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Surficial Geology of the New Brighton Quadrangle, Minnesota

BY JOHN E. STONE

UNIVERSITY OF MINNESOTA PRESS • MINNEAPOLIS, 1966

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Abstract

The New Brighton quadrangle is underlain by as much as 500 feet of glacial drift, which lies directly on Paleozoic sedimentary rocks. The bedrock, which is part of the northern flank of the Twin Cities artesian basin, is traversed by a complex network of buried valleys as much as 400 feet deep that were cut during several cycles of erosion.

Most of the surface morphology and the related deposits were formed about 12,500 years ago, during the advance and retreat of the Grantsburg Sublobe, which produced the following formations in the approximate order of their deposition: (1) the Hillside Sand, a proglacial outwash deposit; (2) the Twin Cities Formation, a complex mixture of gray and red till; (3) the Falcon Heights Sand, a retreatal outwash deposit; (4) the Turtle Lake Sand, a lake deposit; (5) the Arsenal Sand, a kame deposit; (6) the New Brighton Formation, a lake deposit; and (7) the Fridley Formation, another lake deposit. The units have been mapped at the surface and traced in the subsurface.

After the active ice retreated from the immediate area, the West Campus Sand, a valley-train deposit, was deposited. Later, ice in the drift melted to produce many hundreds of kettle holes, some of which are now occupied by lake or swamp deposits; the valley train was dissected, leaving a terrace along the Mississippi River; and a poorly integrated drainage system was produced. In late-glacial and postglacial time, thin deposits of eolian sand, loess, and colluvium were laid down. The most significant changes in the landscape in postglacial time have been made by man, who settled the area in the 1830's and 1840's.

Preliminary data are given on the engineering properties of the surficial deposits. These data in conjunction with the geology are useful for engineering and hydrologic studies, land-use planning, and resource evaluation.

Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES (in Pocket)

Surficial Geology of the New Brighton Quadrangle, Minnesota

INTRODUCTION

This report, the first of a series on the surficial geology of the Minneapolis–St. Paul area, describes the stratigraphy, geomorphology, Quaternary history, and economic geology of the New Brighton quadrangle. Stratigraphic units in the drift that can be mapped at the surface and traced in the subsurface are formally established. A preliminary study of the engineering characteristics of the unconsolidated stratigraphic units is summarized; additional geologic, hydrologic, and engineering data are given in a separate report (Stone, 1966).

The New Brighton quadrangle, covering approximately 54 square miles, occupies parts of Ramsey, Hennepin, and Anoka counties (Fig. 1). The quadrangle includes all of the towns of New Brighton, Arden Hills, and St. Anthony Village and parts of Falcon Heights, Roseville, Shoreview, North Oaks, Mounds View, Blaine, Spring Lake Park, Fridley, Columbia Heights, Hilltop, Lauderdale, and northeast Minneapolis.

The only previous comprehensive reports on the area were prepared by Sardeson (1916) and Schwartz (1936). Sardeson's report is based on reconnaissance and is not sufficiently detailed or accurate for present needs. Schwartz's report concerns mainly the bedrock geology. Other publications that describe some aspects of the geology of the New Brighton area are Winchell (1878; 1888), Upham (1900, pp. 288, 290), Leverett (1932, pp. 44, 79–80, 88–89), and Cooper (1935, pp. 52–65).

Geologic reconnaissance of the New Brighton and surrounding quadrangles was made during the summer of 1962, and the quadrangle was mapped at a scale of 1:24,000 during the summer of 1963 (see Pl. 1). The geomorphology of the area was studied by field observations, topographic maps, and air photos. Data on the surface stratigraphy were obtained primarily in road cuts, borrow pits, and construction excavations, supplemented by shallow auger borings and studies of air photos and county soils maps. Well logs, boring logs, and two gravity profiles were used in compiling the subsurface geology. Color names used in the text were determined with the Munsell Soil Color Chart.

Grain-size analyses were made according to ASTM Designation: D422–61T for the silt and clay fractions (Anonymous, 1961a); the visual-accumulation tube was used for analyzing the sand fraction (Anonymous, 1958). The size classes of gravel, sand, silt, and clay follow the United States Department of Agriculture (Soil Survey Staff, 1951, p. 207). Clay-

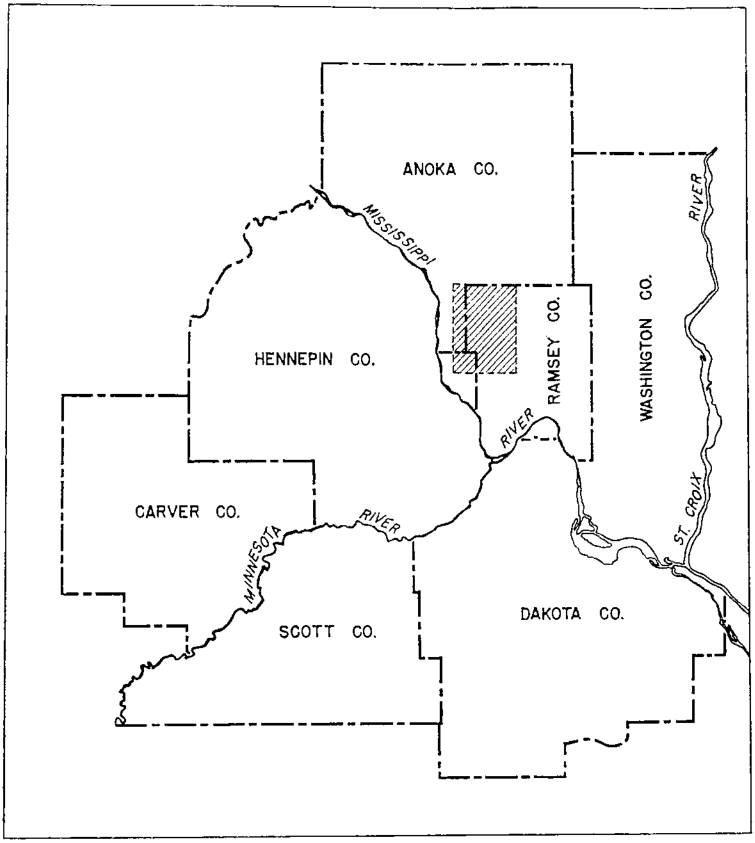

Figure 1. Map of the Minneapolis–St. Paul area, showing location of the New Brighton quadrangle.

mineral analyses were performed on a Norelco X-ray diffractometer scanning at 2° per minute and using copper radiation and a nickel filter. Material < 2 microns was separated by settling in water; oriented samples were sedimented on glass slides; slides were run both untreated and glycolated.

The southern two thirds of the map of the bedrock topography and bedrock geology (Pl. 2) was prepared, in part, by C. M. Payne. The Minnesota Highway Department and the Division of Waters, Minnesota Department of Conservation, generously made available their files containing well logs, boring logs, engineering test data, and other information. P. L. Chandler and G. R. Ford of the Highway Department were especially helpful in supplying data. Several problems concerning the origin of sedimentary structures were discussed with P. E. Cloud, Jr. The soils in the quadrangle were discussed with R. S. Farnham and A. S. Robertson. P. K. Sims and

H. E. Wright, Jr., read the manuscript and made suggestions for improving it.

REGIONAL GEOLOGY

The Minneapolis–St. Paul area is covered by glacial and postglacial deposits to depths of as much as 500 feet except along parts of the bluffs of the Mississippi and Minnesota river valleys where bedrock is exposed. The bedrock consists of approximately 900 feet of lower Paleozoic rocks which overlie late Precambrian red sandstone and, locally, mafic lava flows (see Table 1).

The Paleozoic bedrock is warped into a roughly circular, shallow basin, locally known as the Twin Cities artesian basin. The basin has been eroded so that the beveled edges of the strata encircle the metropolitan area. The Jordan Sandstone, the most important bedrock aquifer, intersects the bedrock surface at a radius of 15 to 25 miles from the center of the basin, which lies between downtown Minneapolis and downtown St. Paul.

The bedrock surface, which is topographically highest in the center of the basin, is cut by an intricate network of deep, relatively narrow bedrock valleys, now largely buried. The intricacy of the network and the fact that the bottoms of the valleys occur at various elevations strongly suggest that valleys were cut during several cycles of erosion.

The eastern and southern parts of the Twin Cities are underlain by gla-

Table 1. Subsurface Bedrock Units in the New Brighton Quadrangle

Rock-Stratigraphic Units	Description	Approximate Thickness (in ft.)
	Ordovician Age	
Decorah Formation	Bluish-gray shale containing thin beds of fossiliferous limestone	75
Platteville Formation	Gray to buff fossiliferous limestone	25–33
Glenwood Formation	Gray to green shale	4–10
St. Peter Sandstone	White friable sandstone; shaly layer occurs near bottom	150–165
Prairie du Chien Formation	Gray to buff dolomite and some sandstone	120–135
	Cambrian Age	
Jordan Sandstone	White, yellow, and brown poorly cemented sandstone	80–100
St. Lawrence Formation	Buff to salmon sandy dolomite and siltstone	50–70
Franconia Formation	Yellow to white sandstone containing glauconite	150–210
Dresbach Formation	White sandstone and interbedded gray shale and sandstone	345–350
	Keweenawan Age	
Hinckley Sandstone	Buff to red sandstone	60
Fond du Lac Formation	Red feldspathic sandstone and arkose	unknown
North Shore Volcanics	Mafic lava flows	unknown

cial deposits of the Superior Lobe, which had flowed into the area from the north and northeast bringing a reddish-brown drift and then retreated about 14,000 years ago (Wright and Ruhe, 1965). The western and northern parts of the area (including the New Brighton quadrangle) are underlain by deposits of the Grantsburg Sublobe, which flowed into the area from the southwest as an offshoot of the Des Moines Lobe, after the Superior Lobe, and then retreated about 12,500 years ago (Wright and Ruhe, 1965). The Grantsburg Sublobe brought gray drift from the west and overrode deposits of the Superior Lobe. These events left behind a rugged morainic topography interrupted by outwash plains, lake plains, and kames and transected by the terraces and flood plains of the Mississippi and Minnesota rivers. Thus, all the surface features and deposits in the Twin Cities area are of Wisconsin Age or younger.

Pre-Wisconsin glacial deposits apparently exist in the buried bedrock valleys of the area, but little is known about them.

BEDROCK GEOLOGY

Bedrock is not exposed at the surface in the New Brighton quadrangle, although a rock quarry, now abandoned and filled, once existed in the extreme southwestern part of the area. The known bedrock units in the subsurface are listed in Table 1; the areal distribution and structure of the units are shown on Plates 2 and 3.

The New Brighton quadrangle lies on the northern flank of the Twin Cities artesian basin, and the Paleozoic rocks accordingly dip generally southward (Pl. 3). The Decorah Formation, Platteville Formation, and St. Peter Sandstone form the bedrock surface beneath the drift except in the buried valleys. Strata as old as the Franconia Formation are cut by the valleys.

The exposed bedrock in the Twin Cities area is jointed, and it is presumed that the bedrock in the map area is similarly fractured. Three prominent joint sets apparently occur in the bedrock units in the Twin Cities area, but the orientations of the joint sets vary somewhat from area to area.

Five faults that cut the Paleozoic bedrock and have stratigraphic throws ranging from about 30 to 70 feet are inferred in the subsurface in the New Brighton quadrangle (Pls. 2 and 3). The faults trend northeastward and are essentially parallel to the Douglas Fault, mapped by Craddock and others (1963, p. 6029) ten miles northwest of the map area. Four of the faults are downthrown on the southeast side (Pl. 2). All the faults are thought to dip steeply toward the downthrown block, but as the exact dips are unknown, the faults are shown as vertical on Plate 3.

BEDROCK TOPOGRAPHY

The buried bedrock surface, a rolling upland with about 80 feet of relief, is cut by several relatively steep-sided, narrow valleys as much as 400 feet deep (Pls. 2 and 3). The deeper parts of some of the valleys are narrower and steeper than would be expected if they had been formed during the same episode of erosion as the upper parts (Pl. 3), possibly indicating that some valleys were rejuvenated at least once. Indeed, drilling by the United States Army Corp of Engineers elsewhere in the Twin Cities area has shown the presence of bedrock terraces along some of the bedrock valleys.

The deepest bedrock valley in the quadrangle, herein named Calhoun Valley for Lake Calhoun, which lies above it in Minneapolis (Pl. 2), is presently recognized as the deepest bedrock valley in the Twin Cities area. Another valley, which meets Calhoun Valley in the center of the map area, is here named Johanna Valley for Lake Johanna, which lies above it in Arden Hills. Judging from the pattern of its tributaries, Johanna Valley almost surely drained northwestward at one time. It is possible that Calhoun Valley also drained northward at the same time (perhaps in preglacial time). Johanna Valley also has tributaries (east-central part of New Brighton quadrangle) that indicate it drained southward as well as northward during its history. The Johanna Valley bottoms 80 feet above the bottom of Calhoun Valley at their junction, suggesting that Calhoun Valley was deepened after Johanna Valley was abandoned.

A striking feature of the bedrock topography in the New Brighton area, as well as in the Twin Cities area as a whole, is the remarkably straight segments of the bedrock valleys. The generally abrupt change in direction from one straight segment to the next was controlled, at least in part, by fractures in the bedrock.

QUATERNARY GEOLOGY

Although closely interrelated, stratigraphy and geomorphology are separated insofar as possible in this section because, first, formal stratigraphic units are established in the drift to emphasize the three-dimensional lithologic and structural character of the various unconsolidated deposits and, second, an attempt has been made to conform to the same rules of stratigraphic nomenclature that apply to pre-Quaternary marine stratigraphy. The use of such formal units facilitates the mapping of subsurface units in the drift.

The formations formally established in this report (Table 2) conform, in general, to the usage of rock-stratigraphic units presented in the 1961 Stratigraphic Code (American Commission on Stratigraphic Nomenclature, 1961). They were selected in part, however, to emphasize the time and mode of origin of the deposits. Furthermore, constructional morphology is considered to be an integral part of the stratigraphic units. For these reasons the definition of some of the units differs from the strict definition of rock-stratigraphic units in the 1961 Code and is similar to that of the morphostratigraphic units of Frye and Willman (1962).

Table 2. Data Pertinent to the Naming of Formations Formally Established in This Report

Formation	Named for	Type Section	Alternate Type Section	Type Area
Hillside Sand	Hillside Cemetery in southwestern part of New Brighton quadrangle	Site F–75.* Cut on face of abandoned gravel pit in SW¼NE¼ Sec. 18, T.29N., R.23W.		SW¼ of New Brighton quadrangle
Twin Cities Formation	Minneapolis and St. Paul, Minn.	Site F–47.* Road cut on north side of the 3rd street, ¼ mi. east of Silver Lake Road in New Brighton, Minn., SE¼NW¼SE¼ Sec. 30, T.30N., R.23W.	Site F–74.* Borrow pit immediately east of Hart Lake and north of 37th St. N.E. in St. Anthony Village, Minn., SE¼SE¼SE¼ Sec. 36, T.30N., R. 24W.	New Brighton quadrangle
Falcon Heights Sand	Falcon Heights, Minn.	Site E–47.* West face of abandoned borrow pit just northeast of intersection of Larpenteur and Hamline aves., Roseville, Minn., SW¼SW¼SE¼ Sec. 15, T.29N., R.23W.	Road cuts along Interstate Highway 94 from Dale St. west to Snelling Ave. in St. Paul, Minn.	NE¼ of St. Paul West quadrangle
Turtle Lake Sand	Turtle Lake in Arden Hills, Minn.			NW¼NW¼ Sec. 14, T.30N., R.23W.
Arsenal Sand	Twin Cities Arsenal in Arden Hills, Minn.	Site F–19.* Arsenal Gravel Pit on Twin Cities Arsenal reservation in Arden Hills, Minn., SW¼NE¼ Sec. 10, T.30N., R.23 W.		SW¼ Sec. 10, T.30N., R.23W.
New Brighton Formation	New Brighton, Minn.			Mapped extent of New Brighton Formation in New Brighton quadrangle
Fine to medium sand facies		Site F–96.* Road cut on east side of Interstate Highway 35W immediately north of tracks of Minneapolis, St. Paul, and Sault Ste. Marie Railroad in New Brighton, Minn., SE/c Sec. 29, T.30N., R.23W.	Site F–97.* Borrow pit immediately east of Long Lake in New Brighton, Minn., SE¼NE¼NW¼ Sec. 20, T.30N., R.23W.	

Table 2. Continued

Formation	Named for	Type Section	Alternate Type Section	Type Area
Silt facies		Site F–41.* Boring for a bridge at southwest corner of intersection of Interstate Highway 35W and Ramsey County Road C in Roseville, Minn., NE/c Sec. 8, T.29N., R.23W.		
Gravelly fine to coarse sand facies		Site F–81.* Cut at rear of lot at 251 Pearl St. in New Brighton, Minn., NW¼SW¼ SW¼ Sec. 29, T.30N., R.23W.	Site F–23.* Gravel pit between Poplar and Jones lakes in New Brighton, Minn., NE¼SE¼ NW¼ Sec. 32, T.30N., R.23W.	
Fridley Formation	Fridley, Minn.			Northern ¼ of New Brighton quadrangle
Fine to medium sand facies		Site F–76.* Drainage ditch at intersection of U.S. Highway 8 and Hillview Road in Mounds View, Minn., NE¼SE¼ SE¼ Sec. 5, T.30N., R.23W.	Site F–24.* Water well for Spring Lake Park, Minn., NE¼ NW¼NE¼ Sec. 1, T.30N., R. 23W.	
Silt facies		Site E–85.* Municipal well no. 3, Fridley, Minn., SW¼SW¼SE¼ Sec. 14, T.30N., R.24W.	Site F–24.* Water well for Spring Lake Park, Minn., NE¼ NW¼NE¼ Sec. 1, T.30N., R.23W.	
West Campus Sand	West Campus, University of Minnesota, Minneapolis, Minn.	Site E–67.* Road cut on north side of U.S. Highway 12 where it passes through the West Campus, University of Minnesota. NE¼SW¼NW¼ Sec. 25, T.29N., R.24W.		Terraces at 830-840-ft. level on both sides of Mississippi River from St. Anthony Falls south to Lake St. Bridge, Minneapolis

* Stone, 1966.

Glacial Stratigraphy

The glacial deposits recognized in the quadrangle, in their approximate order of formation are: (1) various unnamed tills, clays, and sands in the buried bedrock valleys; (2) the Hillside Sand, a proglacial outwash deposit; (3) the Falcon Heights Sand, a retreatal outwash deposit; (4) the Twin Cities Formation, a complex mixture of gray and red till; (5) the Turtle Lake Sand, a lake deposit; (6) the Arsenal Sand, a kame deposit; (7) the New Brighton Formation, a lake deposit; and (8) the Fridley Formation, another lake deposit (Pl. 1). The Twin Cities Formation, however, was formed over a relatively long period of time, and some parts of it are contemporaneous with each of the other units. Most of the other units actually lie on the Twin Cities Formation (Pl. 3). It should be emphasized that in no one place do all of the glacial units occur in stratigraphic superposition.

Those units younger than the Hillside Sand were deposited during the advance and retreat of the Grantsburg Sublobe. All are of mixed western and northeastern provenance because the Grantsburg Ice, which had advanced from the west bringing gray drift characterized by shale and limestone pebbles and by a relatively high proportion of montmorillonite, also picked up reddish-brown drift previously deposited by the Superior Lobe, which had entered the area from the northeast bringing red sandstone, basalt, gabbro, and felsite. Thus, the till deposited by the Grantsburg Ice is a complex mixture of gray and reddish-brown drift (i.e., of mixed western and northeastern provenance). Likewise, all of the stratified drift derived from the till-like debris in the Grantsburg Ice is of mixed provenance.

Data on grain size, clay mineralogy, pebble content, and carbonate content of the various Quaternary units are given in Table 3.

Unnamed Subsurface Units. Several unnamed discontinuous sands, tills, and clays that are generally restricted to the bedrock valleys are recognized in the subsurface (Pl. 3), but little is known about them. A till that is essentially continuous across the quadrangle lies immediately beneath the Hillside Sand. It may have been deposited by the Superior Lobe. Still older tills, separated by sands, occur below this till in at least some of the buried valleys. These lower tills, however, are missing in Calhoun Valley (Pls. 2 and 3), suggesting that this valley was occupied by a stream more recently than the other valleys in the area. These unnamed units, which are thought to be remnants of more extensive deposits that were protected in the bedrock valleys from glacial erosion, are considered to be pre-Grantsburg Wisconsin deposits; some may be pre-Wisconsin.

Hillside Sand. The Hillside Sand, formally established herein (see Table 2), is a very pale brown to brown poorly sorted gravelly to cobbly medium to coarse sand that varies in grain size, percentages of the various types of pebbles, and percentages of the minerals in the $<$ 2-micron fraction. It occurs mostly in the subsurface (Pls. 1 and 3) across the New Brighton quadrangle and is exposed only on the side of the Mississippi River Valley in a large abandoned gravel pit in the southwestern part of the area and in a few other man-made excavations. The Hillside Sand ranges in thickness from about 25 to 150 feet and has an unusually rough and irregular upper surface.

The Hillside Sand is underlain by several types of bedrock and glacial deposits and is overlain by the Twin Cities Formation. The contact of the sand with the overlying Twin Cities Formation varies from sharp to gradational to interlayered. In some places as much as the upper 20 feet of the Hillside Sand is highly contorted as if it had been largely plastic at the time of deformation. At places, beds with well-preserved sedimentary structures such as ripple marks are now vertical.

The formation contains pebbles of red sandstone, basalt, gabbro, and felsite of northeastern provenance as well as pebbles of Cretaceous shale and a high percentage of montmorillonite in some upper parts of the sand, indicating a western provenance.

It is concluded that the Hillside Sand, at least in part, is proglacial outwash derived from mixed red and gray drift in the Grantsburg Ice. The lower part of the Hillside Sand may be outwash produced during the retreat of the Superior Lobe. The irregular upper surface of the formation can be explained as a result of variations in the rate of advance and the rate of melting of the overriding Grantsburg Sublobe. The ice deformed the upper part of the Hillside Sand, probably while it was frozen, and incorporated some of the Hillside Sand into its base.

Twin Cities Formation. The Twin Cities Formation, formally established herein (see Table 2), is a complex mixture of light-gray to very pale brown till and reddish-brown till. The formation is mostly a heterogeneous mixture of sand, silt, clay, pebbles, cobbles, and boulders, but it contains lenses predominantly of silt or sand. Several small lake deposits and several moderate-sized sand deposits occur within the Twin Cities Formation and are described separately (Stone, 1966).

In most parts of the quadrangle the light-gray till, the reddish-brown till, and the silts and sands are complexly mixed in almost all possible ways — large superposed and juxtaposed masses of red and gray till, thin laminations of alternating red and gray till, small blebs of gray till in red or red in gray, and reddish-brown till that results from complete mixing of red and gray tills. In many areas the surface pattern of the mixture of reddish-brown and gray tills is so complex that it is virtually impossible to map them separately. In other parts of the area, however, the gray till overlies the reddish-brown till with a relatively thin zone of obvious intermixing between them. Such areas are mapped as distinct facies within the Twin Cities Formation (Pl. 1).

The light-gray to very pale brown till contains pebbles of white limestone and dolomite and of shale and a high percentage of montmorillonite, indicating a western provenance. Some of the reddish-brown till contains pebbles of red sandstone, basalt, gabbro, and felsite indicative of a northeastern provenance. Some, if not most, of the reddish-brown till in the quadrangle, however, contains montmorillonite and pebbles of limestone

Table 3. Grain Size, Clay Mineralogy, Pebble Content, and Carbonate Percentage of Surficial Deposits, New Brighton Quadrangle

Formation	Percentage of Sand: Silt: Clay	Clay Mineralogy*: Montmorillonite: Illite: Chlorite-&-Kaolinite	Pebble Types†	Percentage of Carbonate Content of <2mu Material
Artificial fill	Variable		Variable	Variable
Alluvium				
Swamp deposits				
Lake deposits	Variable; generally silty, often organic	Proportions vary depending upon source; generally montmorillonitic	Generally absent	
West Campus Sand	96: 1: 3	5.6: 2.2: 2.2 to 7.8: 1.6: 0.6	Basalt and gabbro, red sandstone, granite, felsite, limestone, quartz and quartzite, shale	10
Fridley Formation				
Fine to medium sand	96: 1: 3 to 79: 16: 5	3.8: 3.1: 3.1 to 7.2: 1.4: 1.4	Very few pebbles	2–6
Clayey silt			Very few pebbles	
New Brighton Formation				
Fine to medium sand	97: 1: 2 to 97: 16: 5	6.2: 1.9: 1.9 to 7.2: 1.4: 1.4	Very few pebbles	1.3–6.4
Clayey silt			Very few pebbles	
Gravelly fine to coarse sand	89: 6: 5	6.2: 1.9: 1.9	Granite, limestone and dolomite, basalt, gabbro, chert, felsite, and quartz and quartzite	Up to 15
Arsenal Sand	97: 0: 3 to 96: 1: 3	4.6: 4.0: 1.4	Basalt and gabbro, felsite, granite, red sandstone, limestone and dolomite, and shale	1.3–4.5

Table 3. Continued

Formation	Percentage of Sand: Silt: Clay	Clay Mineralogy*: Montmorillonite: Illite: Chlorite-&-Kaolinite	Pebble Types†	Percentage of Carbonate Content of <2mu Material
Turtle Lake Sand				
Fine to medium sand	97:1:2	6.2:1.9:1.9	Very few pebbles	2–5
Gravelly fine to coarse sand	89:6:5	6.2:1.9:1.9	Limestone and dolomite, basalt and gabbro, chert, felsite, and quartz and quartzite	10
Falcon Heights Sand	99:0:1 to 94:2:4	4.1:2.9:3.0 to 6.0:1.8:2.2	Limestone, granite, basalt and gabbro, chert, felsite, and quartz and quartzite	3–11
Twin Cities Formation				
Gray till	44:38:18 to 61:25:14	3.3:3.6:3.1 to 8.2:1.3:0.5	Limestone and dolomite, granite, basalt and gabbro, shale, chert, quartz and quartzite, and felsite	14–24
Essentially unmixed red till	49:21:20 to 77:18:5	0.6:3.5:5.9‡ to 2.0:5.2:2.8	Basalt and gabbro, red sandstone, granite, felsite and foliated metamorphic rocks	3–15
Hillside Sand	86:9:5 to 98:1:1	3.3:3.6:3.1 to 6.0:2.6:1.4	Basalt and gabbro, granite, limestone, felsite, red sandstone, jasper, white sandstone, quartzite, occasional shale	

*In approximate parts per 10. Nearly all samples also contain some quartz and feldspar. Parts in 10 are based upon X-ray analysis of <2-micron material. Using the recorder traces for glycolated slides, the heights of 001 montmorillonite peaks, 001 illite peaks, and the combined 002 chlorite and 001 kaolinite peaks were measured. The values for montmorillonite were divided by 2 to roughly compensate for the high intensity of the low angle reflections. The peak-height values were then converted to parts in 10 to allow comparison between samples. It should be emphasized that the values derived probably do not indicate an exact measure of the amounts of the constituents, but they give approximate quantities and provide a useful system for comparing samples. The decimals are the result of the arithmetic procedures and do not indicate the accuracy of the numbers. Details of the procedures used and the reproducibility of the results will be presented in a later paper.

†In approximate order of decreasing abundance.

‡Values are for essentially unmixed red till. Actually, the reddish-brown till of the Twin Cities Formation is virtually all mixed with gray till, and the values for these mixed reddish-brown tills vary from 2.0:5.2:2.8 to 5.8:2.1:2.1.

and shale of western provenance as well as pebbles of northeastern provenance.

The Twin Cities Formation generally has a strong fabric with the elongate pebbles oriented essentially parallel to one another. In the map area the pebble orientations are northwest to westward depending upon the part of the quadrangle (the orientations and history are presented diagrammatically on Figs. 2–8; the basic data are in Stone, 1966). The pebbles are also generally parallel to nearly horizontal partings in the till which probably reflect differential flow or shear in the ice that deposited the till.

Four sets of systematic joints occur in the unconsolidated till of the Twin Cities Formation (Fig. 9). These joints, which are essentially like systematic joints in consolidated rock, are best developed in the more clayey tills.

Zones of interlayering of red and gray till in the Twin Cities Formation have been studied by Cushing (1963), who concluded that previously deposited red till of the Superior Lobe had been picked up by ice of the Grantsburg Sublobe, which was carrying gray till into the area from the west, and had been redeposited with the gray till. My studies of the reddish-brown till of the Twin Cities Formation below the zone of interlayering and obvious intermixing suggest that all of the till above the Hillside Sand was deposited by the Grantsburg Sublobe. The evidence leading to this conclusion will be described in a later publication, but is summarized here: (1) data on clay mineralogy, grain-size, and carbonate content indicate that much of the reddish-brown till in the Twin Cities Formation — even masses tens of feet thick and hundreds of feet long — is a mixture of red till originally deposited by the Superior Lobe and gray till brought from the west by the Grantsburg Sublobe (see Table 2); (2) pebbles in the reddish-brown till are oriented parallel to the pebbles in the overlying gray till and in the obviously mixed and interlayered intermediate zone. The orientations of the pebbles are northwest or even west, indicating deposition by the Grantsburg Sublobe rather than by the Superior Lobe, which flowed from the north or northeast (Fig. 2); and (3) the upper part of the Hillside Sand beneath the Twin Cities Formation contains shale and is relatively high in montmorillonite, indicating that the Grantsburg Sublobe was in the area before the Twin Cities Formation was deposited.

Falcon Heights Sand. The Falcon Heights Sand, formally established herein (see Table 2), is a light-gray to very pale brown poorly sorted gravelly medium to coarse sand. The formation occurs only in the southeastern corner of the quadrangle (Pl. 1), but it extends south and east to cover large parts of the adjacent St. Paul West and St. Paul East quadrangles.

The formation contains some pebbles of limestone and shale of western provenance as well as a high proportion of pebbles of red sandstone, basalt, gabbro, and felsite of northeastern provenance. The $<$ 2-micron fraction contains a high percentage of montmorillonite, also indicating a western provenance.

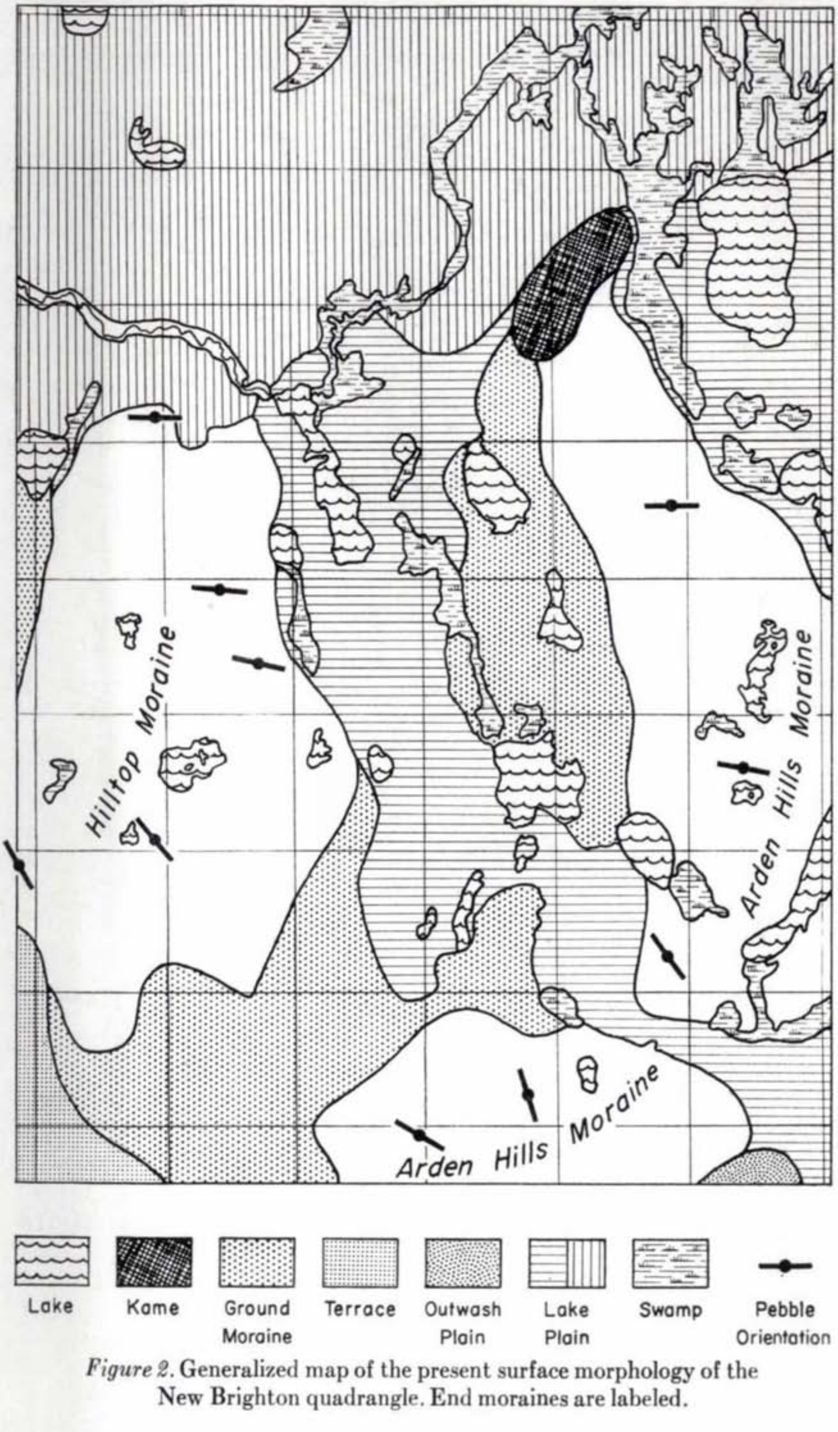

Figure 2. Generalized map of the present surface morphology of the New Brighton quadrangle. End moraines are labeled.

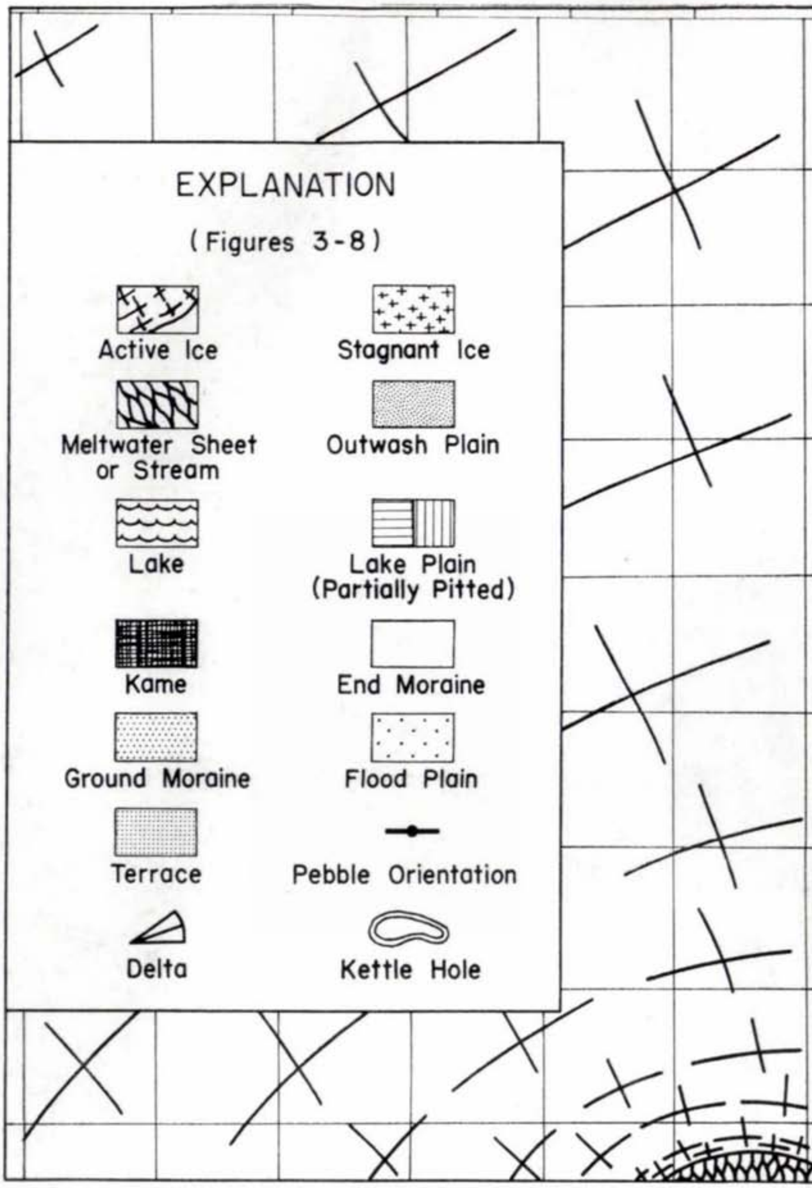

Figure 3. Formation of the Falcon Heights Outwash Plain by meltwater from the Grantsburg Ice.

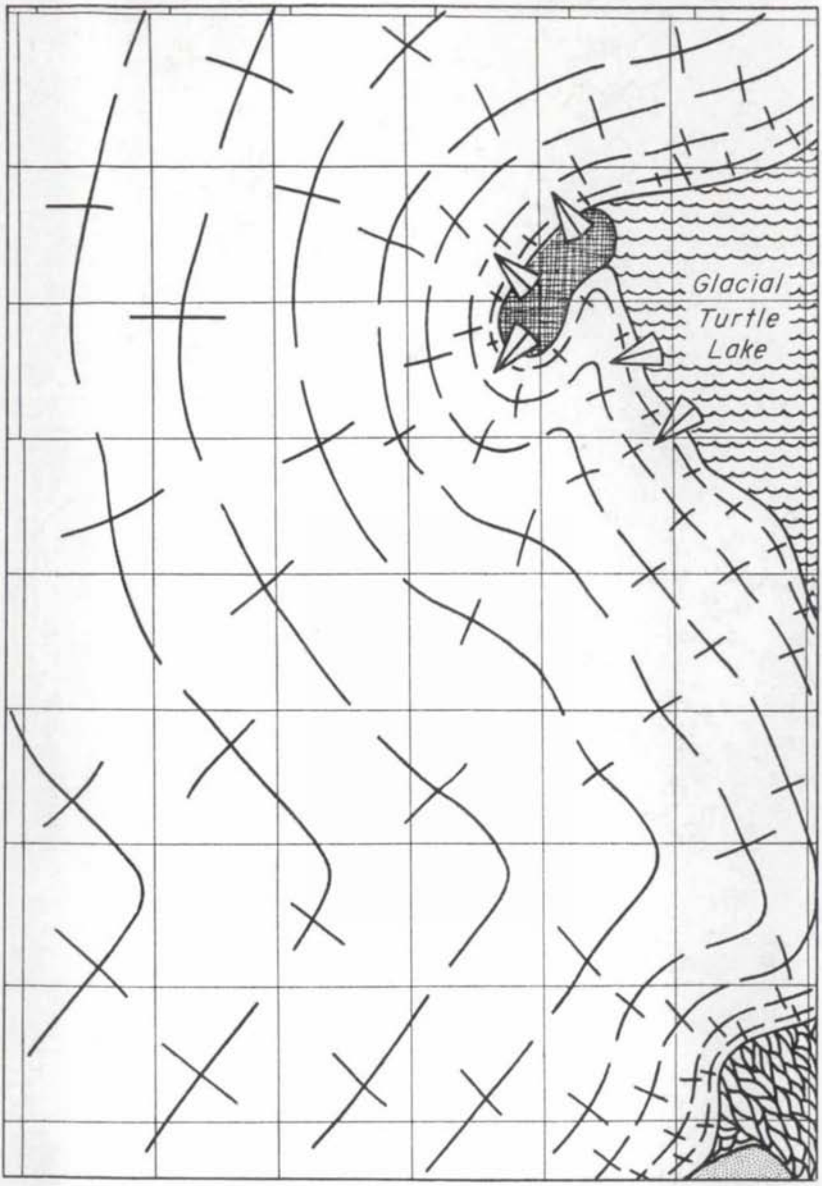

Figure 4. Development of the kame at the Twin Cities Arsenal and of glacial Turtle Lake (see Fig. 3 for key).

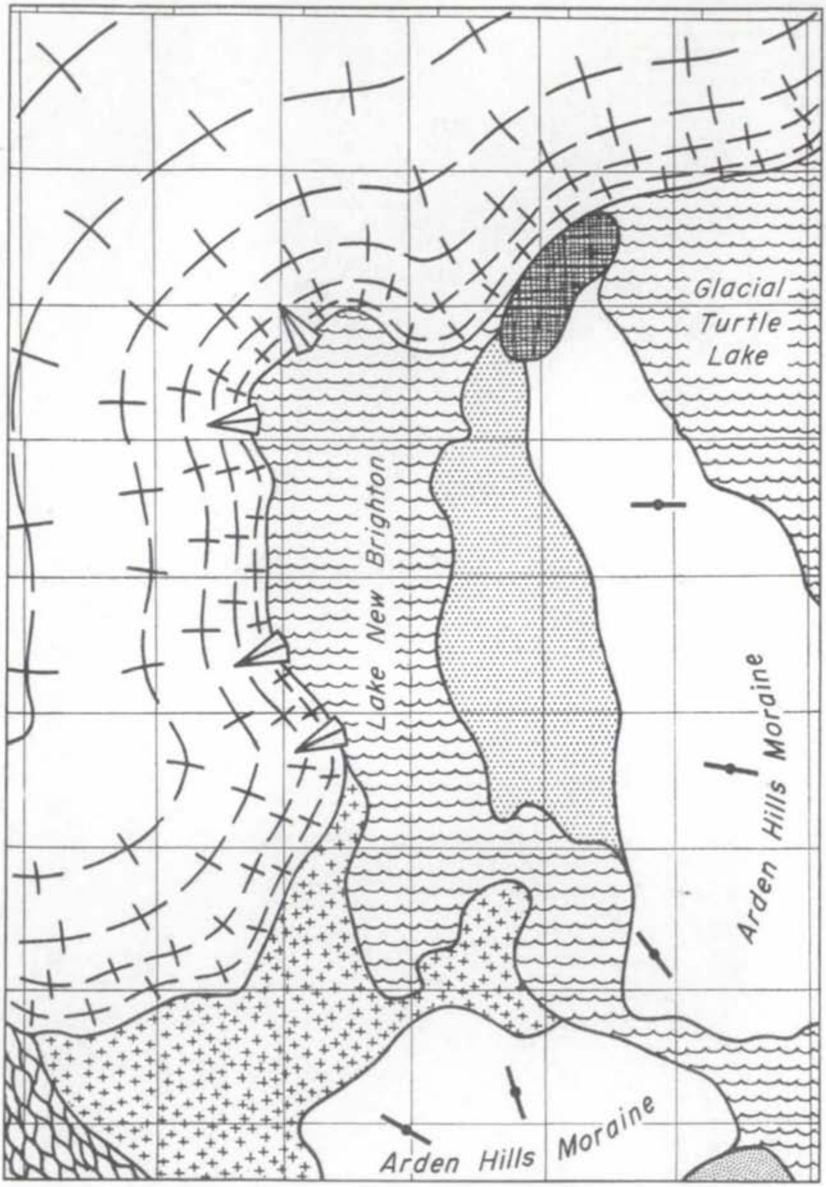

Figure 5. Exposure of the Arden Hills Moraine by the retreating Grantsburg Ice and the formation of Lake New Brighton (see Fig. 3 for key).

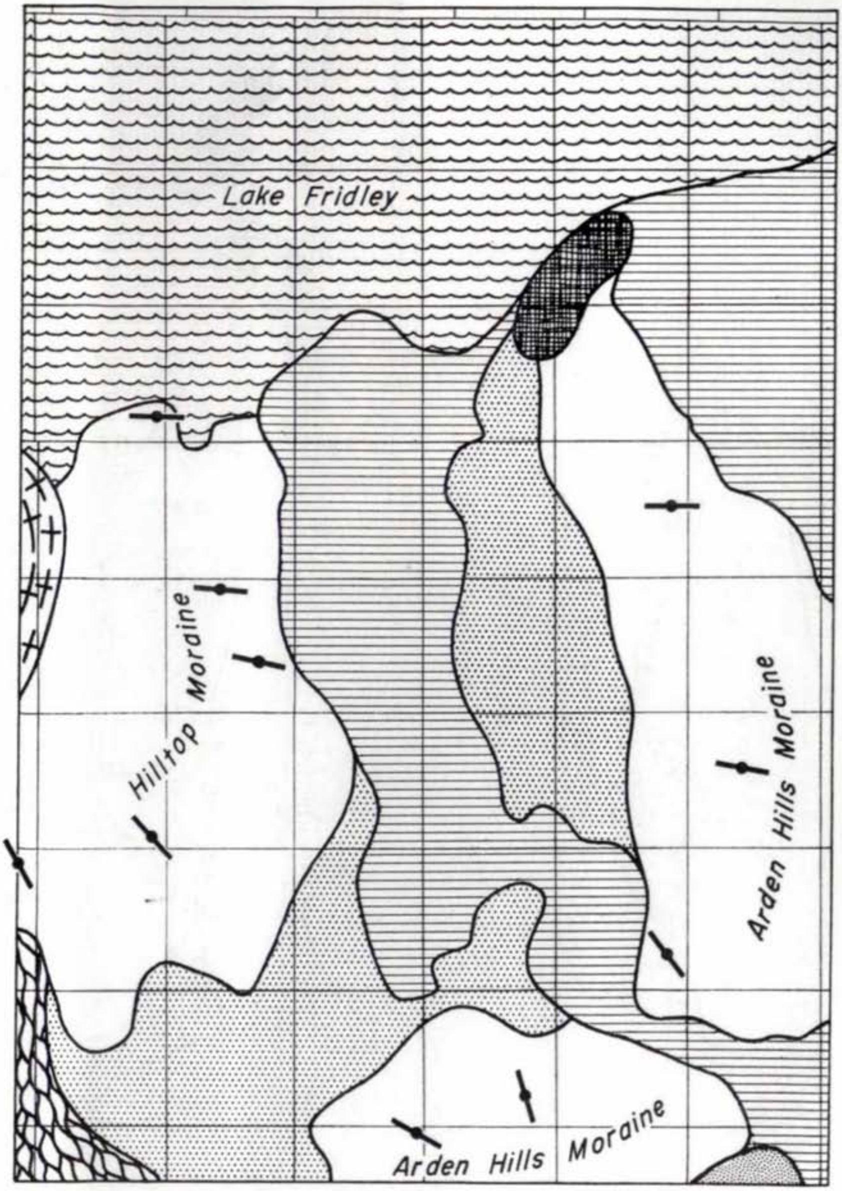

Figure 6. Exposure of the Hilltop Moraine by the retreating Grantsburg Ice and the formation of Lake Fridley. Lake New Brighton and Turtle Lake have been drained (see Fig. 3 for key).

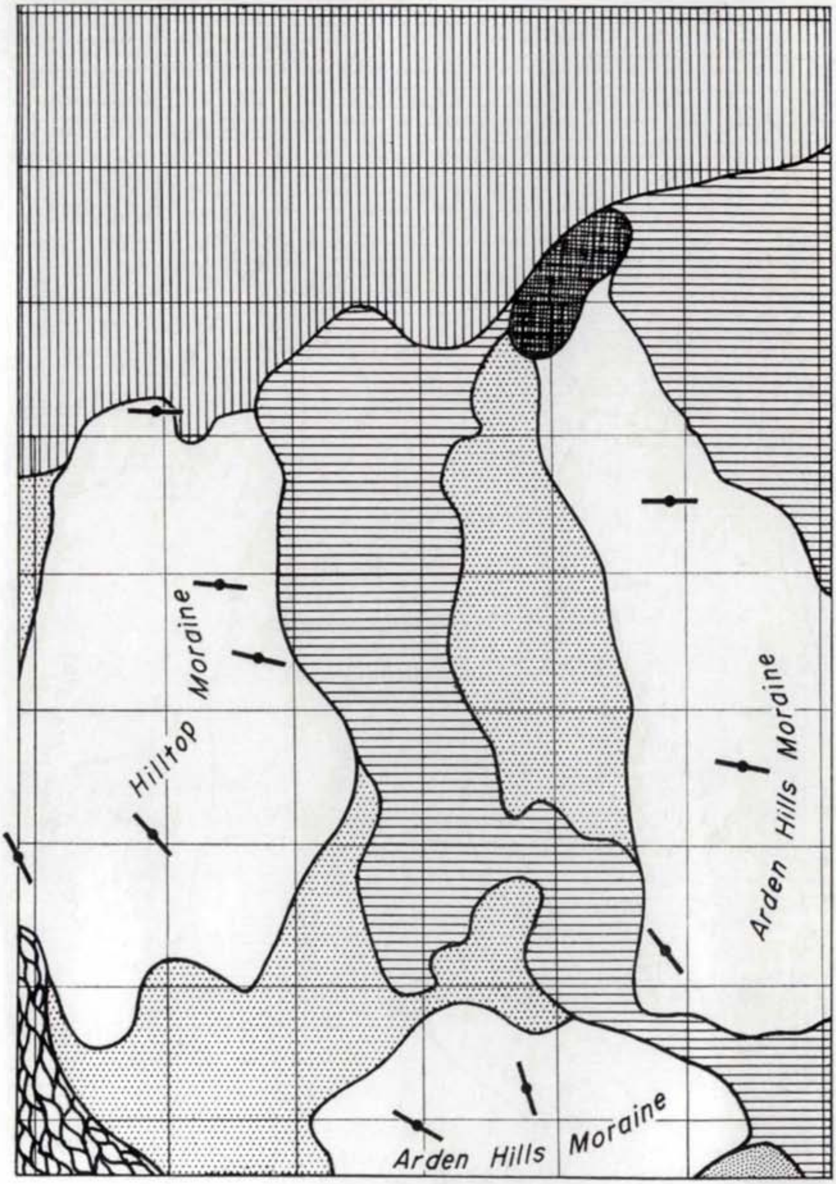

Figure 7. Development of a valley train at an elevation of about 850 feet down the Mississippi Valley after retreat of the Grantsburg Ice. Lake Fridley has been drained (see Fig. 3 for key).

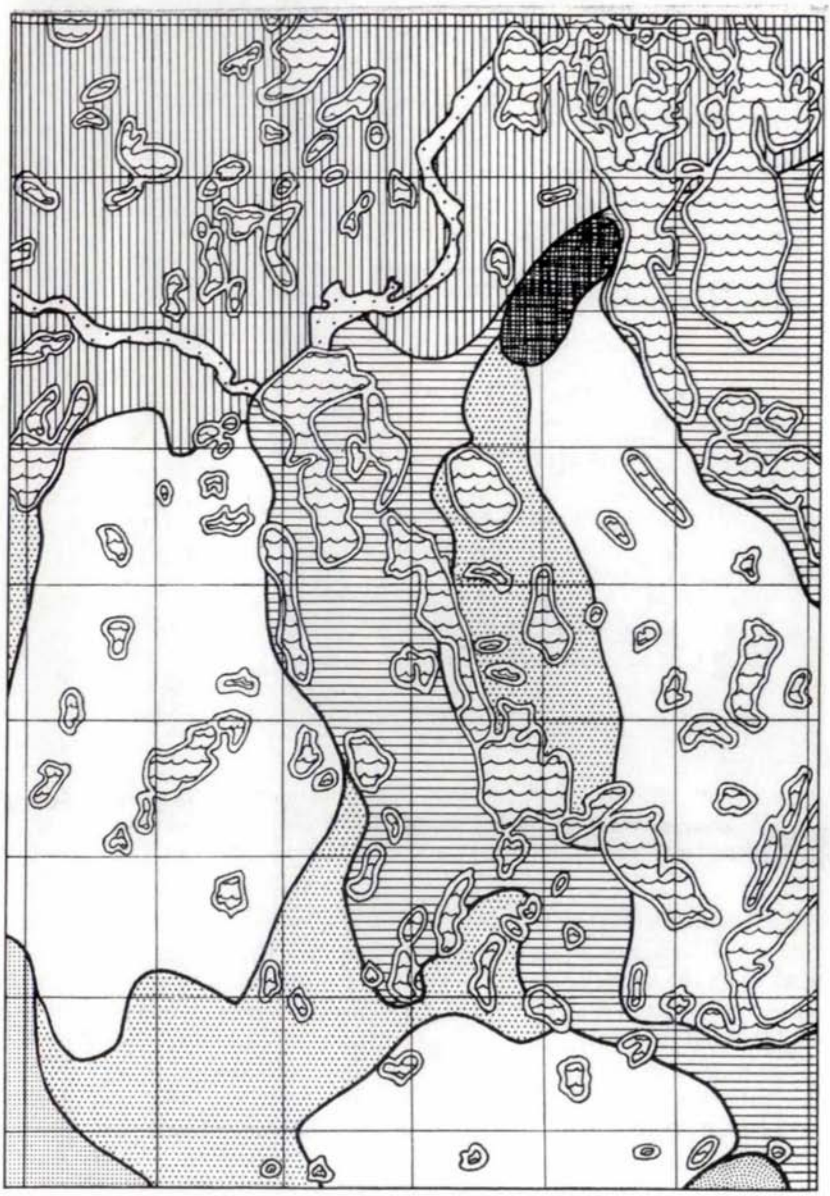

Figure 8. Development of the flood plain along Rice Creek. The 850-foot level has been abandoned by the Mississippi River. Many kettle holes have formed, some of which are occupied by lakes (see Fig. 3 for key). Some of the shallow lakes later became swamps.

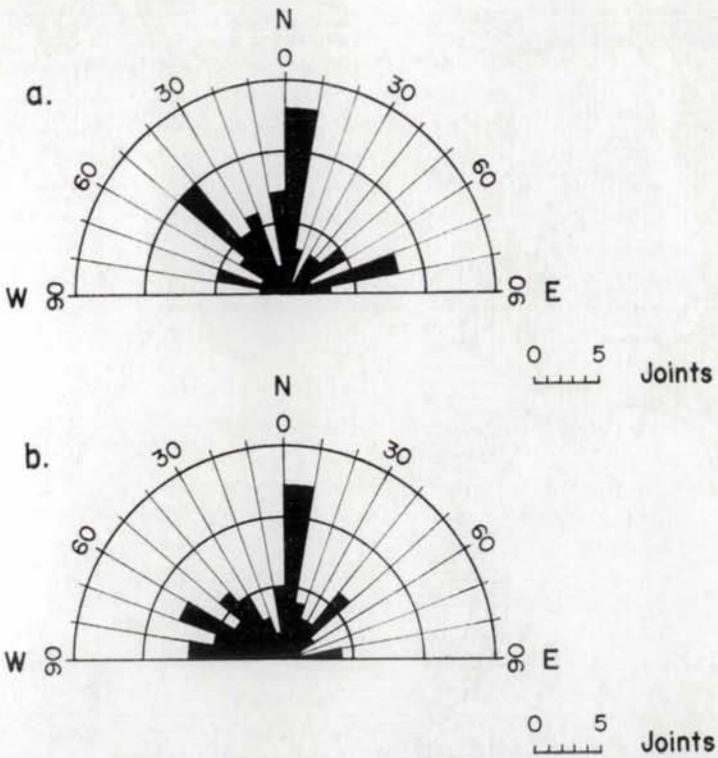

Figure 9. Joint orientations in the Twin Cities Formation. (a) 83 joints in light-gray till (NW¼NE¼NW¼ Sec. 32, T.30N., R.23W.); (b) 78 joints in both light-gray till and reddish-brown till (SW¼SE¼SE¼ Sec. 36, T.30N., R.24W.).

The formation is interpreted as an outwash body deposited by meltwater running off the Grantsburg Ice. The Twin Cities Formation bordering the outwash on the north and west is a mixture of reddish-brown till of northeastern provenance and light-gray till of western provenance; the Falcon Heights Sand undoubtedly was derived from debris like this mixed till.

Turtle Lake Sand. The Turtle Lake Sand, formally established herein (see Table 2), is largely a very pale brown fine to medium laminated to thin-bedded sand with occasional laminae of silt. Each lamina is generally very well sorted. Deposits of poorly sorted cross-bedded gravelly fine to coarse sand occur, however, along the western side of the deposit. The cross-beds dip generally eastward. The Turtle Lake Sand lies directly on the Twin Cities Formation.

All the sands of the formation contain a high percentage of montmorillonite, indicating a western provenance via the Grantsburg Sublobe. The gravelly sands contain pebbles of limestone and shale of western provenance and pebbles of red sandstone, basalt, and gabbro of northeastern provenance. The fine to medium sands are interpreted as having been deposited in a lake marginal to the Grantsburg Ice, and the cross-bedded gravelly fine to coarse sands are interpreted as deltaic deposits laid down by meltwater streams running directly off the ice into the lake. Many of the medium-sized sand grains are well rounded; they probably were picked up by the Grantsburg Sublobe and earlier glaciers from the St. Peter and Jordan sandstones in the Twin Cities area.

Arsenal Sand. The Arsenal Sand, formally established herein (see Table 2), is a light-gray to very pale brown to brown pebbly fine to coarse sand. It is intricately cross-bedded, and abrupt changes in grain size and in sorting are common both vertically and horizontally. Small-scale faults with throws of 2 inches or less are common. Pebbles of red sandstone, basalt, gabbro, and felsite of northeastern provenance are abundant, but a few pebbles of shale and limestone of western provenance also occur.

The sand underlies two prominent knobs in the northeastern part of the quadrangle (Pl. 1); it is interpreted as a kame deposit laid down in a reentrant in the edge of the retreating Grantsburg Sublobe.

New Brighton Formation. The New Brighton Formation, formally established herein (see Table 2), has three distinct but closely related lithofacies: (1) a light-gray to very pale brown fine to medium sand facies, (2) a clayey silt facies, and (3) a gravelly fine to coarse sand facies. Each of the facies contains a high percentage of montmorillonite in the $<$ 2-micron fraction, indicative of a western provenance. The New Brighton Formation overlies the Twin Cities Formation.

The most extensive facies of the New Brighton Formation, a very pale brown fine to medium sand, generally is horizontally laminated to thin-bedded or is cross-laminated with rare thin laminae of clayey silt. Individual laminae of the sand are generally well sorted, but variations in grain size from lamina to lamina are common. The upper 5 to 8 feet, however, generally have been so modified by wind action and weathering that no bedding or lamination is evident. Many of the medium-sized sand grains are well rounded. Some ice-rafted pebbles occur within the sands. Iron-stained layers ranging from a fraction of an inch to 2 feet thick are numerous in the upper 12 feet of the sand. In some places small-scale faulting, probably resulting from differential settlement, is common.

The fine to medium sand is thought to have been deposited in a lake marginal to the retreating Grantsburg Sublobe. The rounded sand grains probably were derived from the local St. Peter and Jordan sandstones by the Grantsburg Ice directly or via older drift deposits in the area. At an elevation of about 905 feet at one locality (site F–96, Stone, 1966), a few sand waves of the type described by Shepard (1963, p. 117) and by Gilbert (1914, pp. 30–34) were found. Typical laminated lake sands occur immediately above and below the sand waves. Such sand waves are formed by currents with a high rate of flow. The evidence indicates that the lake dried up and streams occupied the lake bed for a short time before the lake again came into existence. This interpretation is supported by the occur-

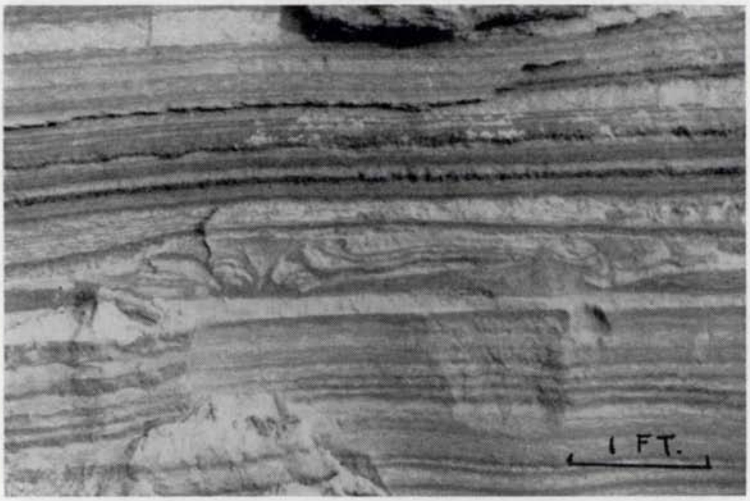

Figure 10. Contorted laminations in the New Brighton Formation (SE¼SE¼SE¼ Sec. 29, T.30N., R.23W.).

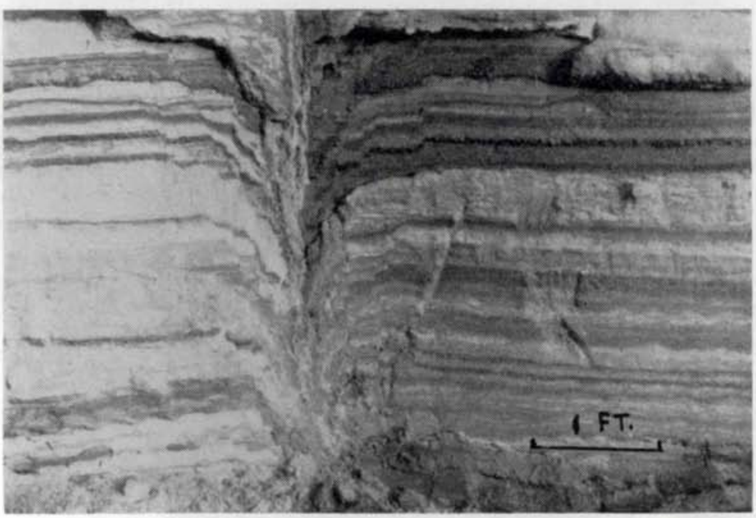

Figure 11. Step-faulted, graben-like structure in the New Brighton Formation (same locality as Fig. 10)

rence of some cross-bedded fluvial deposits at the same site at about the same level. At the same locality, the laminated sands are highly contorted at several levels (Fig. 10). Although the contorted structures resemble submarine slumps or flows; the laminae are preserved, despite their being severely contorted, indicating that the sand could not have been thrown into suspension temporarily as it would have been in a submarine slump or flow. The contortions may have been caused by a sudden increase in the pore pressure in the saturated sand deposit (perhaps caused by an earthquake shock) while the lake still existed. The increase in pore pressure would temporarily destroy the shear strength of the sand, allowing it to deform. As the excess pore pressure would be dissipated quickly in the sand, however, the deforming sand was "frozen" before the original lamination was destroyed. The mobilizing mechanism is thought to be similar to the mechanism triggering submarine landslides (Terzaghi, 1956, pp. 1–7). According to P. E. Cloud, Jr. (oral communication, 1963), such contorted laminations in sand have been produced in the laboratory by P. H. Kuenen with a violent shock to laminated sands in a glass fish tank. Several vertical fractures were observed in the New Brighton Formation at site F–96. One (Fig. 11) is a zone of microfaulting approximately 2 feet wide that can be traced vertically at least 20 feet.

The next most abundant facies in the New Brighton Formation is clayey silt, which forms beds and lenses irregularly distributed throughout the formation. In some areas (e.g., Secs. 4 and 5, T.29N., R.23W.; Secs. 33 and 34, T.30N., R.23W.) large deposits of silt occur (see boring logs for sites F–40 and F–41 in Stone, 1966). The silt is thought to have been deposited in the same lake as the fine to medium sand facies but in less turbulent water. About 7 feet of very tough clay, probably formed by desiccation, occur at an altitude of about 875 feet at site F–41. Possibly the clay was part of the same exposed lake bottom represented by sand waves and fluvial cross-beds at site F–96, two miles to the north. Some pebbles occur within the silt and are considered to be ice-rafted.

The third lithofacies, a light brown gravelly fine to coarse sand, occurs irregularly in deposits along the western and northwestern sides of the formation. These deposits are thought to have been produced by debris-charged meltwater running off the Grantsburg Ice when it bounded the western and northern sides of the lake (Fig. 5).

Fridley Formation. The Fridley Formation, formally established herein (see Table 2), has two lithofacies almost identical to corresponding facies in the New Brighton Formation: light-gray to very pale brown fine to medium sand and gray clayey silt. Both lithologies contain a high percentage of montmorillonite in the $<$ 2-micron fraction, indicating a western provenance.

The fine to medium sand is generally horizontally laminated or bedded but may be cross-laminated; small ripple marks are common. Many of the medium-sized sand grains are well rounded. At places the sand is cut by small faults, probably caused by differential settling. Some laminae and small lenses of silt occur in the sand, as do a few pebbles. In some areas the upper 5–10 feet of the sand appear to have been reworked by the wind. The upper 10–12 feet of the sand generally have numerous iron-stained layers ranging in thickness from a fraction of an inch to 2 feet.

The clayey silt occurs as both large and small irregular bodies, commonly with laminae of sand. The silt bodies generally interfinger with bodies of sand. A few pebbles occur throughout the silt.

The Fridley Formation is thought to have been deposited in a lake. The fine to medium sand probably was spread across the lake bottom by currents and wave action. The silt bodies probably were deposited in quiet parts of the lake far removed from the currents created by the meltwater streams flowing into the lake. The irregular distribution of silt probably resulted from erratic shifting of the ice margin and from fluctuations in the meltwater streams that flowed from the ice. The scattered pebbles in the fine to medium sand and in the silt are thought to be ice-rafted.

Late-Glacial and Postglacial Stratigraphy

Late-glacial time is defined in this report as the time after active ice retreated from a local area and during which glaciers still affected the area (e.g., time during which meltwater from a far-distant glacier flowed in a valley through the area or during which eolian deposits were produced by strong winds generated by a glacier in the vicinity). Postglacial time is defined as that time after which a glacier has ceased to have an effect on a given local area. The late-glacial and postglacial deposits are described in their approximate order of formation.

West Campus Sand. The West Campus Sand, formally established herein (see Table 2), is a varicolored generally cross-bedded gravelly fine to coarse sand that contains lenses of silt, gravel, and moderately well-sorted sand. In general, the sand decreases in grain-size upward, and accordingly the grains are generally fine- to medium-sized at the surface. In some places iron-stained layers like those in the New Brighton and Fridley formations are found where fine to medium sand occurs at the surface. The West Campus Sand is interpreted as a valley train deposit laid down in late-glacial time by meltwater from the retreating Grantsburg Sublobe.

Eolian Sand. Eolian sand was not mapped separately but is included with both the New Brighton and the Fridley formations. In general, the wind-deposited sand differs from the lake sand from which it was derived in that it is better sorted and finer-grained and lacks structures like those a few feet below in the undisturbed lake-deposited sands. Eolian cross-bedding, though present, is only rarely evident.

In the quadrangle eolian sand has been deposited as a thin sheet 1–3 feet thick, and only locally is it heaped into small sand dunes about 5 feet high. Undoubtedly the sand has moved sporadically, mainly during periods of severe drouth, since the time the glacial lakes of the area disappeared. Evidence for one such renewal of movement is found in an abandoned borrow pit described as site F–97 (Stone, 1966); at this locality a soil has been truncated by wind action and covered by eolian sand. J. W. Gruner (oral communication, 1963) reports that large-scale movement of sand on the Anoka Sand Plain was common during the drouth of the mid-1930's.

Loess. Loess occurs as thin patchy deposits as much as 1.5 feet thick; it was not mapped as a separate unit. The loess generally is masked by the soil.

Lake Deposits. Most of the lakes in the map area that occupy kettle holes contain some sediments. Borings indicate that much of the lake sediment is highly organic (H. E. Wright, Jr., written communication, 1965). Marl occurs in some lakes, and peat is at the margins of many. A few lakes contain substantial deposits of transported peat, which has no surface manifestation (P. L. Chandler, oral communication, 1964). It is probable that lake deposits occur beneath many of the swamp deposits as well as in the present lakes.

Swamp Deposits. Swamp deposits consist of organic matter such as peat and of organic clay, silt, and sand. Peat especially is abundant. It should be emphasized that the swamp deposits vary extremely in thickness.

Alluvium. The only substantial deposit of alluvium in the quadrangle is in the northwestern part, along Rice Creek. The alluvium is primarily silty sand, silt, and clay and is of unknown thickness. Possibly alluvium also lies beneath the marshes along Rice Creek in the north-central part of the map area.

Colluvium. Colluvium occurs on all slopes in the quadrangle; the lower boundary often is marked by a thin layer of pebbles. The composition and texture of the colluvium depends upon the composition and texture of the upslope material from which it was derived. Colluvium ranges from 1–2 feet thick on the slopes to as much as 5 feet thick in closed depressions.

Two factors suggest that the majority of colluviation occurred during a relatively short period of time. First, the zone of pebble accumulation at the base of the colluvium indicates an earlier period of erosion during which only the pebbles lagged behind on the slopes. Second, the soils on the colluvium are well developed and undisturbed, indicating that colluviation essentially stopped before the soils began to form.

Artificial Fill. Artificial fill includes a great variety of material ranging from trash to natural material hauled various distances. Where the fill is more than 2 feet thick, it was mapped along the roads. Large areas of fill, usually in former swamps or lakes, also were mapped.

Geomorphology

The surface morphology of the quadrangle is dominated by partially collapsed lake plains and morainic topography (Fig. 2). Two lake plains are at an elevation of about 930 feet, and one is at an elevation of about 910 feet. That the two end moraines (i.e., the Arden Hills and the Hilltop Moraines, herein formally named for Arden Hills and Hilltop, Minnesota) trend north-south is significant because it indicates that the morainic topography in the area was produced by the Grantsburg Sublobe. This interpretation is supported by the orientations of elongate pebbles in the till of the moraines (Fig. 2). Previously, these small moraines were considered to be part of the huge St. Croix Moraine deposited by the Superior Lobe, which apparently trends east-west in the Minneapolis–St. Paul area (see Leverett, 1932, p. 44, Pl. 3).

The outwash plain extending into the southeastern corner of the map area is herein formally named the Falcon Heights Outwash Plain for Falcon Heights, Minnesota, and for the Falcon Heights Sand which underlies it. The terrace crossing the southwestern corner of the quadrangle is herein formally named the Fort Snelling Terrace for Fort Snelling, which lies upon the terrace at the confluence of the Mississippi and Minnesota rivers.

Of the many hundreds of kettle holes in the map area, only those occupied by major lakes and swamps are shown on Figure 2 (see Pl. 1 for details).

WEATHERING AND SOILS

Most of the materials at the surface have been subjected to weathering since the retreat of the Grantsburg Sublobe. Weathering has produced oxidation to a depth of about 15–30 feet, leaching of carbonate to a depth of 4–10 feet, and the formation of moderately developed soils. The soils of the area have been mapped and described in the county soil reports of Ramsey County (Smith and Kirk, 1916), Anoka County (Smith and others, 1918), and Hennepin County (McMiller and others, 1929). The soils are briefly described and related to the geology in Table 4.

The upper part of the fine to medium sands of the Turtle Lake, New Brighton, and Fridley formations generally contains reddish-brown, essentially horizontal but irregular layers that have several times as much iron oxide and clay as the surrounding sand. Such layers also occur locally in the West Campus Sand, especially where it consists of well-sorted fine to medium sand at the surface. As many as twenty-five separate iron-stained layers may be present (see Cooper, 1935, Fig. 18.D, p. 53). The layers are uneven and vary in thickness from a fraction of an inch to a maximum of about 2 feet. The layers generally show no direct relation to the texture or the bedding of the sand and are, therefore, secondary. Probably, as stated by Cooper (1935, p. 54), the layers were developed during successive still-stands in the water table. This mechanism is supported by observations that the essentially horizontal iron-stained layers intersect the sides of knolls and project out across adjoining depressions that probably were occupied in the past by lakes. Presumably, the iron oxide accumulated at the water table and remained behind when the water table dropped. The irregularity of the layers can be explained by a slight settling of the still mobile iron oxide accumulation when it was left behind. It is probable that weathering originally mobilized the iron oxide.

A truncated and buried soil developed on lake sand in the New Brighton Formation occurs in NW¼ Sec. 20, T.30N., R.23W., and is described as site F–97 in Stone (1966). The buried soil is covered by as much as 6 feet of

Table 4. Soil Series in the New Brighton Quadrangle

Soil Series	Brief Description of Solum	Great Soil Group	Brief Description of Subsoil	Geologic Units over Which Soils Occur
Hayden	Light-gray to gray-brown loam	Gray-brown podsol	Light yellowish-brown to yellowish-brown glacial till	Twin Cities Formation
Miami*	Brown to light-brown loam and fine sandy loam	Gray-brown podsol	Brown or yellowish-brown to mottled brown or yellow and gray glacial till	Twin Cities Formation
Gloucester*	Brown or light-brown to yellowish-brown or reddish-brown loam	Gray-brown podsol	Yellowish-brown glacial till	Twin Cities Formation
Thurston	Light-brown to dark-brown to almost black loam	Brunizem	Yellow to light-brown sand and gravel; sometimes with a reddish tinge	Hillside Sand and deltaic deposits of Turtle Lake Sand and New Brighton Formation
Hempstead*	Dark-brown to black silt loam	Brunizem	Brown to yellowish-brown coarse sand and gravel	Falcon Heights Sand
Hinckley	Brown to light-brown loamy fine sand	Regosol†	Yellowish-brown to faintly reddish-brown sand and gravel	Turtle Lake, New Brighton, and Fridley formations
Merrimac*	Light-brown to brown fine sand and loamy fine sand	Regosol†	Yellowish-brown to brown sand and gravel	Turtle Lake, New Brighton, and Fridley formations
Hubbard	Dark-brown to yellowish loamy sand and sandy loam	Brunizem	Brown to dark yellowish-brown fine to medium sand	West Campus Sand
Webster	Dark-gray to black silty clay loam	Humic gley	Dark-gray to light-gray till commonly with mottles of orange, yellow, or red	Colluvium in depressions on Twin Cities Formation

* Used in the Ramsey County Soil Report (Smith and Kirk, 1916), but no longer used in Minnesota. Miami and Gloucester are essentially equivalent to Hayden, Hempstead to Waukegan, and Merrimac to Zimmerman.

† Fairly close to gray-brown podsol.

sand on which trees as much as 50 feet high are growing. Apparently, the lower soil was truncated and buried by eolian action, probably during a period of drouth.

SYNTHESIS OF QUATERNARY HISTORY

In immediately pre-Quaternary times the center of the Twin Cities basin was topographically high. The bedrock upland was a rolling surface with about 80 feet of relief into which had been cut valleys as much as 400 feet deep (Pl. 2). Drainage may have been northward.

Presumably the area was glaciated during the Nebraskan, Kansan, and Illinoian glacial ages, and during the Aftonian, Yarmouth, and Sangamon interglacial ages the area was subjected to long periods of erosion during which integrated drainage systems probably were established. Apparently, the major valleys cut down through the glacial drift into the underlying bedrock to form a network of bedrock valleys that, after several cycles, had become quite complex. Some of the bedrock valleys were occupied by streams during more than one cycle.

Probably during the early and middle Wisconsin Age thick glacial ice completely covered the Twin Cities area. By about 14,000 years ago (Wright and Ruhe, 1965), however, the edge of the ice had retreated into Minnesota, and the Superior Lobe flowing from the north and northeast deposited a reddish-brown till — possibly the unnamed till of Plate 3. The Superior Lobe then retreated, possibly depositing part of the Hillside Sand. About 13,000 years ago (Wright and Ruhe, 1965) the Grantsburg Sublobe advanced into the area from the southwest bringing a gray drift. Much of the previously deposited red drift was incorporated into the Grantsburg Ice. As the ice advanced across the New Brighton quadrangle, proglacial outwash of irregular thickness was deposited and overridden, producing at least the upper part of the Hillside Sand. The overriding ice probably deposited till (i.e., the Twin Cities Formation) throughout the time that it flowed actively in the quadrangle, during both advance and retreat.

During westward retreat of the Grantsburg Sublobe stabilization of the edge of the ice across the southeastern corner of the quadrangle resulted in the formation of the large Falcon Heights Outwash Plain and the related Falcon Heights Sand, which extend southeastward across the present city of St. Paul (Fig. 3). The position of the edge of the ice at this time is inferred from the position of the inner (iceward) edge of the outwash plain.

Later, the edge of the active ice retreated slightly in the southeastern corner of the quadrangle and even more from the area east of the quadrangle, so that a large reentrant was produced in the northeastern part of the quadrangle (Fig. 4). Most of the reentrant was occupied by an ice-marginal lake, here named Glacial Turtle Lake for the Turtle Lake Sand deposited in the lake. Glacial Turtle Lake was contained between active ice on the north and west and high ground and stagnant ice on the east and south. Deltas were formed along the western edge of the lake where debris-charged meltwater from glacial ice ran into the lake. The present altitude of the bottom of this short-lived lake is approximately 930 feet. The westernmost end of the reentrant was indented by another, smaller reentrant in which the Arsenal Sand, a large kame deposit, was laid down. The position of the ice front at that time is shown by the deltaic and kame deposits on the west and by remnants of a north-facing ice-contact escarpment on the north. The area north of the lake plain is presently about 20 feet lower than the bottom of Glacial Turtle Lake and was necessarily occupied by ice, for if ice had not been present there, the lake basin could not have existed.

Later, while active ice continued to occupy the northern part, the edge of the ice in the southern two thirds of the quadrangle retreated westward, uncovering the Arden Hills Moraine (see Fig. 5). Much of the moraine in the map area is oriented north-south, but it trends southwestward in the southernmost part of the quadrangle. In the northern part of the quadrangle the moraine disappears beneath a lake plain (see Figs. 2, 8) and, it is thought, bends sharply eastward to join a moraine exposed at the surface just east of the map area. Both the north-south orientation of the moraine and a nearly east-west orientation of pebbles in the till (Figs. 2 and 5) indicate that the Grantsburg Sublobe was flowing nearly due east in the east-central part of the quadrangle just before this retreat.

The same retreat of the ice produced a long, narrow ice-marginal lake, here named Lake New Brighton for New Brighton, Minnesota, and for the New Brighton Formation, sediments of which were deposited in the lake, mostly west of the Arden Hills Moraine. Lake New Brighton was bordered by active ice on the west and north, by high ground on the south, and by the Arden Hills Moraine on the east, except in the southeastern part of the quadrangle where the lake crossed the moraine (see Fig. 5). Deltaic deposits, interfingering with till on the west and with lake sediments on the east, were formed along the west and north sides of the lake. The western sides of some of the deltas show ice-contact slopes facing west, suggesting that active ice extended completely to the edge of Lake New Brighton while the deltas were forming. Sand waves, fluvial cross-bedding, and desiccated clay at one level within the New Brighton Formation indicate that the lake disappeared for a short time and was then reestablished. The position of the edge of the ice front at this time (Fig. 5) is inferred from the orientation of the Hilltop Moraine, from the position of the deltaic deposits and the contact between till and lake deposits on the west, and from the position of a delta and the remnants of a north-facing escarpment on the north. The area north of the lake plain is presently about 20 feet lower than the New Brighton Lake Plain and must have been occupied by ice. Stagnant ice probably occupied the south-central part of the area (Fig. 5) because no glacio-fluvial deposits occur there adjacent to the Hilltop Moraine.

The rapid westward retreat of the edge of the ice in the southern three-fourths of the quadrangle while ice continued to occupy the entire northern fourth probably was an effect of topography, for the northern fourth is topographically lower than the remainder of the area. As a result, the ice in the northern fourth of the quadrangle was thicker and thus remained active longer.

The edge of the ice then retreated from the area entirely, except for a small protrusion in the west-central part of the quadrangle, exposing the Hilltop Moraine (see Fig. 6). Glacial Turtle Lake and Lake New Brighton had disappeared because the northern glacier margins of the lake basins had been removed. A large new ice-marginal lake (here named Lake Fridley for Fridley, Minnesota, and for the Fridley Formation deposited in the lake) was formed between active ice on the west and southwest and high ground on the south and east. The Hilltop Moraine is oriented largely north-south along the western side of the quadrangle but curves westward in the southwest part of the area. In the northern part of the quadrangle the moraine disappears beneath the sediments that were deposited in Lake Fridley and, it is thought, swings sharply east to join the Arden Hills Moraine. That the edge of the Grantsburg Sublobe was oriented north-south in the west-central part of the quadrangle before this retreat is shown by the north-south elongation of the Hilltop Moraine and by the nearly west-east orientation of elongate pebbles in the till of the moraine of this area (see Figs. 2 and 6). The position of the ice in Figure 6 is deduced from the fact that Lake Fridley in the northern part of the quadrangle could not have existed unless the low area immediately west of the quadrangle and presently occupied by the Mississippi River had been blocked by ice.

When the Grantsburg Sublobe retreated into the lowland presently occupied by the Mississippi River, Lake Fridley was drained, and a valley train was established along the present course of the Mississippi River at an elevation of about 850 feet (Fig. 7). The valley train extended only into the southwestern corner of the quadrangle. The outwash deposited at that time is the West Campus Sand.

Later, probably when Glacial River Warren began to drain Lake Agassiz, the Mississippi River cut downward, abandoning the 850-foot level and leaving a wide terrace (see Fig. 11).

With time a poorly integrated drainage developed in the area, and Rice Creek was formed. The Mississippi cut downward in successive steps, and Rice Creek, which flows into the Mississippi, did likewise. This undoubtedly contributed to a general lowering of the water table in the area, particularly in the Turtle Lake Sand and the New Brighton and Fridley formations. When the water table dropped in successive steps, iron oxide, accumulated at the water table, was left behind as iron-stained layers. There are as many as twenty-five layers, ranging in thickness from a fraction of an inch to 2 feet.

As the water table fell and the sand dried out, some of the dry sand was blown into a few low sand dunes, and silt was winnowed out to be deposited downwind as loess. The relatively small number of dunes in the map area probably results from the fact that vegetation was well established before the sand dried out.

Blocks of ice in the drift began melting to produce hundreds of kettle holes, many of which are now occupied by lakes or swamps (see Fig. 11 and Pl. 1). Marl occurs beneath peat in some of the swamp areas, indicating that these were open lakes for a while. Some of the kettle holes in the quadrangle are aligned above bedrock valleys, indicating that ice blocks filled substantial portions of these valleys (see Pls. 1 and 2). Pike Lake and Long Lake are aligned above Calhoun Valley, and Lake Josephine and Lake Johanna are aligned above Johanna Valley. Round Lake and Valentine Lake are above one of the tributaries of Johanna Valley. Snail Lake is above the large bedrock valley that cuts across the northeastern corner of the quadrangle. Other kettle holes aligned above these bedrock valleys are occupied by swamps. The subsurface information indicates that the deposits in the bedrock valleys probably are pre-Grantsburg (Pl. 3). Thus, the blocks of ice that caused the kettle holes aligned above the bedrock valleys must have been remnants of pre-Grantsburg ice, possibly left during the retreat of the Superior Lobe or still earlier in the Wisconsin Age.

Soon after the retreat of the ice, there apparently was a period of accelerated colluviation that produced 1 to 5 feet of deposits in those areas with a relief of 10 or more feet (e.g., in morainic areas). This may have resulted from a period of heavy rainfall or lack of vegetation, or both.

After colluviation had essentially ceased, poorly to moderately well-developed soils were produced in most of the area. The soils indicate that all of the land surface of the area was covered by deciduous forest except for the Falcon Heights Outwash Plain and the terrace in the southwestern corner of the area, which were covered with grass (Table 3). Weathering also produced leaching and oxidation below the solum.

In postglacial time wind erosion has modified the terrane slightly, especially during periods of drouth. On the whole, however, the most significant changes in the landscape in postglacial time have been made by man, who settled the area during the 1830's and 1840's.

The interpretation of glacial events presented here differs from past interpretations in two important respects. First, it has been assumed that the morainic topography of the area was part of the St. Croix Moraine produced by the Superior Lobe and that the Grantsburg Sublobe merely plastered a thin veneer of grayish drift on top of the St. Croix Moraine (Leverett, 1932, pp. 79–80; Schwartz, 1936, p. 63; Wright, 1953, p. 465). The present interpretation is that the morainic topography in the New Brighton area was produced entirely by the Grantsburg Sublobe. The St. Croix Moraine either was destroyed in this area by the Grantsburg Sublobe itself or perhaps was destroyed in pre-Grantsburg time by meltwater from the retreating Superior Lobe. Second, the Anoka Sand Plain was thought by Cooper (1935, pp. 58–59) to have been deposited by the retreating Grantsburg Sublobe entirely as an outwash plain, which was then reworked by the ice-marginal Mississippi River. The part of the Anoka

Sand Plain in the New Brighton quadrangle, however, is made up of segments of three partially collapsed lake plains produced in lakes marginal to the retreating Grantsburg Sublobe. These are the lake plains of Glacial Turtle Lake (930 feet), Lake New Brighton (930 feet), and Lake Fridley (910 feet). The interpretation that these are lake plains is supported by the occurrence of lake deposits (i.e., deltas and still-water structures in sands that interfinger with large bodies of silt). Furthermore, riverine features are lacking on the part of the Anoka Sand Plain in the New Brighton quadrangle. Finally, the plain slopes westward, although the Mississippi River supposedly flowed eastward across the plain to the St. Croix River.

ECONOMIC GEOLOGY

Economic geology is broadly interpreted in this report to include most practical applications of geology.

ENGINEERING GEOLOGY

The available engineering test data for the glacial deposits are published separately (Stone, 1966) but are summarized in Table 5. Data on grain size, clay mineralogy, pebble content, and carbonate content are summarized in Table 3. Generalized descriptions of the engineering properties of the surficial map units are given in Table 6.

The geologic map (Pl. 1) can be used as an engineering-feasibility map for planning purposes and for correlating engineering test data and the results of engineering experience with the various geologic units. The data in this report and the companion report (Stone, 1966) can be used for engineering evaluation of specific sites; for most purposes, however, this information should be supplemented by geological and engineering studies on the site. For example, heavy structures founded on the fine to medium sand of the New Brighton and Fridley formations would probably be affected by silt within or below the sand. Thus, borings on the site for any proposed heavy structures would be advisable in areas underlain by these formations.

Virtually all the unconsolidated materials in the map area contain a relatively high percentage of montmorillonite in the clay size fraction. In the sands where the total clay is at most a low percentage, the effect of the montmorillonite is negligible. On the other hand, in the tills, particularly the gray tills, and in silt and clay deposits, the effects of montmorillonite on swelling, bearing capacity, consolidation characteristics, and permeability are significant.

Except in the southwestern part of the area, where the Platteville Formation lies directly beneath the West Campus Sand, bedrock is generally too deeply buried to be used for founding heavy structures. In testing for bedrock foundations, borings should be carried into the St. Peter Sandstone, because large natural caverns have been found locally in the formation in the Twin Cities area.

Table 5. Engineering Test Data for Surficial Deposits, New Brighton Quadrangle*

Geologic Unit	Textural Classification†	Percentage of Liquid Limit	Plasticity Index	Percentage of Optimum Moisture‡	Maximum Density (lb./cu. ft.)‡	Standard Penetration Test (in blows/ft. penetration)§	Shear Strength (lb./sq. ft.)‖	AASHO Classification¶	Unified Soil Classification**
Artificial fill	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable
Alluvium	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable
Swamp and marsh deposits									
Peat						3–5	76–325		Pt
Lake deposits	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable
West Campus Sand	Sand	NP	NP					A-1-b (0)	SP
Fridley Formation									
Fine to medium sand facies	Sand to loamy sand	NP	NP	12.3–13.0	106.6–109.5	10–50		A-3 (0)	SP
Clayey silt facies	Silt	24–53	6–16			1–5	300–500	A-4 (8)	CL-ML to CH
New Brighton Formation									
Fine to medium sand facies	Sand to loamy sand	NP	NP	9.3–13.5	106.6–120.8	10–51		A-3 (0)	SP
Clayey silt facies	Silt	24–53	6–16	17.0–19.7	105.4–110.0	1–5	34–420	A-4 (8)	CL-ML to CH
Gravelly fine to coarse sand facies	Gravelly sand	NP	NP	10.5	107.3			A-1-b (0)	SW
Arsenal Sand	Sand	NP	NP	14.5	106.9			A-1-b (0)	SP
Turtle Lake Sand									
Fine to medium sand facies	Sand to loamy sand	NP	NP	9–13	106–118	10–50		A-3 (0)	SP
Gravelly fine to coarse sand facies	Gravelly sand	NP	NP					A-1-b (0)	SW
Falcon Heights Sand	Sand	NP	NP					A-1-b (0)	SP
Twin Cities Formation									
Light-gray till	Sandy clay	25–35	5–13	13.5–16.0	108.0–118.5	20–35	1,972–2,642	A-4 (3–5)	CL-ML to SC
Reddish-brown till (including mixed)	Loam	15–34††	1–12††	10.8–13.5	116.6–125.0			A-4 (1–6)	SMd to SC
Hillside Sand	Sand	NP	NP	8.0–9.0	125.6–128.0	9–26		A-1-b (0)	SW to SP

* Tests are on material below the solum of the soil profile.
† Soil Survey Staff (1951, pp. 205–223).
‡ Anonymous (1961b, pp. 302–306).
§ Anonymous (1964).
‖ Anonymous (1963).
¶ Committee on Classification of Materials for Subgrades and Granular Type Roads (1945).
** Anonymous (1953).
†† Essentially unmixed reddish-brown till has liquid limits of 15–24 and plasticity indexes of 1–8.

Table 6. Generalized Description of Engineering Properties of the Surficial Deposits of the New Brighton Quadrangle

Geologic Unit	Permeability	Workability	Susceptibility to Frost Heaving	Slope Stability	Foundation Conditions	Possible or Reported Uses
Artificial fill	Extremely variable	Variable but generally easy to excavate and compact	Extremely variable	Generally stable	Generally subject to compaction under load unless compacted when emplaced; compressible, low-strength lake or swamp deposits may be beneath old fills; borings through old fills often advisable	
Alluvium	Low to moderate	Easily excavated; easy to compact except where organic content high	High where clayey and silty; moderate where sand dominant	Moderately stable	Moderate bearing strength in sandy material; low bearing strength in clayey, silty, and organic materials, which are also subject to excessive consolidation	Surface material usable as topsoil for lawns; sandy alluvium usable as fill
Swamp deposits	Generally very low	Generally makes very poorly compressible fill; peat may be easier to dredge than excavate	Fine-grained organic materials highly susceptible	Generally unstable	Generally very poor; low bearing strength and high consolidation common; generally should be excavated and backfilled if fill or structure to be emplaced	Peat usable as fertilizer and soil conditioner
Lake deposits	Variable but generally low	May be difficult to excavate because under water; dredging may be most effective method of excavation; organic, clayey, and silt materials difficult to compact	Generally high	Generally unstable	Generally poor; low bearing strength and high consolidation general; should be excavated before fill or structure is emplaced	Fills for non-bearing areas such as playgrounds

Table 6. Continued

Geologic Unit	Permeability	Workability	Susceptibility to Frost Heaving	Slope Stability	Foundation Conditions	Possible or Reported Uses
West Campus Sand	Moderate to very high	Easily excavated and compacted to rather dense fill	High in clay and silt; moderate in fine to medium sand; low in coarse sand	Unstable and free-running on $>30^\circ$ slopes; susceptible to wind and rain erosion	Sands have moderate to high bearing strength where confined; susceptible to erosion by running water	Fill
Fridley and New Brighton Formations						
Fine to medium sand facies	Moderate; higher laterally than vertically	Easy to excavate; generally must be compacted by vibration or with smooth rollers	High in fine sand; moderate in medium sand	Generally stands temporarily in steep or vertical cuts but eventually becomes unstable on $>30^\circ$ slopes; susceptible to wind and rain erosion	Moderate to fairly high bearing strength; subject to moderate compaction by vibration	Fill
Clayey silt facies	Very low	Easy to excavate except below water table	Very high	Very poor	Very low bearing strength and subject to excessive consolidation	Fill for non-bearing areas such as playgrounds constructed on swampy areas
Gravelly fine to coarse sand facies (New Brighton Formation only)	Moderate to high	Easy to excavate and compact	Moderate to low susceptibility	Unstable and free-running on $>30^\circ$ slopes; susceptible to wind and rain erosion	Moderate to high bearing strength where confined; susceptible to erosion by running water	Fill
Arsenal Sand	High	Easy to excavate and compact to high density	Low	Unstable and free-running on $>30^\circ$ slopes; finer sands susceptible to wind and rain erosion	Generally high bearing strength where confined; susceptible to erosion by running water	Concrete aggregate and fill

Table 6. Continued

Geologic Unit	Permeability	Workability	Susceptibility to Frost Heaving	Slope Stability	Foundation Conditions	Possible or Reported Uses
Turtle Lake Sand						
Fine to medium sand facies	Moderate; higher laterally than vertically	Easy to excavate; generally must be compacted by vibration and/or smooth rollers	High in fine sand; moderate in medium	Will generally stand temporarily in steep or vertical slopes but eventually becomes unstable on >30° cuts; susceptible to wind and rain erosion	Moderate to fairly high bearing strength; subject to moderate compaction by vibration	Fill
Gravelly fine to coarse sand facies	Moderate to high	Easy to excavate and compact	Moderate to low	Unstable and free-running on >30° slopes; susceptible to wind and rain erosion	Moderate to high bearing strength where confined	Fill
Falcon Heights Sand	Moderate to high	Easily excavated and compacted to a rather dense fill	Generally low	Unstable and free-running on >30° slopes; susceptible to wind and rain erosion	Generally high bearing strength where confined	Fill; poor for concrete aggregate because of high shale content
Twin Cities Formation						
Light-gray till	Low except along joints	Moderately easy to excavate and moderately difficult to compact	High to moderate susceptibility	Will stand in moderately dry steep cuts but likely to slump and flow on wet steep cuts, especially in spring thaw	Moderate bearing strength when wet, high when dry; desirable to keep dry beneath footings because of relatively high montmorillonite content	Makes adequate fill
Reddish-brown till	Low to moderate	Easy to excavate and compact into a rather dense fill unless mixed with large amount of gray till	Moderate	Will stand in moderately steep cuts	Generally high bearing strength	Fill
Hillside Sand	High	Easy to excavate and compact	Moderate	Unstable and free-running on >30° slopes; susceptible to wind and rain erosion	High bearing strength where confined	Concrete aggregate and fill

Should utility tunnels be driven through the St. Peter Sandstone in the New Brighton quadrangle, as has been done in other parts of the Twin Cities area, some difficulty is likely to be encountered because several drift-filled valleys are known to cut through the St. Peter (Pl. 2) and others may be present. Where the Platteville Formation has been removed by preglacial or interglacial erosion, the underlying St. Peter tends to be soft and subject to caving. Experience in tunneling in the Twin Cities has shown that intersecting joints in the St. Peter can cause unexpected rockfalls. It is possible also that the faults in the bedrock could cause similar difficulties or water problems during tunneling.

Ground-Water Geology

A part of the Hillside Sand, parts of the Fridley and New Brighton formations, and the sands and gravels in the buried bedrock valleys appear to contain large quantities of water and to merit careful hydrologic study. The units are sufficiently near the surface to be artificially recharged. Although this near-surface water is subject to pollution, the water could be treated at least as easily as surface water and would have the advantage of being more constant in temperature and quality than surface water.

The major bedrock aquifers in the New Brighton quadrangle are the St. Peter Sandstone, the Prairie du Chien Formation, the Jordan Sandstone, the Franconia Formation, and the sandstones of the Dresbach and Hinckley formations. Wherever these units are confined by aquicludes the contained water is under artesian pressure. The quantity, availability, and quality of water in these formations has been summarized by the Division of Waters, Minnesota Conservation Department (Anonymous, 1961c, pp. 10–12).

The bedrock aquifers are recharged mainly by the infiltration of water down through the glacial drift into the truncated edges of the units around the periphery of the Twin Cities basin. The upper bedrock units, however, receive a substantial part of their recharge by infiltration from directly above through the glacial drift and one or more bedrock units (Anonymous, 1961c, p. 10). Significant amounts of water probably move downward along joints in glacial till and along fractures in the bedrock.

Sand and Gravel

Sand and gravel occur as small pockets in the Twin Cities Formation and in the deltaic deposits of the New Brighton Formation and the Turtle Lake Sand. The locations and descriptions of known deposits are given in Stone (1966). Large amounts of fine to medium sand are available from the Fridley Formation, the New Brighton Formation, and the Turtle Lake Sand. The only commercial sand and gravel operation presently in the quadrangle is in the Arsenal Sand (Marshall, 1963, pp. 36–42). Several million cubic yards remain in this deposit. An abandoned sand and gravel pit in the southeastern part of the map area is in the Hillside Sand. The best potential source of sand and gravel in the map area is the Hillside Sand, which is sufficiently near the surface in many parts of the area to be mined after stripping the overlying Twin Cities Formation (see Pl. 3). All active and abandoned gravel pits and borrow pits are shown on Plate 1.

Marl

Only two occurrences of marl are reported in the quadrangle (Stauffer and Thiel, 1933), but it may be more widespread. The eastern and southern parts of Pike Lake, in Secs. 19 and 20, T.30N., R.23W., are underlain by marl. The partially drained marsh at the southern end of the lake is underlain by four to eight feet of marl containing 35 per cent soluble carbonate. In Sec. 18, T.30N., R.23W., at the northwestern end of Long Lake, about two feet of marl that contains approximately 50 per cent soluble carbonate grades into clay at depth.

Peat

Most of the swamp deposits mapped on Plate 1 are peat. A detailed exploration of each deposit would be necessary to determine the thicknesses and types of peat in the various deposits. Some lakes contain deposits of transported peat, which has no surface expression.

Land-Use Planning

The information in this report can be useful for both local and regional planning. It can assist in planning transportation routes, in establishing zoning with respect to foundation conditions and sand and gravel resources, and in assuring sites for future artificial recharge of ground water.

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