name is the village of New York Mills in Otter Tail County, Minnesota. New York Mills is located on the New York Mills, East 7.5 minute quadrangle.

The New York Mills Formation consists of glacial sediment. Fluvial sediment inclusions and sand lenses were not observed in the glacial pebble-loam. The base of the New York Mills Formation was not found in any outcrop in the study area, but the sediment of the formation is assumed to unconformably overlie the pebble-loam of the Sebeka Formation (see the discussion of the Sebeka Formation). The oxidized pebble-loam of the New York Mills Formation has a pale yellow color (5Y 7/3) when dry and an olive color (5Y 5/4) when wet. Unoxidized pebble-loam was not observed because the surface outcrops that were studied did not extend deep enough to expose it. The glacial pebble-loam of the New York Mills Formation is composed of an average of 50% sand, 30% silt, and 20% clay (Table 1). Pebbles are abundant but relatively insignificant when compared to the proportions of the other components present. The very-coarse-sand fraction of the pebble-loam contains an average of 65% igneous-rock and metamorphic-rock fragments, 31% carbonate-rock fragments, and 4% shale fragments (Table 1). The inconspicuous weak jointing present in the pebble-
loam contrasts the relatively conspicuous jointing present in the pebble-loam part of the Dunvilla Formation. The very friable pebble-loam of the New York Mills Formation is similar to the pebble-loam part of the Sebeka Formation in that respect.

The type area of the New York Mills Formation is the New York Mills area. The location of the type section of the New York Mills Formation is NW\(_4\), NW\(_4\), SW\(_4\) Sec. 14, T. 135 N., R. 38 W. The type section can be reached by proceeding one mile south and one mile west of New York Mills on highway number 67, continuing westward on highway number 14 for two and two-third miles, turning north on the gravel road, and proceeding a third of a mile. The type section consists of 3 metres of exposed pebble-loam in the road cut on the east side of the road. The pebble-loam exposed here has a pale yellow color (5Y 7/3) when dry and an olive color (5Y 5/4) when wet. One sample was collected from a depth of 2 metres and analyzed for its texture and the lithology of the very-coarse-sand fraction. The sample contained 64% sand, 23% silt, and 13% clay, and the lithology of the very-coarse-sand fraction was 70% igneous-rock and metamorphic-rock fragments, 25% carbonate-rock fragments, and 5% shale fragments.

The pebble-loam of the type section is unbedded, weakly jointed, and very friable. The similarity between the color of the sediment immediately adjacent to joint planes and the color of the bulk of the sediment suggests that the weak jointing has not appreciably increased the permeability of the sediment. The use of jointing and permeability as distinguishing characteristics of glacial sediment is examined more thoroughly later in this discussion.
The New York Mills Formation overlies the Sebeka Formation and underlies the Dunvilla Formation. The relationships between the New York Mills Formation and the Sebeka Formation are described in the discussion of the Sebeka Formation. The more abundant igneous-rock and metamorphic-rock fragments and the fewer shale fragments in the very-coarse-sand fraction of the New York Mills Formation distinguish it from the pebble-loam part of the Dunvilla Formation. The New York Mills Formation contains an average of 65% igneous-rock and metamorphic-rock fragments and 4% shale fragments, whereas the Dunvilla Formation contains an average of 40% and 35% respectively (Table 1). The location of an example section that contains pebble-loam of both formations is SW₁/₄, SW₁/₄, SE₁/₄ Sec. 26, T. 136 N., R. 42 W. Pebble-loam of the Dunvilla Formation is exposed in the upper 2 metres of the outcrop. This pebble-loam has a light gray color (5Y 7/2) when dry and an olive gray color (5Y 5/2) when wet. The sediment is unbedded. A sample was collected from a depth of 1.5 metres and analyzed for its texture and the lithology of the very-coarse-sand fraction. The sample contained 40% sand, 33% silt, and 27% clay, and the lithology of the very-coarse-sand fraction was 45% igneous-rock and metamorphic-rock fragments, 16% carbonate-rock fragments, and 39% shale fragments. The pebble-loam of the upper 2 metres is moderately jointed, and the sediment immediately adjacent to the joint planes is stained and has a reddish-brown color. The pebble-loam of the upper 2 metres is friable but sticks together readily when a moist hand sample is squeezed. Pebble-loam of the New York Mills Formation is exposed for 2.5 metres and extends to an unknown depth beneath the pebble-loam of the Dunvilla Formation. This pebble-loam has a pale yellow color.
(SY 7/3) when dry and an olive color (SY 5/3) when wet. The sediment is unbedded. A sample was collected from a depth of 4 metres. The sample was analyzed and found to contain 54% sand, 30% silt, and 16% clay. The lithology of the very-coarse-sand fraction was 63% igneous-rock and metamorphic-rock fragments, 28% carbonate-rock fragments, and 9% shale fragments. The pebble-loam of the lower 2.5 metres is weakly jointed, and although reddish-brown staining is present along joint planes, it is not as prominent as that of the upper 2 metres of the outcrop. The pebble-loam of the bottom 2.5 metres of the outcrop is very friable and does not stick together readily when a moist hand sample is squeezed. It appears that water can percolate through the pebble-loam of the New York Mills Formation nearly as readily as it does along the joint planes that are present. The pebble-loam of the Dunvilla Formation contains less sand and more clay than that of the New York Mills Formation. Therefore, the pebble-loam of the Dunvilla Formation is less permeable, and infiltrating water preferentially moves along the joint planes. This probably explains why there is more oxidation and color-staining of the sediment immediately adjacent to joint planes in the Dunvilla Formation. The contact between the two units exposed in this outcrop is not distinct. The slight concentration of boulders present near the contact could be described as a weakly developed boulder pavement. This is generally the nature of the contact between the pebble-loam parts of the two units throughout the study area.

The pebble-loam of the New York Mills Formation was also found to underlie the fluvial sediment of the Dunvilla Formation. The location of an example section is SE1/4, SE3/4, SW1/4 Sec. 12, T. 137 N., R. 43 W.
This outcrop is grass-covered, gently inclined, and requires considerable excavation with a digging tool to expose the sediment. Fluvial sediment of the Dunvilla Formation is exposed in the upper 2.5 metres of the outcrop. The fluvial sediment is moderately sorted medium-grained to coarse-grained sand, gravelly sand, and sandy gravel. This sediment is variably interbedded from dune crossbedded to horizontally bedded. The pebble fraction contains, in order from most abundant to least abundant, igneous-rock and metamorphic-rock fragments, carbonate-rock fragments, and shale fragments. When viewed in direct sunlight, the general color of the fluvial sediment is tan. Pebble-loam of the New York Mills Formation is exposed in the lower 3 metres of the outcrop and extends to an unknown depth. This pebble-loam is pale yellow (SY 8/3) when dry and pale olive (SY 6/3) when wet. A sample was collected from a depth of 3.5 metres. The sample was analyzed and found to contain 39% sand, 31% silt, and 30% clay. The lithology of the very-coarse-sand fraction of the sample was 60% igneous-rock and metamorphic-rock fragments, 34% carbonate-rock fragments, and 6% shale fragments. The pebble-loam is unbedded, weakly jointed, and very friable. The contact between the fluvial sediment and the pebble-loam is sharp. Fluvial sediment of the Dunvilla Formation is exposed at the surface in a broad area that expands a large part of the central part of the study area. This outcrop was the only one found that exposes the material that underlies this broad area of fluvial sediment.

The glacial sediment of the New York Mills Formation is thought to have been deposited by glacial ice that came from about due north because the very-coarse-sand fraction contains a large proportion of
Canadian Shield rock (igneous and metamorphic) and a moderate proportion of Winnipeg Lowland rock (carbonate).

The stratigraphic position and small proportion of shale fragments in the very-coarse-sand fraction of the pebble-loam suggest that the New York Mills Formation correlates with the lower unit of the Red Lake Falls Formation in northwestern Minnesota (Harris and others, 1974; Sackreiter, 1975) and possibly correlates with the "Granite Falls Till" in southwestern Minnesota (Matsch, 1971) (Table 2).

A radiocarbon date from organic silt on top of a unit that is equivalent to the "Granite Falls Till" near Pillsbury in eastern Todd County is greater than 40 000 BP (Wright, 1972). This suggests an Early Wisconsinan age for the possibly correlative New York Mills Formation.

Dunvilla Formation

The Dunvilla Formation is exposed in the central part of the study area (Figure 19). The source of its name is the village of Dunvilla in Otter Tail County, Minnesota. Dunvilla is located on the Otter Tail County general highway map (scale about 1 : 125 000).

The Dunvilla Formation consists of glacial and fluvial sediment. The glacial pebble-loam part of the Dunvilla Formation is light gray (5Y 7/2) when dry and olive gray (5Y 5/2) when wet. Because of oxidation, this color becomes slightly lighter and yellowish towards the top of surface outcrops. The glacial pebble-loam of the Dunvilla Formation is composed of an average of 40% sand, 35% silt, and 25% clay (Table 1). Pebbles are abundant but relatively insignificant when compared to the proportions of the other components.
present. The very-coarse-sand fraction of the pebble-loam contains an average of 40% igneous-rock and metamorphic-rock fragments, 25% carbonate-rock fragments, and 35% shale fragments (Table 1). The pebble-loam is unbedded, moderately jointed, and friable. The color of the sediment that is immediately adjacent to the joint planes is reddish-brown.

Lens-shaped deposits of medium-grained to coarse-grained sand are present in the pebble-loam (see the description of the type section). The sand lenses are not a distinguishing characteristic of the pebble-loam of the Dunvilla Formation because they are rare.

Increased oxidation occurs along joint planes and in the sand lenses because groundwater preferentially moves along these features. The oxidation produces iron oxides which stain the individual grain surfaces and give the related sediment its reddish-brown color.

The fluvial sediment part of the Dunvilla Formation inter­tongues with the pebble-loam part of the formation and is exposed at the surface in the Outwash District. Stratigraphic evidence for the intertongueing relationship was not found. However, some of the beds of the fluvial sediment contain large proportions of shale fragments. The pebble-loam part of the Dunvilla Formation contains a larger proportion of shale fragments than the pebble-loam of any of the other lithostratigraphic units present in the area. Therefore, it is thought that the fluvial sediment was deposited by water flowing from the same melting glacial ice that was contemporaneously depositing the pebble-loam part of the Dunvilla Formation. This fluvial sediment is included in the Dunvilla Formation in an effort to maintain strati-
graphic consistency. It is not considered a distinguishing part of the formation.

The fluvial sediment is nicely exposed in a road cut at NE¼, NE¼, SW¼ Sec. 21, T. 137 N., R. 40 W. About 4 metres of the sediment is exposed here and it extends to an unknown depth. The sediment is moderately sorted medium-grained to coarse-grained sand, gravelly sand, sandy gravel, and gravel. The sediment is variably interbedded from dune crossbedded to flat bedded. The lithology varies from bed to bed. Most of the beds contain about one-half igneous-rock and metamorphic-rock fragments, one-fourth carbonate-rock fragments, and one-fourth shale fragments. However, some beds contain as much as three-fourths shale fragments. The colors of individual beds range from tan to dark gray. Darker colors are the result of larger proportions of shale fragments. Two other sections of the sediment of the Dunvilla Formation are described in the discussion of the New York Mills Formation.

The type area of the Dunvilla Formation is the Dunvilla area. The location of the type section of the Dunvilla Formation is NW¼, SW¼, SW¼ Sec. 26, T. 137 N., R. 42 W. It can be reached by proceeding two miles northeast of Dunvilla on highway number 59, turning south on highway number 31, and traveling two miles. The type section consists of 5 metres of exposed glacial pebble-loam in the road cut on the east side of the highway. The color of the pebble-loam exposed here is light gray (5Y 7/2) when dry and olive gray (5Y 5/2) when wet. The pebble-loam is unbedded, moderately jointed, and friable. The color of the sediment immediately adjacent to joint planes is reddish-brown. One sample of the pebble-loam was collected from a depth of 3 metres. It
was analyzed for its texture and the lithology of the very-coarse-sand fraction. The sample contained 36% sand, 32% silt, and 32% clay, and the lithology of the very-coarse-sand fraction was 38% igneous-rock and metamorphic-rock fragments, 20% carbonate-rock fragments, and 42% shale fragments. Lens-shaped deposits of fine-grained to medium-grained sand are present within the pebble-loam. The general color of the sand is reddish-brown. When viewed in cross-section, the lenses vary in size from about 15 centimetres wide and 4 centimetres thick to about 3 metres wide and 0.5 metre thick. The sand lenses take up about one-fifth of the total exposed surface of the outcrop. It is thought that the sand was deposited by small streams of water flowing over the surface of superglacial debris as the glacial ice thawed.

The Dunvilla Formation overlies the New York Mills Formation and underlies the Barnesville Formation. The relationships between the Dunvilla Formation and New York Mills Formation are described in the discussion of the New York Mills Formation. The most useful characteristic in distinguishing the pebble-loam of the Dunvilla Formation from the pebble-loam of other units is the great amount of shale. It contains an average of 35% shale fragments in the very-coarse-sand fraction, more than any other unit (Table 1).

The pebble-loam part of the Dunvilla Formation underlies sediment of the Barnesville Formation in an outcrop located in the SE², SE², SW² Sec. 11, T. 137 N., R. 45 W. This is the only outcrop observed that contains sediment of both formations. The glacial pebble-loam of the Barnesville Formation is exposed in the upper 1.5 metres of the outcrop. This pebble-loam is unbedded and weakly jointed. It has blocky structure and breaks into irregularly-shaped rectangular
pieces that vary in size from about 5 millimetres to about 15 millimetres. The blocky structure is a diagnostic property of the pebble-loam of the Barnesville Formation. The color of the pebble-loam is pale yellow (5Y 7/3) when dry and olive (5Y 5/3) when wet. A sample was collected from a depth of 1 metre. The sample was analyzed and found to contain 20% sand, 41% silt, and 39% clay. The lithology of the very-coarse-sand fraction of the sample was 41% igneous-rock and metamorphic-rock fragments, 44% carbonate-rock fragments, and 14% shale fragments. One metre of tan, obscurely bedded, fine-grained to medium-grained sand is exposed beneath the pebble-loam of the Barnesville Formation. Pebble-loam of the Dunvilla Formation is exposed for 2 metres and extends to an unknown depth beneath the bed of sand. The color of this pebble-loam is pale yellow (5Y 7/3) when dry and olive (5Y 5/4) when wet. The pebble-loam is unbedded and moderately jointed. Its friable nature contrasts the blocky nature of the pebble-loam exposed in the upper 1.5 metres of the outcrop. A sample was collected at a depth of 3.5 metres. It was analyzed and found to contain 28% sand, 40% silt, and 32% clay. The lithology of the very-coarse-sand fraction of the sample was 39% igneous-rock and metamorphic-rock fragments, 28% carbonate-rock fragments, and 33% shale fragments.

The pebble-loam part of the Dunvilla Formation is thought to have a northwestern source area because the very-coarse-sand fraction contains a large proportion of rock (shale) derived in southern Manitoba and northeastern North Dakota. It was deposited by glacial ice which came from the northwest. When the glacial ice became stagnant,
meltwater flowed on top of and from the stagnant ice and deposited the fluvial sediment part of the Dunvilla Formation.

Stratigraphic position suggests that the Dunvilla Formation correlates with the upper unit of the Red Lake Falls Formation in northwestern Minnesota (Harris and others, 1974; Sackreiter, 1975), the Dahlen Formation is northeastern North Dakota (Hobbs, 1975), and the "New Ulm Till" in southwestern Minnesota (Matsch, 1971) (Table 2).

The Dunvilla Formation is Late Wisconsinan in age. Two radiocarbon dates from below the "New Ulm Till" in southwestern Minnesota are about 20,000 BP (Ruhe, 1969). Numerous radiocarbon dates from above the "New Ulm Till" in southwestern Minnesota and Iowa indicate that deposition ceased about 14,000 BP (Matsch, 1971). Dates in North Dakota are several thousand years younger suggesting that the tops of the correlative formations are younger toward the north (Clayton, 1966).

**Barnesville Formation**

The Barnesville Formation is exposed at the surface in a north-south belt that is located in the west-central part of the study area (Figure 19). The source of its name is the city of Barnesville in Clay County, Minnesota. Barnesville is located on the Barnesville 15 minute quadrangle.

The Barnesville Formation consists of glacial sediment. The glacial pebble-loam of the Barnesville Formation is pale yellow (5Y 7/3) when dry and olive (5Y 5/3) when wet. The glacial pebble-loam of the Barnesville Formation is composed of an average of 21% sand, 41% silt, and 38% clay (Table 1). The pebble-loam contains
significantly fewer pebbles than the pebble-loam of the other lithostratigraphic units. The very-coarse-sand fraction of the pebble-loam contains an average of 42% igneous-rock and metamorphic-rock fragments, 45% carbonate-rock fragments, and 13% shale fragments (Table 1). The pebble-loam is unbedded and weakly jointed. It has blocky structure and breaks into irregularly-shaped pieces that vary in size from about 5 millimetres to about 15 millimetres.

The base of the formation was observed in one outcrop. That outcrop is described in the discussion of the Dunvilla Formation. At that location a layer of obscurely bedded, fine-grained to medium-grained sand underlies the pebble-loam of the Barnesville Formation. The lateral persistence of the sand is unknown, therefore, the sand is not included as an integral part of the formation. The texture and obscure bedding characteristic of the sand suggest that it may be of eolian origin.

The type area of the Barnesville Formation is the type section area. The location of the type section of the Barnesville Formation is NW¼, NW¼, NW¼ Sec. 14, T. 137 N., R. 45 W. The type section can be reached by proceeding three and one-half miles east of Barnesville on highway number 34, turning north on highway number 31, traveling two and one-eighth miles, turning west on the gravel road, and proceeding a half of a mile. The type section consists of 6 metres of exposed pebble-loam in the road cut on the south side of the road. The pebble-loam exposed here is pale yellow (5Y 7/3) when dry and olive (5Y 5/3) when wet. The pebble-loam is unbedded, weakly jointed, and has the characteristic blocky structure of the formation. Two samples were collected from the exposure at depths of 1.5 metres and 4
metres. The samples were analyzed for their texture and the lithology of the very-coarse-sand fraction. The first sample contained 18% sand, 44% silt, and 38% clay, and the lithology of the very-coarse-sand fraction was 49% igneous-rock and metamorphic-rock fragments, 38% carbonate-rock fragments, and 13% shale fragments. The second sample contained 19% sand, 34% silt, and 47% clay, and the lithology of the very-coarse-sand fraction was 40% igneous-rock and metamorphic-rock fragments, 46% carbonate-rock fragments, and 14% shale fragments.

The Barnesville Formation overlies the Dunvilla Formation. The pebble-loam of the Barnesville Formation is considerably more clayey and contains significantly fewer shale fragments in the very-coarse-sand fraction than the pebble-loam part of the Dunvilla Formation. It contains an average of 38% clay and 13% shale fragments, whereas the Dunvilla Formation contains an average of 25% and 35% respectively (Table 1). An exposure containing the pebble-loam of both formations is described in the discussion of the Dunvilla Formation. The relationships between the Barnesville Formation and the Sherack Formation are described in the discussion of the Sherack Formation.

The glacial sediment of the Barnesville Formation is thought to have the same northwestern source area as the glacial sediment of the Dunvilla Formation. However, the Barnesville Formation contains a smaller amount of shale than the Dunvilla Formation. When the glacial ice that deposited the Barnesville Formation advanced over southern Manitoba and northeastern North Dakota, a large proportion of the shale bedrock in those areas was probably covered by glacial sediment
that is laterally equivalent to the Dunvilla Formation. Therefore, a smaller amount of shale was incorporated into the ice.

The Barnesville Formation is known to be Late Wisconsinan in age because of its stratigraphic position above the Dunvilla Formation. It is apparently older than the Huot Formation (Harris and others, 1974; Harris, 1975; Sackreiter, 1975), which has its southernmost extent north of this area. However, no stratigraphic evidence has been found in northwestern Minnesota to prove this. There were no stratigraphic units found in the literature that could be correlated with the Barnesville Formation. It is not known how far south the Barnesville Formation extends. However, its limited eastward extent suggests that it may not extend very far to the south.

Sherack Formation

The Sherack Formation is exposed at the surface in the Lake-Plain District at the west end of the study area (Figure 19).

This unit is composed of interbedded silt and clay which is lacustrine in origin. A formal description is contained in Late Quaternary Stratigraphic Nomenclature, Red River Valley, North Dakota and Minnesota (Harris and others, 1974).

The sediment of the Sherack Formation grades laterally to the east into lacustrine offshore sand, silt, and clay, which in turn grades into lacustrine shoreline sediment. These sediments were deposited during a late phase of Lake Agassiz. The shoreline sediment referred to above is a small part of the sediment that is exposed in the Shoreline-Complex District. The bulk of the shoreline sediment exposed in the Shoreline-Complex District was deposited during an earlier phase of Lake Agassiz.
The lacustrine shoreline sediment overlies the glacial sediment part of the Barnesville Formation. The location of an exposure that contains lacustrine shoreline sediment and pebble-loam of the Barnesville Formation is SW¼, SW¼, SE¼ Sec. 5, T. 137 N., R. 45 W. Lacustrine shoreline sediment is exposed in the upper 0.9 metre of the outcrop. The sediment is composed of medium-grained to coarse-grained sand and a small amount of organic debris. The sediment is flat bedded. When viewed in direct sunlight, the sediment has a yellowish-tan color. One metre of glacial pebble-loam of the Barnesville Formation is exposed beneath the shoreline sand. The contact between the two types of sediment is sharp. The pebble-loam is unbedded, weakly jointed, and has the characteristic blocky structure of the Barnesville Formation. It has a pale yellow color (5Y 7/3) when dry and an olive color (5Y 5/3) when wet. One sample was collected from a depth of 2 metres and was analyzed for its texture and the lithology of the very-coarse-sand fraction. It contained 28% sand, 42% silt, and 30% clay, and the lithology of the very-coarse-sand fraction was 43% igneous-rock and metamorphic-rock fragments, 54% carbonate-rock fragments, and 3% shale fragments.

The texture and stratigraphic position of the Sherack Formation distinguishes it from other lithostratigraphic units in the study area. North of the study area the Sherack Formation is underlain by the Argusville Formation and Brenna Formation (Harris, 1975). The Argusville and Brenna Formations are massive, obscurely laminated clays of lacustrine origin. In the study area the Sherack Formation is thought to be underlain by the Argusville Formation. The Poplar
River Formation occurs as scattered deposits of sand and gravel beneath the Sherack Formation (Harris and others, 1974). The sediment in the core of the small compaction ridge in the Lake-Plain District is thought to be sediment of the Poplar River Formation.

The Sherack Formation extends northward where it has been studied in considerable detail (Harris and others, 1974; Harris, 1975; Sackreiter, 1975; Arndt, 1975).

The Sherack Formation is early Holocene in age. It was deposited as offshore sediment in the Lake Agassiz basin between 10 000 and 9 500 BP (Harris and others, 1974).
LATE CENOZOIC HISTORY

An unknown number of glaciations occurred in this general region during late Cenozoic time. Most of the evidence for these glaciations is locked in the subsurface stratigraphy. An effort is made here to base historical interpretations on facts obtained in this and similar studies. More absolute age dates are needed to resolve the interpretation differences that now exist in the literature. The late Cenozoic history of the study area will be discussed event by event from oldest to youngest. This study is restricted to the surface and, therefore, deals with only the latest of events.

A schematic time-distance diagram showing periods of deposition of formations present in the study are presented in Figure 20.

Glacial ice advanced into the area from the northeast during pre-Wisconsinan or Early Wisconsinan time and deposited the glacial sediment of the Sebeka Formation of this study and the Marcoux Formation (Harris and others, 1974; Harris, 1975; Sackreiter, 1975) of northwestern Minnesota (Figure 21). This advance of glacial ice probably occurred contemporaneously with the advance of glacial ice that came out of the Superior Lowland and deposited the "Hawk Creek Till" (Matsch, 1971) of southwestern Minnesota. The glacial sediment of the Sebeka Formation is thought not to have the same source area as the "Hawk Creek Till" because its lithology is not characteristic of the rock outcrops found around the Lake Superior basin. If drumlins
Fig. 20. Schematic time-distance diagram showing periods of deposition of formations present in the study area.
Fig. 21. Late Cenozoic events in the study area and adjacent areas.

a. Pre-Wisconsinan or Early Wisconsinan advance of glacial ice from the northeast. Deposition of the Sebeka Formation and formation of Sebeka drumlin morphology.

b. Middle or Early Wisconsinan advance of glacial ice from the north. Deposition of the New York Mills Formation.

c. Lostwood Glaciation. Late Wisconsinan advance of glacial ice from the northwest. Deposition of the Dunvilla Formation.
are considered to be depositional landforms, the Sebeka drumlins would have been formed by the glacial ice that deposited the Sebeka Formation. If they are considered to be erosional landforms, a later advance of glacial ice from the northeast would have had to occur to form the drumlins. Evidence for a second advance of glacial ice from that direction is not present at the surface in the study area. Therefore, until further stratigraphic work is done, the Sebeka drumlins are thought to be depositional landforms.

The ice of the next advance entered the area from about due north in Early Wisconsinan time. After eroding the igneous and metamorphic outcrops in the Canadian Shield and the carbonate outcrops in the Winnipeg Lowland, it melted back and deposited the New York Mills Formation of this study, the lower unit of the Red Lake Falls Formation (Harris and others, 1974; Sackreiter, 1975) of northwestern Minnesota, and the "Granite Falls Till" (Matsch, 1971) of southwestern Minnesota (Figure 21). H. E. Wright (1972) suggests that the ice advance (Wadena Lobe) that deposited the "Granite Falls Till" entered Minnesota from the northwest. The "Wadena Lobe" was then diverted to the southwest by interference with the "Rainy Lobe" which was then located in central-northern Minnesota. He also suggests that the Sebeka drumlins (Wadena Drumlin Field) were created by the Wadena Lobe and are composed of glacial sediment that has a northwestern source area. However, this study finds the Sebeka drumlins to be composed of glacial sediment that has a northeastern source area. This fact coupled with the sharp geomorphic boundary that exists between the New York Mills Formation and the Sebeka drumlin area suggest
are considered to be depositional landforms, the Sebeka drumlins would have been formed by the glacial ice that deposited the Sebeka Formation. If they are considered to be erosional landforms, a later advance of glacial ice from the northeast would have had to occur to form the drumlins. Evidence for a second advance of glacial ice from that direction is not present at the surface in the study area. Therefore, until further stratigraphic work is done, the Sebeka drumlins are thought to be depositional landforms.

The ice of the next advance entered the area from about due north in Early Wisconsinan time. After eroding the igneous and metamorphic outcrops in the Canadian Shield and the carbonate outcrops in the Winnipeg Lowland, it melted back and deposited the New York Mills Formation of this study, the lower unit of the Red Lake Falls Formation (Harris and others, 1974; Sackreiter, 1975) of northwestern Minnesota, and the "Granite Falls Till" (Matsch, 1971) of southwestern Minnesota (Figure 21). H. E. Wright (1972) suggests that the ice advance (Wadena Lobe) that deposited the "Granite Falls Till" entered Minnesota from the northwest. The "Wadena Lobe" was then diverted to the southwest by interference with the "Rainy Lobe" which was then located in central-northern Minnesota. He also suggests that the Sebeka drumlins (Wadena Drumlín Field) were created by the Wadena Lobe and are composed of glacial sediment that has a northwestern source area. However, this study finds the Sebeka drumlins to be composed of glacial sediment that has a northeastern source area. This fact coupled with the sharp geomorphic boundary that exists between the New York Mills Formation and the Sebeka drumlin area suggest
that the ice of this advance overrode the glacial sediment of the Sebeka Formation and the already existing drumlin morphology from the north.

Fluvial sediment was deposited on top of the glacial sediment of the Sebeka Formation in the extreme northeast corner of the study area during Late Wisconsinan time. The fluvial sediment is thought to have been deposited by rivers that flowed westward from melting glacier ice which had advanced from the northeast and had its terminus at the St. Croix Moraine (Wright, 1972).

During the Late Wisconsinan Lostwood Glaciation (Clayton, 1972), ice of two separate advances flowed from the northwest and passed through the area. The ice of the first advance deposited the glacial sediment of the Dunvilla Formation of this study, the upper unit of the Red Lake Falls Formation (Harris and others, 1974; Sackreiter, 1975) of northwestern Minnesota, and the "New Ulm Till" (Matsch, 1971) of southwestern Minnesota (Figure 21). The glacial ice flowed south down the Red River Lowland and is thought to have deposited the bulk of the surface glacial sediment in western Minnesota. The lateral margin of the glacial ice is thought to have extended as far east as Perham. When the glacial ice stagnated, meltwater flowed on top of and from the stagnant ice and deposited the fluvial sediment that now underlies the Outwash District. The ice of the second advance covered a much smaller area than that of the first advance. The ice of the second advance overrode part of the sediment of the Dunvilla Formation and deposited the glacial sediment of the Barnesville Formation (Figure 22). Evidence for the overriding is present in the Glacial-Upland District about 5 kilometres southeast of
Fig. 22. Late Cenozoic events in the study area and adjacent areas.

a. Lostwood Glaciation. Late Wisconsinan advance of glacial ice from the northwest. Deposition of the Barnesville Formation.

Barnesville. In that area subglacial shear marks that trend northwest-southeast are superimposed on superglacial-collapse topography.

As the ice of the Lostwood Glaciation melted back, meltwater collected in the Red River Lowland to form Lake Agassiz. This marked the beginning of the Lockhart Phase of Lake Agassiz (Moran and others, in press). The lake was bounded on the north by the shrinking glacier and the lake emptied southward into the Minnesota River trench by way of Browns Valley in northeastern South Dakota. The lake was initially at the Herman level. As the outlet at Browns Valley cut down through Pleistocene sediment, the lake level was irregularly lowered, forming Norcross Beach and Tintah Beach. The outlet was finally cut down to Precambrian bedrock when Lake Agassiz stabilized at the Campbell level. Four well-developed beaches at different elevations are present in the Shoreline-Complex District of the study area, providing evidence for the different stages of Lake Agassiz during the Lockhart Phase. From highest to lowest these are Herman Beach, Norcross Beach, Tintah Beach, and Campbell Beach.

At the end of the Lockhart Phase, the shrinking glacier had melted back far enough to open the eastern outlet of Lake Agassiz in Ontario; the lake rapidly drained through Lake Nipigon and into northern Lake Superior, leaving much of the Red River Valley dry during the Moorhead Phase (Moran and others, in press). During the Moorhead Phase a river system developed on the lake bed and its channel sediments now core the small compaction ridge that is present in the Lake-Plain District.

In early Holocene time the lake again rose to the Campbell level, when the eastern outlet was blocked by a readvance of ice in
Ontario. This marked the beginning of the Emerson Phase (Moran and others, in press), and it was during the Emerson Phase that the Sherack Formation was deposited (Figure 22). Lake Agassiz emptied about 9500 BP (Harris and others, 1974).

Subaerial erosion and deposition dominated geological activity from early Holocene time to the present. Thin eolian sediments were deposited during dry climatic periods, and moist periods produced the soil profiles that are present today.
SUMMARY

A reconnaissance map of the surficial sediment in the Comstock-Sebeka area was prepared at a scale of 1 : 250 000 (Plate 1). Surface materials present in the area include sand, silt, and clay that was deposited by present river systems; eolian sand; bog peat, muck, and organic clay; lacustrine shoreline sand and gravel; lacustrine offshore sand, silt, and clay; sand and gravel that was deposited by rivers that flowed from melting glacier ice, and glacial pebble-loam. The materials mapped are variable in thickness but are more than a metre thick.

The area is divided into four geomorphic districts (Figure 2) on the basis of underlying materials and interpreted genesis. Compaction ridges and intersecting lineations are two very subtle types of features that disturb the generally flat surface of the Lake-Plain District. The district is underlain by offshore sediment that was deposited in the Lake Agassiz basin in Early Holocene time. The Shoreline-Complex District is characterized by low-relief north-south trending beach ridges and wave-cut scarps. The lacustrine shoreline sediment that underlies the district was deposited at the margin of Lake Agassiz during Late Wisconsinan and Early Holocene time. Characteristic morphologies of the Glacial-Upland District include subglacial-sheared features (drumlins and flutings), subglacial-thrust features (push-ridges), englacial-collapse features (washboard moraine), superglacial-collapse features (hummocky topography), meltwater...
channels, eskers, and esker complexes. The glacial and fluvial sedi-
ment that underlies the district ranges in age from pre-Wisconsinan
to Late Wisconsinan. The Outwash District is characterized by col-
lapsed-outwash morphology (hummocky topography) and pitted outwash
plains. The district is underlain by fluvial sediment that was de-
posited by water that flowed on top of and from melting glacier ice.

Four lithostratigraphic units are defined and named for the
first time in this study. They are the Sebeka, New York Mills,
Dunvilla, and Barnesville Formations (distribution shown in Figure 19).
The units, which are characterized by distinctive texture and lithology
of the very-coarse-sand fraction of the glacial pebble-loam (Table 1),
are readily recognized in the field by differences in color, struc-
ture, and texture.

The Sebeka Formation consists of glacial and fluvial sediment.
The formation is distinguished by its very sandy texture and very large
proportion of igneous-rock and metamorphic-rock fragments in the very-
coarse-sand fraction of the glacial pebble-loam. The fluvial sediment
underlies the glacial sediment and is not considered a distinguishing
part of the formation. The pebble-loam part of the Sebeka Formation
was deposited during a pre-Wisconsinan or Early Wisconsinan advance of
 glacial ice from the northeast.

The New York Mills Formation consists of glacial sediment that
was deposited in Early Wisconsinan time during an advance of glacial
ice from about due north. The glacial pebble-loam is characterized by
its sandy texture and the moderate amount of carbonate-rock and the
small amount of shale in the very-coarse-sand fraction.
The Dunvilla Formation consists of glacial and fluvial sediment. The large amount of shale in the very-coarse-sand fraction characterizes the glacial pebble-loam of the formation. The fluvial sediment intertongues with the glacial sediment and underlies the Outwash District. The glacial sediment of the Dunvilla Formation was deposited by glacial ice that advanced into the area from the northwest in Late Wisconsinan time. Meltwater that flowed on top of and from the stagnant ice deposited the fluvial sediment of the formation.

The Barnesville Formation consists of glacial pebble-loam that is characterized by its clayey texture, blocky structure, and stratigraphic position above the Dunvilla Formation. It was deposited by glacial ice that came from the northwest in Late Wisconsinan time. The ice of this advance was less extensive that was the ice that deposited the Dunvilla Formation.

All of these formations except for the Barnesville Formation can be correlated with other lithostratigraphic units in the region (Table 2). Correlations are based mainly on similarities in lithology and stratigraphic position.

As the ice of the Late Wisconsinan glaciation melted back, meltwater collected in the Red River Lowland to form Lake Agassiz. The bulk of the sediment in the Shoreline-Complex District was deposited at the margin of Lake Agassiz during Late Wisconsinan time. The offshore silt and clay of the Sherack Formation was deposited in the Lake Agassiz basin during Early Holocene time. Lake Agassiz drained about 9 500 BP.
APPENDIX
DATA ON THE SURFACE SAMPLES

Samples of glacial pebble-loam were collected from road cuts, railroad cuts, drainage ditches, and gravel pit cuts. The percentage of sand, silt, and clay was determined for each sample. The percentage of igneous-rock and metamorphic-rock fragments, carbonate-rock fragments, and shale rock fragments in the very-coarse-sand fraction was determined. "Counts" refer to the total number of very-coarse-sand fragments (including the above three categories plus miscellaneous very-coarse-sand fragments). The percentage of miscellaneous very-coarse-sand grains is not included. The depth from which the sample was collected is given. The elevation that is given was taken from a topographic map.

The location for 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.
Table 3. Tabulated surface data.
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Table 4. Means and standard deviations for site averages of lithostratigraphic units.
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<td>Mean</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>n = 26</td>
<td>Standard Deviation</td>
<td>11.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Sebeka Fm.</td>
<td>Mean</td>
<td>66</td>
<td>21</td>
</tr>
<tr>
<td>n = 17</td>
<td>Standard Deviation</td>
<td>4.1</td>
<td>3.4</td>
</tr>
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REFERENCES


