THE GEOLOGY AND UNDERGROUND WATERS OF NORTHEASTERN MINNESOTA

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THE GEOLOGY AND UNDERGROUND WATERS OF NORTHEASTERN MINNESOTA

BY

GEORGE A. THIEL

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FOREWORD

In 1924 the Minnesota Geological Survey began the task of compiling up-to-date information on the underground waters of Minnesota. Dr. Ira S. Allison carried on much of the work for the northwestern portion of the state and prepared Bulletin 22, *The Geology and Water Resources of Northwestern Minnesota,* which was published in 1932. Shortly thereafter, Professor Thiel began the revision of the data for the southern half of Minnesota which had originally been discussed in the United States Geological Survey Water-Supply Paper 256 by C. W. Hall, O. E. Meinzer, and M. L. Fuller. Dr. Thiel's revision appeared as Minnesota Geological Survey Bulletin 31 in 1944.

The present bulletin completes the series on the underground waters of Minnesota and makes available in published form data on the underground water resources of every county in the state. These bulletins cannot be considered final because water will continue to be developed as long as people inhabit the state. The Minnesota Geological Survey will therefore welcome cooperation in keeping up its file of data on underground waters and will be pleased to answer inquiries not covered by the published material.

The state owes a debt to Professor Thiel for the very large amount of painstaking work which has gone into Bulletins 31 and 32. The three bulletins are available from the University of Minnesota Press at a moderate price.

Attention should also be called to the fact that all legal matters regarding underground, as well as surface waters, are by act of the legislature placed under the jurisdiction of the Department of Conservation.

G. M. Schwartz

ACKNOWLEDGMENTS

The author gratefully acknowledges his obligations to the scores of well drillers and engineers who cooperated wholeheartedly in furnishing logs of wells and drill cuttings for purposes of correlation. He is deeply indebted to N. H. Winchell and his assistants who did the pioneer work on the geology of northeastern Minnesota.

The author gladly expresses his gratification to Dr. H. A. Whittaker and O. E. Brownell of the State Board of Health and their field representatives who supplied numerous logs of municipal wells and placed at the author's disposal hundreds of analyses of surface and underground waters. Many of these analyses are included in the individual county reports.

The geologic maps of the counties covered by this report were made from the formational boundaries shown on the geologic map of the state published by the Minnesota Geological Survey in 1932. A few minor revisions were made by the author. Most of the data on the stratigraphy of the St. Croix valley was taken from Bulletin 29 of the Minnesota Geological Survey, which was assembled mainly by C. R. Stauffer. The author is especially indebted to Dr. Stauffer for the privilege of reproducing numerous measured sections of the stratigraphic succession in the east-central counties of the state.

Most of the events of the Pleistocene and the geographic distribution of various types of glacial drift are taken from the reports by Frank Leverett and F. W. Sardeson. The physiography and drainage changes in east-central Minnesota during late Wisconsin and postglacial time is taken for the most part from the work of W. S. Cooper as published in Bulletin 26 of the Minnesota Geological Survey.

Grateful acknowledgment is due also to the State Department of Conservation, especially to Walter Olson of the Division of Water and Drainage for the assistance his division offered in collecting data on the dewatering of mines on the Vermilion and Mesabi iron ranges.

Finally, special thanks are extended to G. M. Schwartz, director of the Minnesota Geological Survey, for his kindness in criticizing the whole manuscript.

G. A. T.

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INTRODUCTION

The purpose of the present investigation was to bring up to date the data on the subsurface geological structure and underground waters of northeastern Minnesota (Figure 1). The latest previous work on ground water in this area was done in 1896 and 1898 by the Minnesota Geological and Natural History Survey under the direction of N. H. Winchell. The results of that investigation were published in volume 4 of the Final Report of that survey, which was submitted January 1, 1899, and published under the direction of the Board of Regents of the university.

Since the report was published, nearly a half century ago, there has been marked development in agriculture and great progress in industry, each with an accompanying increase in the public and private demand for water. Requests for information come from municipalities, from industries, and from private individuals. To meet this demand the Minnesota Geological Survey decided to restudy the area in order to give greater practical service to the citizens of the state.

The assembling and correlating of data now available from outcrops and well records makes it possible not only to evaluate the hydrologic properties of the various rock formations, but also to estimate the capacities of underground reservoirs and to predict the rates of movement of confined water in the natural underground conduits. Furthermore, in communities for which the data at hand are not sufficient to warrant a definite assertion, a statement of the probabilities will serve better than nothing as a basis for prospecting for underground water. Proceeding in a haphazard manner commonly results in the careless expenditure of public and private funds.

The composition of any water determines to a great extent its value for domestic and industrial uses. Consequently the quality of the water from the various geological horizons and from the different kinds of glacial drift is considered and compared. Nearly all the analyses were made by the laboratory of the State Board of Health.

The North Shore of Lake Superior has become famous as a summer resort region. The recent development along this shore from Duluth to Grand Portage consists of taverns, groups of cabins, and resort hotels. It is estimated that there are approximately 150 such resorts near Lake Superior. The problem of supplying water for this tourist industry is an exceedingly difficult one. The difficulty is due to the fact that the area is underlaid by lava rocks that are quite impervious to ground water. For this reason considerable lake water is used for domestic purposes. However, in some localities the lake water is polluted with sewage to such an extent that the use of untreated lake water has become a health hazard. One of the purposes of this investigation was

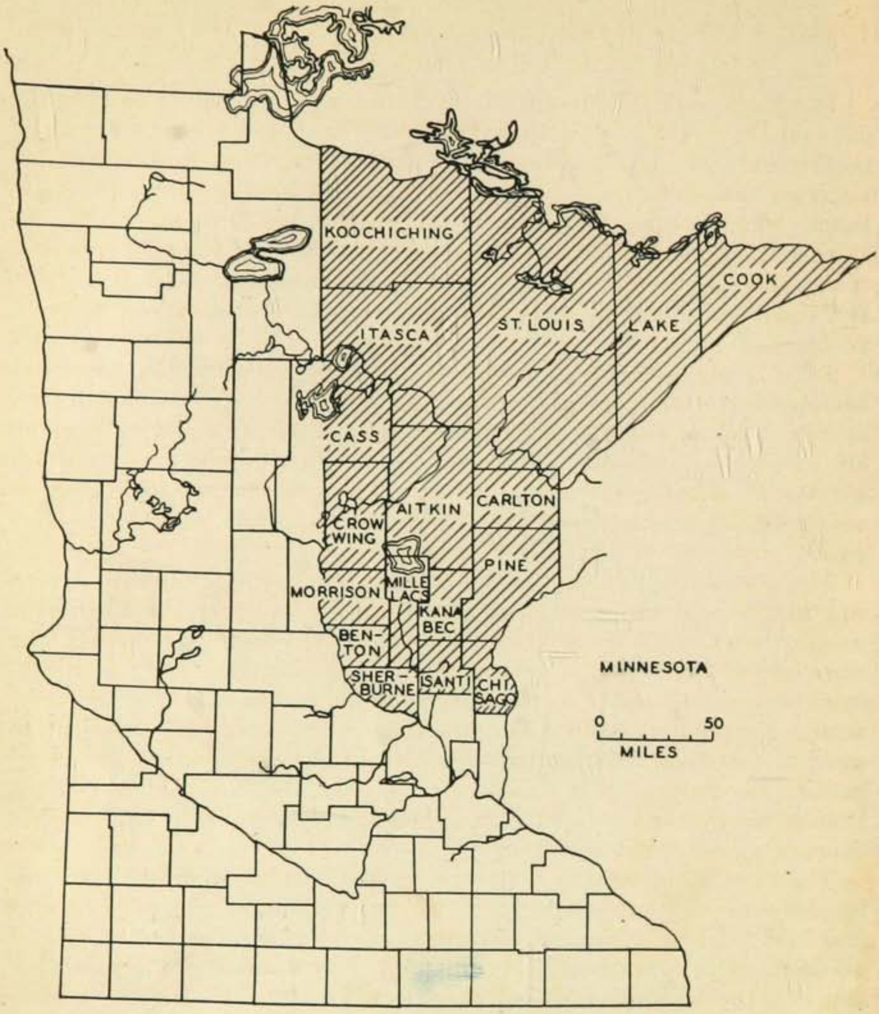

FIGURE 1. — Outline map of Minnesota, showing the area treated in this bulletin.

to determine the types of water supplies now being used and to find and recommend sources of water other than Lake Superior.

The relation between the character of the water supply of a community and its health is now well established. With the proper sanitary control of water supplies through supervision of well construction and by bacteriological examination of water, sanitation has been greatly improved and the incidence of illness from gastrointestinal disease has been lowered. Health officers and geologists have cooperated on numerous water supply problems.

I. THE PHYSIOGRAPHY, STRATIGRAPHY, AND STRUCTURE OF NORTHEASTERN MINNESOTA

PHYSIOGRAPHY

Most of the area of Minnesota under consideration in this report occupies the southwestern part of the Laurentian Upland, one of the major physiographic divisions of the North American continent, the boundaries of which coincide roughly with the Canadian Shield. This province is commonly restricted to pre-Cambrian rocks and its boundaries are drawn accordingly. The counties in east-central Minnesota, however, belong to the province that is commonly referred to as the Central Lowlands. There is no sharp topographic boundary separating these two regions (Figure 2).

The Lake Superior region includes three topographic provinces: (1) the highlands of St. Louis, Cook, and Lake counties, which form a peneplain with hilly upland and lowland subdivisions; (2) a lowland plain surrounding the peneplain on the south and west; and (3) the deep basin of Lake Superior. The highland region may be further subdivided into (1) highlands underlain by massive crystalline rocks, such as granite and gabbro, and (2) those underlain by sedimentary and metamorphic rocks which occur as alternating weak and resistant zones that have been exposed by the erosion of folded and tilted strata. The regions of more uniform igneous rocks have high plain areas of slight relief with a few widely separated monadrocks, whereas the regions with belts of sediments have narrow plateaus, monoclinal ridges, and isolated mesas in the intermediate lowland areas.

The general level of the peneplain lies between 1000 and 1700 feet above sea level. It is somewhat lower locally and at a few points it rises in monadrocks to heights a little above 2200 feet. The maximum relief of the peneplain (excluding the floor of the basin of Lake Superior) is less than 1400 feet.

From Duluth northward and curving somewhat to the northeast is a zone 12 to 25 miles wide which is underlaid by a great homogeneous intrusive mass called the Duluth gabbro. Over this area the peneplained surface stands a little higher than over the sediments and slates farther to the west. Toward its northeast end, near the Pigeon River, the topography over the gabbro shows the same parallelism as that which characterizes the region of Gunflint Lake.

The Gunflint district shows a most striking development of east-west monoclinal ridges and valleys, the latter occupied by long narrow lakes. The courses of the valleys are largely determined by the subsurface structure, which is a series of alternating slates and intruded sills, all dipping gently to the south. A broad view of this district from the high peaks or in the transverse valleys shows gentle dip slopes to the south

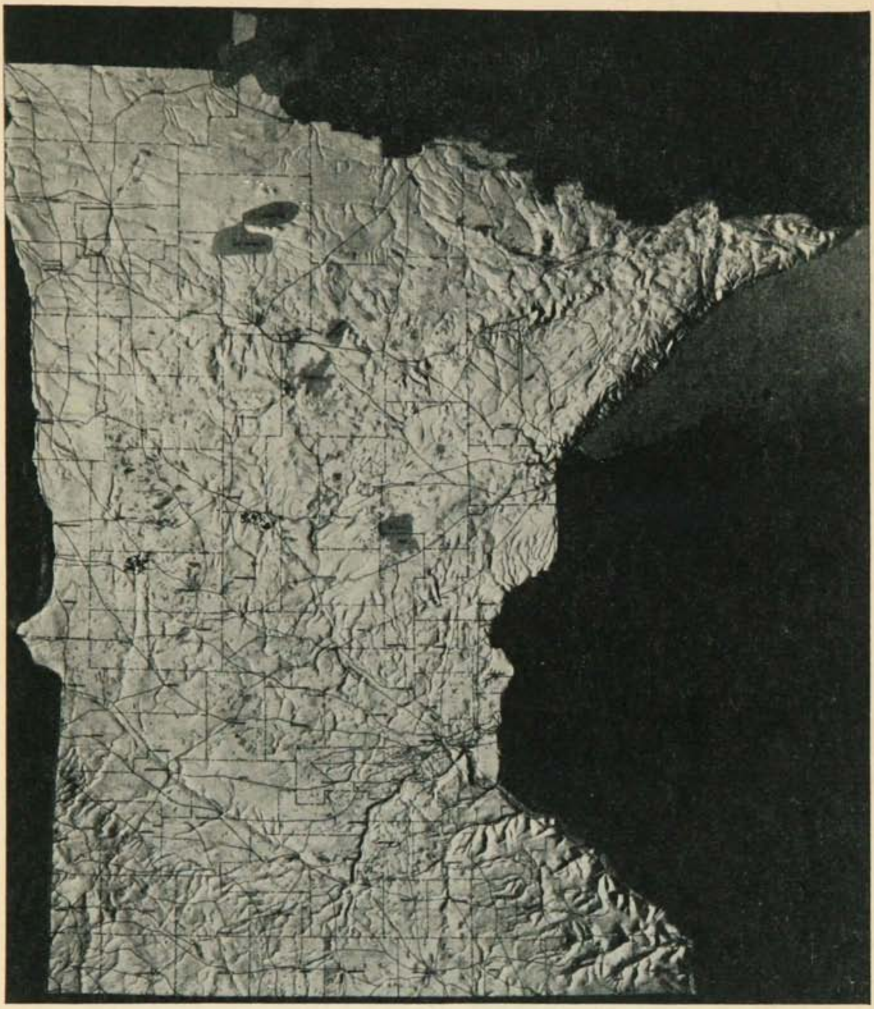

FIGURE 2. — Photograph of relief model of Minnesota. (Courtesy Department of Geography, University of Minnesota.)

and steep cliffs or talus slopes facing north. The general impression is that of a series of saw-tooth mountains.

South of the Gunflint, between it and Lake Superior, are the Misquah Hills, which reach an elevation of 2230 feet above sea level. These are the highest points in the state. Some distance south of the hills is a zone 10 to 15 miles wide that parallels the shore of Lake Superior and is characterized by monoclinal ridges with their dip slopes toward the lake. These ridges are the outcropping edges of the Keweenawan trap flows that merge with the gabbro plateau to the west. To the east this district breaks off abruptly to the basin of Lake Superior along the pronounced Duluth escarpment, which is from 400 to 800 feet high.

West of the gabbro plateau is an area of 10,000 square miles called the St. Louis Plain, a poorly drained upland 1300 to 1400 feet above sea level. It is an area of moderate relief, underlain by thick homogeneous slates. The western part of the plain is so deeply covered by glacial drift that the bedrock surface is scarcely a factor in the topography. This peneplained area extends from the gabbro plateau northwestward to the Giants (Mesabi) Range.

Southwestward from Lake Superior is a lowland zone less than 20 miles wide which is bordered on the north by an extension of the Duluth escarpment and on the south by a westward extension of the Douglas Range of northern Wisconsin. This area is a downfaulted block of Keweenawan sandstone (Figure 33), covered by a thick mantle of glacial drift and glacial lake sediments. The flatness of this plain is due to wave erosion and lacustrine deposition on the floor of glacial Lake Duluth. Streams now crossing the plain from the adjacent uplands have cut young, deep valleys almost to the level of Lake Superior.

To the north of the St. Louis Plain is the Mesabi or Giants Range, which is a more or less continuous ridge nearly 100 miles long and varying in altitude from 50 to 500 feet above the general level of the Laurentian peneplain. It extends from the region a few miles north of Grand Rapids northeastward to beyond Birch Lake in eastern St. Louis County. The range is crossed by several wind gaps and water gaps, such as the one occupied by Wine Lake and the Embarrass River. This valley appears to have been superimposed on the rocks of the range and suggests the former presence of younger sedimentary strata over the granites and greenstones which occur along the axis of the present topographic ridge. The valley has been cut into the granite to a depth of approximately 300 feet. A similar gap occurs north of the village of Mesaba and still another is occupied by the Dunka River, which flows northward into Birch Lake at the east end of the range.

The area north of the Giants Range is at the general level of the Laurentian peneplain, with uplands on massive Algoman granites and lowlands over zones of slates and schists. The lowlands start 150 to 200 feet below the hilltops and many of the low areas are occupied by lakes. This type of topography continues northward to Rainy Lake and the Rainy River on the international boundary.

The area to the west and south of the west end of the Giants Range is partly in the Mississippi River drainage basin. It is covered with a thick mantle of glacial drift and consequently the present topography is a product of morainic deposition. The northern part of this region is a lacustrine plain that represents the eastern part of the floor of glacial Lake Agassiz. The drift area to the south is moderately undulating, with some areas which are knolly or hilly, and others which are nearly level. Many of the larger low areas are occupied by lakes such as Leech Lake and Lake Winnibigoshish.

Most of the area south and east of the city of Princeton in Mille Lacs County is part of the Anoka sand plain.[1] This is a region of flat or gently undulating topography which stands about 100 feet above the Mississippi River, or a little over 900 feet above sea level. It was formed by outwash sediments reworked by waters from the east margin of the glacier where the waters were deflected by the Grantsburg sublobe. Locally wind action has superimposed dune topography on the plain. The area has many broad, shallow basins occupied by bogs, swamps, and lakes.

STRATIGRAPHIC RELATIONS

The following column of stratigraphic succession is based on the classification now commonly used in Minnesota.

Geologic Column of Minnesota

- Cenozoic (Quaternary)
  - Pleistocene
    - Eldoran
      - Recent (marl, peat, alluvium)
      - Wisconsin drift
    - Centralian
      - Sangamon (loess deposits and soil)
      - Illinoian drift
    - Ottumwan
      - Yarmouth (interglacial forest beds)
      - Kansan drift
    - Grandian
      - Aftonian (old soils and erosion)
      - Nebraskan drift
- Mesozoic
  - Cretaceous
    - Colorado series
      - Coleraine (Benton) formation
    - Dakota series
      - Dakota formation
        - Ostrander member
- Paleozoic
  - Devonian
    - Senecan series
      - Cedar Valley limestone
  - Ordovician
    - Cincinnatian series
      - Maquoketa formation
        - Wykoff member
        - Dubuque member

[1] Cooper, W. S., The history of the Upper Mississippi River in late Wisconsin and postglacial time: Minn. Geol. Survey Bull. 26, pp. 39–58, 1935.

GEOLOGIC COLUMN OF MINNESOTA — *Continued*

- Mohawkian series
  - Galena formation
    - Stewartville member
    - Prosser member
    - Decorah shale member
      - Ion submember
      - Guttenberg submember
  - Platteville formation
    - Spechts Ferry member
    - McGregor member
    - Glenwood member
- Chazyan series
  - St. Peter sandstone
- Beekmantownian series
  - Shakopee dolomite
  - Root Valley sandstone
  - Oneota dolomite
  - Blue Earth siltstone
  - Kasota sandstone

Cambrian
- St. Croixian series
  - Jordan sandstone
    - Van Oser member
    - Norwalk member
  - St. Lawrence formation
    - Lodi member
    - Nicollet Creek member
  - Franconia formation
    - Bad Axe member
    - Hudson member
    - Taylors Falls member
    - Ironton member
  - Dresbach formation
    - Galesville member
    - Eau Claire member
    - Mt. Simon member

Proterozoic
- Keweenawan
  - Upper Keweenawan
    - Lake Superior series
      - Hinckley sandstone (Devils Island)
      - Fond du Lac beds (Orienta)
  - Middle Keweenawan
    - Keweenaw Point volcanics, Duluth gabbro, Beaver Bay complex, Logan sills, and some Central Minnesota granites
  - Lower Keweenawan
    - Puckwunge formation, consisting of sandstones and conglomerates
- Huronian (see U.S. Geological Survey Professional Paper 184)
  - Virginia and Rove slates
  - Biwabik and Gunflint formations
  - Pokegama and Sioux quartzites
- Algoman
  - Giants Range, Vermilion, McGrath, Warman Creek, St. Cloud, and other granites

GEOLOGIC COLUMN OF MINNESOTA — *Continued*

Temiskaming (sometimes called Lower Huronian)
  Knife Lake slates, including Agawa formation, Ogishke conglomerates, and other sediments
Archeozoic
  Laurentian
    Saganaga and other granites
  Keewatin
    Soudan iron formation
    Ely greenstone

ARCHEOZOIC ERA

The term Archeozoic is taken from the Greek words for "ancient" or "primitive" and "life." It was introduced because the rocks that had been supposed to have no signs of life were found to afford evidence of the existence of simple forms of life. The oldest known rocks are commonly referred to the Archeozoic era. In Minnesota the Archeozoic includes the Keewatin and Laurentian systems.

KEEWATIN SYSTEM

The Keewatin was named by Lawson from exposures on Lake of the Woods on the Canadian side of the boundary.[2] However, the rocks extend into Minnesota and the same name is applied here. In this state the Keewatin rocks are divided into the Ely greenstone and the Soudan iron-bearing series (Figure 3).

Ely Greenstone.—The type exposures of the greenstone occur in and near the city of Ely and in the shafts of the iron mines, where a considerable thickness of the formation has been penetrated.

Lithologically the greenstone is composed mainly of basaltic rocks which vary in texture and mineral composition. Some of the rocks are products of lava flows, others are intrusives, and still others are fragmental products of volcanism. The chief varieties are ellipsoidal, schistose, diabasic, siliceous, and tuffaceous. Oval or ellipsoidal structures can be found in most large exposures and these are the safest criterion for the recognition of the greenstone and the establishment of its age relations.

The greenstone rocks are exposed at intervals in a zone 5 to 25 miles wide from Basswood Lake southwestward in Itasca County. The details of their geographic extent in western St. Louis and Itasca counties are unknown because of the thick mantle of glacial drift in those regions. The most important outlying area of greenstone which has been correlated with the Ely greenstone is found in the so-called Virginia Horn of the Mesabi Range. This area extends from about 2 miles east of Virginia to Wine Lake, a distance of 11 miles. Another small area occurs to the south between Eveleth and Gilbert, and still smaller areas may be seen north of Mountain Iron, north of Hibbing, and north of Nashwauk.

The Ely greenstone has usually been considered to be the base of the

[2] Lawson, A. C., The geology of Lake of the Woods: Canadian Geol. and Nat. Hist. Survey, Ann. Rept., vol. 1, No. cc, pp. 10–15, 1885.

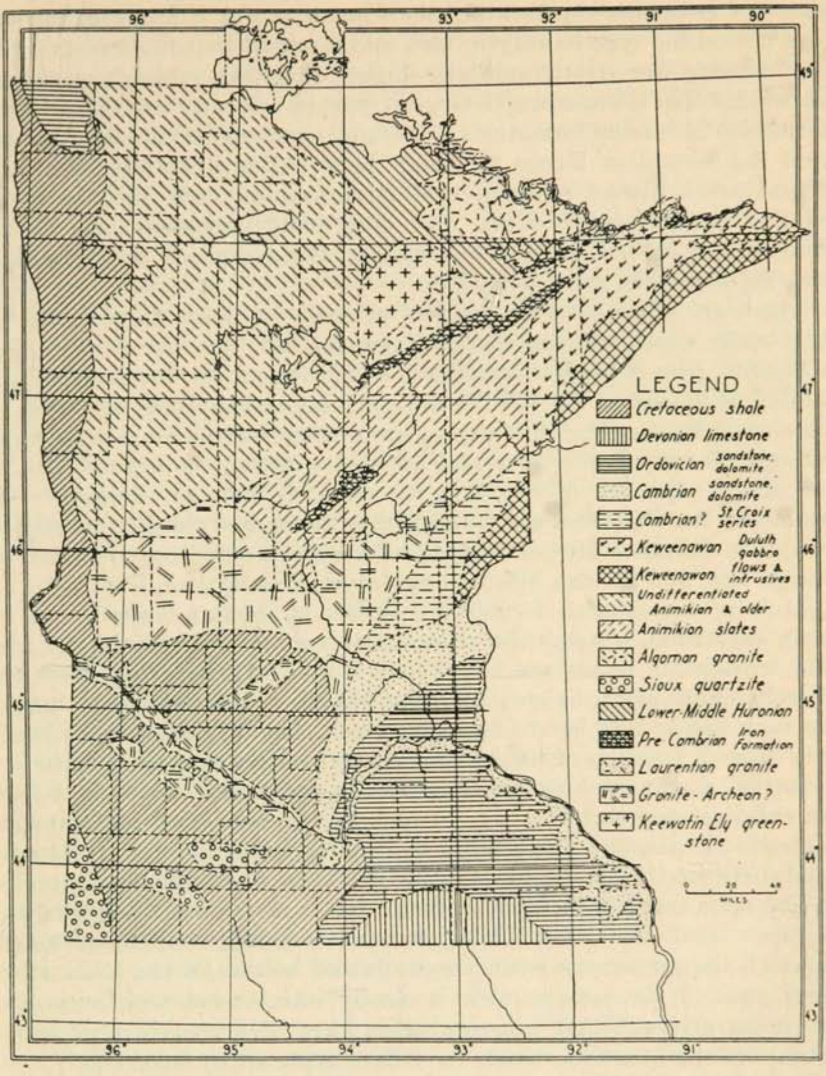

FIGURE 3. — Geologic map of Minnesota. (After Schwartz, Bulletin 19, Minnesota Geological Survey.) What is here called Lower-Middle Huronian is better known as the Knife Lake series.

Archeozoic. However, there is the possibility of an older formation below the Ely in adjacent areas in Canada. This formation is called the Coutchiching and was named and described by Lawson in 1887, on the basis of exposures largely on the Minnesota shores of Rainy Lake.[3] A com-

[3] Lawson, A. C., Geology of the Rainy Lake region: Am. Jour. Sci., 3rd ser., vol. 33, pp. 473–480, 1887.

mittee of geologists representing the Canadian and U.S. geological surveys visited the type locality in 1905 and reported that the schists called Coutchiching are stratigraphically higher than the schists mapped as Keewatin.[4] The Minnesota Geological Survey encountered the problem in 1922–25 in tracing formations across and around the Vermilion granite from the Vermilion Range to Rainy Lake. After a restudy of several critical areas, Grout reported that structural methods such as cross-bedding, gradational bedding, and drag folds indicated that all the Minnesota localities gave evidence that the sediments were younger than the Keewatin greenstones.[5]

There are other outlying areas of greenish intrusive diorites and related rocks which are classified as Keewatin, but their age is uncertain.

Soudan Iron-Bearing Formation.—This formation was named from Soudan Hill located on the Vermilion Range about one mile east of the city of Tower. The chief exposures of these iron-bearing rocks occur between Tower on the west and an area a few miles beyond Ely on the east, a distance of less than 30 miles. A number of smaller exposures of the formation are found within the area of the Ely greenstone for 12 or 15 miles farther east. The most accessible outcrops are on Tower, Lee, and Soudan hills and on Jasper Peak east of Tower.

Most of the Soudan formation consists of interlaminated bands of finely crystalline quartz, iron oxides, and various mixtures of the two. The ferruginous bands are bright red to brown in color, whereas the siliceous bands are light gray to white. Where iron oxides are abundant, the dark bands may be steel gray to black. The individual color bands vary from a fraction of an inch to several inches across and give the formation a very striking appearance. The red phases of the formation are called jasper and the banded rock of the formation is commonly referred to as jaspilite. In certain localities the formation has argillaceous bands between the bands of iron oxides and these are commonly graphitic.

The main mass of the Soudan formation is above the Ely greenstone and as a result of intense folding, it is often found in pitching troughs in which the greenstone forms the walls and bottom of the folds. However, some of the jaspery rock is clearly interbedded with successive basalt extrusives. Where iron-ore bodies have been concentrated in the formation, the quartzose bands have been replaced by hematite.

Laurentian System

The term Laurentian has been used since 1854 when it was applied to granite and other old rock north of the St. Lawrence River in Canada. The term is now limited to the oldest granites and does not include those that cut post-Keewatin sediments. The major mass of definitely

[4] Hayes, C. W., *et al.*, Report of the Special Committee for the Lake Superior region: Jour. Geol., vol. 13, pp. 95, 103, 1905.

[5] Grout, F. F., Coutchiching problem: Geol. Soc. Am. Bull., vol. 36, pp. 351–364, 1925.

Laurentian granite in northern Minnesota is the Saganaga granite. Its structure and field relations have been studied in detail by Grout.[6] A very striking petrographic feature is the occurrence of quartz in patches up to half an inch across. The Saganaga is the only granite in Minnesota with this peculiarity and it serves to identify the granite mass as a unit some 15 by 25 miles across.

The granite occurs mainly in the northwestern townships of Cook County in the region of Saganaga and Sea Gull lakes. In this region erosion by weather and by glaciation left the greenstone standing higher than granite in many of the surrounding hills. Thus the granite area is topographically lower than the greenstone and gabbro areas to the south.

The intrusive relation of Saganaga granite to greenstone is well shown in the west half of the granite area. Granite dikes cut the greenstone from the northwest part of Cache Bay to the end of the northeast arm of Saganaga Lake, and fragments of greenstone, as inclusions, a few inches to a few feet across, are widely scattered in the granite. Locally inclusions are clustered into swarms of spindle-like fragments. Several other granite masses in Minnesota may be of Laurentian age, but none are in contacts with sediments which prove their age.

PROTEROZOIC

An exceedingly long erosion interval followed the intrusion of the Laurentian granite. The magnitude of this interval is indicated by the unconformable relation of the Proterozoic sediments on the Saganaga granite. The interval was long enough to wear off an unknown but probably great thickness of greenstone and interbedded Soudan iron formation that originally were the roof of the granite batholith. It is believed that from 5000 to 10,000 feet were removed by erosion.

Knife Lake Series

The oldest Proterozoic rocks are represented by a thick series of sediments of various types known as the Knife Lake series. This name is taken from Knife Lake on the international border, where the slates and associated conglomerates and cherts are exposed over wide areas. These rocks occur in a zone 10 to 15 miles wide and 70 miles long, extending from Saganaga Lake southwestward to beyond Lake Vermilion. Scattered exposures are known far west and southwest into Koochiching County. The Saganaga granite is its eastern border and the Duluth gabbro and the Giants Range granite, both intrusive into the Knife Lake series, form the southern borders. The northern and western limits of the area are indefinite; intrusive granites have altered the rocks to such an extent that their identity becomes uncertain.

Other large areas that may be underlain by rocks of the same age

[6] Grout, F. F., Structural features of the Saganaga granite of Minnesota-Ontario: Rept. of 16th Internat. Geol. Congress, Washington, 1933, pp. 255–270, 1936.

as the Knife Lake series include the Rainy Lake region and the area of the Thomson formation near Cloquet and Carlton. The age relation of the Thomson formation is discussed in the report on Carlton County.

The Knife Lake sediments are highly folded and faulted. The folding is close and the limbs of the folds are usually nearly vertical. Most of the faulting is parallel to the regional cleavage and schistosity. The faults, many of which show displacements totaling several miles, cut the region into a number of segments each of which has its own structural peculiarities. Because of the structural complexity, it is difficult to estimate the thickness of the Knife Lake series but they are undoubtedly more than 10,000 feet thick.[7]

Algoman Intrusives

The name Algoman was first applied to rocks in the western Ontario district of Algoma, where granites were found cutting the sediments that are now correlated with the Knife Lake series. In northern Minnesota the granite which most clearly cuts the Knife Lake slates and yet is older than the next recognized sediments in that area is the Giants Range granite. Many other masses are undoubtedly of the same age but are not exposed in contact with both the older and younger sedimentary series. Of these the Vermilion granite batholith of northern St. Louis County has the most exposures. Recent petrographic studies indicate that many of the granites in Aitkin, Morrison, Benton, Mille Lacs, and Stearns counties are of the same age.

The Giants Range granite is a batholith about 100 miles long and as much as 15 miles wide. The mass is topographically prominent, rising from a flat, drift-covered area in Itasca County to a prominent ridge as high as 400 feet above its surroundings north of the productive part of the Mesabi Iron Range. Farther northeastward, in the region east of White Iron Lake, many granite areas are exposed but are not as prominent in the topography.

North of the Giants Range and beyond a narrow belt of slates and schists lies the Vermilion granite batholith, which occupies an area some 30 by 80 miles. Its south margin lies a few miles north of Vermilion Lake and it extends from there northward to beyond the international boundary. This mass of granite is nowhere in contact with Animikie sediments to prove that it is older than the Upper Huronian series, but petrographic evidence indicates that it is pre-Keweenawan and consequently the granite is generally accepted as Algoman in age.

Animikie Group

The Animikie is represented by a group of sedimentary rocks which occupy the southern slopes of the Giants Range and extend an unknown

[7] Gruner, J. W., Structural geology of the Knife Lake area of northern Minnesota: Geol Soc. Am. Bull., vol. 52, pp. 1576–1642, 1941.

distance southward beneath the glacial drift. The area of outcrop along their northern boundary varies from less than 1 mile to 5 miles or more. On the Mesabi Range the beds dip at a low angle toward the southeast. Their upper edges are truncated by erosion and consequently they appear at the surface in narrow belts which parallel the range. The most northerly belt represents the lower or older beds and the southerly belts, the higher or younger strata of the series. Rocks of the same age may occur in the Cuyuna Range in central Minnesota. However, since there are no outcrops in the area between the two ranges, the relative age of the two iron-bearing formations has not been definitely established.

The Animikie sediments lie on the truncated edges of the Knife Lake slates, on the exposed Algoman granites of the Giants Range, and on the Keewatin greenstones. These age relationships indicate an exceedingly long post-Algoman erosion interval before the deposition of the overlying strata.

From the base upward the Animikie comprises (1) the Pokegama quartzite, consisting mainly of quartzite but containing a conglomerate at its base; (2) the Biwabik formation, consisting of ferruginous cherts, iron ores, slates, and siliceous carbonate rocks; and (3) the Virginia slate. The lithological characters of these rocks are described in the report on St. Louis County.

Keweenawan

LOWER KEWEENAWAN

The Lower Keweenawan rocks are coarse, clastic sediments represented by the Puckwunge formation. This term was first applied to a series of exposures in the valley of Puckwunge Creek (now called Stump River) in eastern Cook County. Exposures of this formation in Minnesota are limited to two general areas. The most accessible exposures are in the region just west of Duluth, from the valley of the St. Louis River northward about 45 miles to Sec. 17, T. 49 N., R. 15 W. The other area lies 140 miles north of Duluth, where outcrops of sandstone and some conglomerate extend from Sec. 22, T. 64 N., R. 3 E., eastward in a narrow belt to Grand Portage Bay and the islands off Pigeon Point. The exposure farthest east is on Lucille Island south of Pigeon Point.

At the type locality the sandstone is nearly white, uniform in texture, and only moderately cemented. It is overlaid by a massive basalt flow which silicified the sandstone for a few inches below the flow and gave it a quartzitic texture. In the Duluth area the largest exposures of the Puckwunge occur along a west-facing bluff in Secs. 17 and 21, T. 49 N., R. 15 W. Here the main portion of the sandstone resembles that in the Grand Portage region. The formation probably does not exceed 200 feet in thickness and at places is much less. Several sections giving the details of the lithology are included in the report on Cook County.

MIDDLE KEWEENAWAN

The Middle Keweenawan is predominantly basic igneous rocks which occur as flows and intrusive masses. They occupy the southeastern part of St. Louis County and most of Lake and Cook counties, and are composed for the most part of basalts, gabbro, and diabase. The basalts represent hundreds of lava flows that were poured out over a region of low relief. They have a total thickness of about 2500 feet. The gabbro was intruded as a giant sill, the floor of which settled and produced a huge saucer-shaped lopolith. The northwestern rim crosses eastern St. Louis County and northern Lake County, and the southern rim is in northern Wisconsin and upper Michigan. This foundering of the floor of the lopolith tilted the surface rocks in the whole area from Lake Superior northward to the Mesabi Range, and consequently the flows now dip from 5° to 15° toward the southeast.

The gabbro lopolith was intruded after an unknown thickness of flows had accumulated. The magma spread along or near the unconformity between the Keweenawan and the older rocks. It is impossible to determine how many flows had been extruded before the advent of the gabbro, but since it is a coarse-grained rock, it does not seem likely that its intrusion could have occurred at a depth of less than several thousand feet. The thickness of the gabbro is estimated at 1400 feet.

In the region east of the gabbro, a number of thin beds of conglomerate and sandstone occur between flows, indicating a period of erosion between some of the flows. There is one interflow sedimentary bed for about every ten flows and most of the sediments are less than 10 feet thick. They consist for the most part of fine-grained sandstones that are buff to pinkish in color and some show cross-bedding similar to that seen in sand dunes. One sandstone bed 114 feet thick occurs in Leif Ericson Park, Duluth. It is cut by a basaltic dike and ends at a fault of unknown displacement. Several thin beds of conglomerate occur between flows or at the base of sandstones. The conglomerate pebbles are composed of dense basalt and many of the larger boulders are amygdaloidal.

Numerous dikes and sills of a medium-textured, dark-colored rock called diabase are seen cutting the flows, the gabbro, and the sediments. The sills range in thickness from 30 to nearly 1600 feet and have a total thickness of about 5000 feet. Most of the dikes are from 1 to 10 feet thick. Many dikes along the shore of Lake Superior have been made conspicuous by differential erosion. Because of their greater resistance to erosion, they form headlands that extend out for some distance from shore.

Practically all the lava flows are highly vesicular in their upper portions. The vesicles are now filled with secondary amygdular minerals, such as calcite, quartz, agate, and various types of zeolites. Many of the latter have been weathered out and occur as pebbles in the beach gravels.[8]

In central Minnesota the red and pink granites in Benton and Sherburne counties are lithologically similar to the red granite which crops out extensively in the region of St. Cloud and Rockville. These red granitic rocks are thought to be of Middle Keweenawan age. Isolated outcrops as far north as Freedhem in Morrison County and as far east as the Rum River valley in Mille Lacs County are undoubtedly related to the same intrusive mass. Skillman refers them to the Stearns magma series.[9]

UPPER KEWEENAWAN

The Upper Keweenawan is represented by the Fond du Lac beds and the Hinckley sandstone.

The Fond du Lac Beds.—The strata classified as the Fond du Lac beds are dark red to pink arenaceous shales and red to brown argillaceous to arkosic sandstones. These sediments, derived largely from pre-existing Keweenawan sediments and acidic igneous rocks, are named from a quarry at Fond du Lac. The rocks form conspicuous cliffs along the St. Louis River southwest of Duluth, and they crop out also in the banks of the Snake River north of Mora.

The Fond du Lac beds are composed of interbedded massive sandstones and thinly laminated shales. Some of the sandstone strata are slabby and thin-bedded, with seams of bluish-green and red shale. Pebble horizons are common and locally there are very minor amounts of clear, white sandstone. The massive sandstone strata vary from 1 to 8 feet in thickness and the shale facies are generally less than 5 feet thick. Locally, however, they are as much as 25 feet thick. The formation as a whole ranges from several hundred to more than 2000 feet in thickness.

The sandstones are conspicuously cross-bedded and some ripple marks are well preserved. The associated red and mottled shales have mudcrack patterns and a few indefinite trails that may or may not be of organic origin. The strata are only slightly disturbed from their original position and are scarcely affected by metamorphism. Some of the mica along the parting planes in the slabby sandstone may be a product of anamorphism. The beds dip from 3° to 10° toward the southeast.

The geographic extent of the formation is not definitely known. An outcrop has been reported as far north as Floodwood in St. Louis County, but this observation has not been verified. Southward from the outcrops

[8] For a detailed description of the lithology and structure of the Keweenawan igneous rocks of northeastern Minnesota, see Grout, F. F., Contribution to the petrography of the Keweenawan: Jour. Geol., vol. 18, pp. 633–657, 1910; Grout, F. F., The lopolith; an igneous form exemplified by the Duluth gabbro: Am. Jour. Sci., 4th ser., vol. 46, pp. 516–522, 1918; Sandberg, A. E., Section across Keweenawan lavas at Duluth, Minnesota: Geol. Soc. Am. Bull., vol. 49, pp. 795–830, 1938; Schwartz, G. M., A guidebook to Minnesota Trunk Highway No. 1: Minn. Geol. Survey Bull. 20, 1924.

[9] Skillman, Margaret, unpublished thesis, University of Minnesota, 1946.

on the St. Louis and Snake rivers, it has been penetrated by a number of deep wells which indicate that it is continuous in the pre-Cambrian trough that extends in a general north-south direction across east-central and southeastern Minnesota.

The following sections are typical.

Section along St. Louis River, Downstream from Powerhouse
(Measured by C. R. Stauffer)

	THICKNESS (feet)
5. Drift, red clay and stony gray	150
FOND DU LAC BEDS	
4. Sandstone, gray streaked with red, medium to coarse, arkosic, thin- to massive-bedded, ripple-marked	75
3. Shale, red to chocolate, often mottled or streaked with gray. Although argillaceous, it may be arenaceous, ripple-marked, and mud-cracked	25
2. Sandstone, red to gray, arkosic, fairly massive, although grading into thin-bedded, gray-spotted, cross-bedded, and micaceous	60
1. Shale, red to chocolate, sandy; shaly sandstone, grading into the sandstone above. The shales are gray-streaked and micaceous and extend to the level of the St. Louis River	75

Section Exposed just below Dam at Power Plant near Fond du Lac
(Measured by Clemens Nelson)

	THICKNESS (feet)
7. Fine-grained, cross-bedded, red sandstone. Some red and green shaly layers	3
6. Massive, red sandstone	3
5. Red and green shaly sandstone	4
4. Thin-bedded, fine-grained sandstone	5
3. Massive, fine-grained sandstone	8
2. Thin-bedded, red, fissile shale	13
1. Talus to river level	36

Section Exposed along Little Creek in Sec. 1, T. 48 N., R. 16 W.
(Measured by Clemens Nelson)

	THICKNESS (feet)
10. Fine-grained red sandstone	3
9. Fine- to medium-grained gray sandstone	2
8. Fine-grained red sandstone	3
7. Covered interval	9
6. Fine-grained red sandstone	13
5. Covered interval	25
4. Shaly red, micaceous sandstone	3
3. Shaly green and micaceous sandstone	2
2. Medium-grained, light-gray sandstone, few quartz pebbles (Puckwunge)	3
1. Quartz-pebble conglomerate (Puckwunge)	5

Hinckley Sandstone.—The Hinckley sandstone was described by Winchell in his annual report for the year 1882, but the name was not proposed until the final report was published in 1888.[10] The type section

[10] Winchell, N. H., Minn. Geol. and Nat. Hist. Survey, 11th Ann. Rept., pp. 125–128, 1882; The geology of Minnesota: Final Rept., Minn. Geol. and Nat. Hist. Survey, vol. 2, pp. xxii, 55, 286, 1888.

of the formation at Hinckley exposed a ledge about 9 feet high which extended for 250 feet or more along the east side of the Northern Pacific Railway just north of the Grindstone River. The sandstone is coarse to fine, usually medium-grained, yellowish to salmon-pink and red or nearly white. The color is due to varying amounts of iron, which may form part of the cementing material and which occurs as either limonite or hematite. At many places the rock is well indurated and hence suitable for building stone, curbing, paving blocks, and even crushed stone. The fact that the formation contains very little feldspar and very few accessory minerals suggests that it was derived from an older sandstone that had previously passed through several cycles of sedimentation.

The Hinckley sandstone crops out almost continuously for a distance of nearly 20 miles along the Kettle River in the southwestern part of Pine County. In the region of Sandstone it forms castellated bluffs as much as 50 to 100 feet in height above the valley. Some of the tributaries of the Kettle River have cascades or waterfalls which at places tumble 50 feet or more over the resistant beds of the sandstone. Beyond the major valleys the rock passes beneath the glacial drift which is not cut through by the smaller streams.

In the quarry wall at Sandstone, where a section of approximately 100 feet of the Hinckley formation is exposed, the strata vary from a few inches to several feet in thickness, although several more massive beds may be observed. The lower half of this section contains thin beds of shale, some of which have been broken and recemented to form intraformational conglomerates. In the old quarry at Hinckley the beds are approximately horizontal, but farther toward the northeast the strata dip from 3° to 5° toward the southeast. Cross-bedding is common but not conspicuous. In the vicinity of the upper falls to the north of Sandstone, the cross-bedding is inclined southward at angles varying from 10° to 35°.

In Pine County the Hinckley sandstone is more than 500 feet thick. The quarry at Sandstone and the cliffs along the river near the quarry expose about 100 feet, and the well at the federal prison south of the city penetrates 465 feet of sandstone which must be assigned to this formation. However, the Hinckley becomes progressively thinner southward from its type locality, averaging only about 150 feet in thickness in the region of Minneapolis and St. Paul.

South of the outcrops in Pine and Kanabec counties, the Hinckley formation passes beneath the Cambrian sandstones of the St. Croixian series. Cambrian strata are encountered above the Hinckley in the wells of southern Chisago County, and the deep wells as far south as Faribault, Mankato, and Rochester encounter a sandstone similar to or identical with the Hinckley, which occurs between the red Fond du Lac beds and the lowest sandstone (Mt. Simon) of the St. Croixian series.

East of Rochester the Hinckley sandstone thins rapidly and pinches out against the westward-dipping surface of the pre-Cambrian granite, which occurs at a depth of approximately 500 feet at the city of Winona.

Good exposures of the Hinckley other than those near Hinckley and Sandstone may be observed along the Net River north of Holyoke, along the Willow River several miles east of the village of Willow River, and along the Kettle River near Rutledge. An excellent artificial exposure that is very accessible occurs along the highway cut west of Askov, where the road descends into the valley of the Kettle River.

Sections of Hinckley Sandstone in Quarries, West Bank of Kettle River, Sandstone
(Measured by S. Goldich)

	THICKNESS (feet)
11. Drift, thin cover, bedrock striated	0.7
HINCKLEY SANDSTONE	
10. Sandstone, very coarse, light yellow to buff and brown, cross-bedded, massive or thick beds	10.0
9. Sandstone, massive and coarse like that above, but with some fine-grained, thin beds. Good quarry stone	10.0
8. Sandstone, salmon-colored to brown, thin-bedded, ripple-marked, massive, coarse, and cross-bedded at the base	13.3
7. Sandstone, thin-bedded, hard, fine-grained, red to yellow	2.7
6. Sandstone, massive, medium-grained, pink to buff and red. Good quarry stone.	18.0
5. Sandstone, fine to coarse, pink to reddish. A 2-foot and a 4-foot bed.	6.0
4. Sandstone, massive, cross-bedded, light yellow to pink.	10.0
3. Sandstone, coarse-grained, well-cemented, pink.	15.0
2. Sandstone, massive to thin-bedded, ripple-marked, pink to buff.	8.0
1. Sandstone, partly covered to level of Kettle River	8.0
Total	101.7

The contact between the Hinckley sandstone and the Fond du Lac beds is not exposed; hence it is known only from well samples and well drillers' logs. Apparently the pink and red color of the Hinckley grades downward into the Fond du Lac red beds without very great or sudden change in megascopic character. The well at the federal prison near Sandstone illustrates this point. Here red sandstone with all the petrographic characteristics of typical Hinckley sandstone occurs at least 350 feet

Well at the Federal Prison, Drilled in 1938, 1050 Feet A.T.

	THICKNESS (feet)	DEPTH (feet)
7. Drift, sand, gravel, and boulders	25	25
HINCKLEY SANDSTONE		
6. Sandstone, yellow and pink	85	110
5. Sandstone, dark red	60	170
4. Sandstone, pink	130	300
3. Sandstone, red, soft	45	345
2. Sandstone, pink and yellow	75	420
1. Sandstone, bright red	45	465

above the base of the Hinckley. It is for this reason that the Hinckley sandstone has been designated occasionally as the uppermost member of the red clastic series.[11]

The top of the Hinckley sandstone is not known to be exposed in this area. In the region of outcrops along the St. Croix valley north and south of Taylors Falls, the basal members of the St. Croixian series, the Mt. Simon and the fossiliferous Eau Claire, rest unconformably on the lava flows of the Middle Keweenawan.

Drill cuttings from wells west of the St. Croix valley in Pine and Chisago counties indicate a similar relationship as far west as Rush City and Rock Creek. In southeastern Kanabec County and northern Isanti County, drilling indicates the presence of both the Eau Claire and the Mt. Simon members over the Hinckley sandstone. This same relationship exists in the area of the Twin Cities and from there southward at the base of the Paleozoic rocks of the southeastern part of the state.

PALEOZOIC ROCKS

East-central Minnesota contains a thick succession of Paleozoic formations comprising various beds of limestone, shale, and sandstones, all of which are of Cambrian or Ordovician age. Rocks of the Devonian period are limited to a few counties along the southern border of the state, and those of Silurian and Carboniferous ages are not known in Minnesota.

Cambrian System

The Cambrian system is represented in Minnesota by the St. Croixian series, which is of Upper Cambrian age. The formations constituting this series have much in common throughout. It is distinctly a sandstone series, with a certain percentage of dolomite prevailing in the sandy beds at numerous horizons. Glauconite (greensand) also is common throughout the series, although it is rare in some parts and very much concentrated in others. The following stratigraphic classification shows its general characteristics and its relationship to beds above and below.

Stratigraphic Classification of Minnesota Cambrian (St. Croixian Series) with Relationship to Beds Above and Below*

	THICKNESS (feet)
Beekmantownian Series	
Oneota Dolomite	
St. Croixian Series	
Jordan Sandstone (Winchell)	
Van Oser Member (Winchell)	
Coarse sand, massive beds, white to brown or red, sand grains often reconstructed. Sparingly fossiliferous. *Tellerina-Saukiella* faunule.	20–35
Norwalk Member (Ulrich)	
Medium to fine, white to yellow sand constituting the rock at the type locality.	

[11] Atwater, G. I., and Clement, G. M., Pre-Cambrian and Cambrian relations in the Upper Mississippi Valley: Geol. Soc. Am. Bull., vol. 46, pp. 1669–1672, 1935.

	THICKNESS (feet)
Usually unfossiliferous but at some places, such as Marine and the Osceola bridge, abundantly fossiliferous. *Eurekia-Osceolia* faunule.	65–85
St. Lawrence Formation (Winchell)	
Lodi Member (Ulrich)	
Dolomitic shale and siltstone. *Dikelocephalus minnesotensis* faunule. The Stillwater trilobite bed of Owen	10–50
Nicollet Creek Member (Stauffer, Schwartz, and Thiel)	
Dolomite, sprinkled through with grains of glauconite. The quarry beds of this formation are along the Minnesota River. *Scaevogyra-Billingsella* faunule	0–40
Franconia Formation (Berkey)	
Bad Axe Member (Twenhofel, Raasch, and Thwaites)	
Dolomitic, vermicular, fine-grained sandstone and beds of sandy glauconite. *Dikelocephalus postrectus* faunule	40–65
Hudson Member (Twenhofel, Raasch, and Thwaites)	
Sandstone and sandy glauconitic shales. *Idahoia-Ptychaspis* faunule	35–70
Taylors Falls Member (Stauffer, Schwartz, and Thiel)	
Medium-grained gray to buff sandstone. Type of formation. May be abundantly fossiliferous; several subfaunules can be distinguished. *Conaspis* faunule	15–100
Ironton Member (Ulrich)	
Gray to yellow-brown sandstone. Reworked sands from the beds below. *Camaraspsis-Irvingella* faunule	10–25
Dresbach Formation (Winchell)	
Galesville Member (Trowbridge)	
Medium to coarse, nearly barren, yellow to white, friable sandstone	0–50
Eau Claire Member (Ulrich)	
Mostly a very fossiliferous gray to brownish sandstone with some shaly beds. This is Winchell's type of the formation. *Crepicephalus* faunule. First trilobite bed of Owen	15–225
Mt. Simon Member (Ulrich)	
Coarse gray to white sandstone with quartz pebble zones. Crops out in Pine County and is penetrated in deep wells elsewhere	85–200
LAKE SUPERIOR SERIES	
Hinckley Sandstone	

* After Stauffer and Thiel, Minn. Geol. Survey Bull. 29.

DRESBACH FORMATION

The Dresbach formation is divided into three members, of which the lowest is the Mt. Simon, the middle is the Eau Claire, and the upper is the Galesville.

Mt. Simon Member.—The Mt. Simon is a coarse, white to pink and brown sandstone, with some conglomerate or quartz pebble horizons. Its textural composition is shown in Table 1. This member is from 80 to 200 feet thick. It is typically exposed in the hill called Mt. Simon, near Eau Claire, Wisconsin. Its outcrops in Minnesota are confined to the valley of the St. Croix River and its tributaries above St. Croix Falls. It is one of the very best water-producing horizons in Minnesota. The water, which enters the sandstone largely from the eroded margins lying beneath the glacial drift, is nearly everywhere under artesian pressure and usually rises above or nearly to the surface within the valleys of the Mississippi and St. Croix rivers and some of their tributaries.

Eau Claire Member.—This is the middle portion of the Dresbach

TABLE 1. — SUMMARY OF THE TEXTURAL CHARACTERISTICS OF THE MT. SIMON SANDSTONE

Stratigraphic Position (feet from top)	Textural Characteristics				
	Median Diam. (mm.)	Coef. of Sorting	Coef. of Skewness	Effective Size (mm.)	Uniformity Coef.
		WELL NO. 1 *			
325–331	0.37	1.26	1.31	0.214	1.64
331–370	0.29	1.47	1.07	0.203	1.42
490–520	0.34	1.19	0.97	0.241	1.27
520–525	0.24	1.31	0.87	0.142	1.41
525–527	0.34	2.30	2.21	0.103	3.78
527–530	0.24	1.42	1.03	0.101	2.47
530–531	0.31	1.68	0.96	0.179	1.03
531–535	0.31	1.48	1.00	0.164	1.37
535–630	0.25	1.37	0.98	0.141	1.08
630–670	0.33	1.52	0.77	0.224	1.43
670–693	0.23	1.42	0.95	0.104	1.12
Average	0.295	1.49	1.09	0.165	1.63
		WELL NO. 2 †			
225	0.260	1.530	0.940	0.084	4.12
250	0.400	1.620	0.930	0.110	4.27
275	0.450	1.564	0.754	0.143	3.61
300	0.350	1.640	0.996	0.141	3.14
350	0.343	1.621	1.064	0.162	2.68
400	0.375	1.580	1.666	0.181	2.88
425	0.256	1.656	1.261	0.104	3.33
450	0.228	1.367	0.833	0.093	3.00
Average	0.350	1.590	0.930	0.126	3.46

* From drill cuttings, Montrose city well.
† Samples from levee well, Red Wing.

formation. In general, it is a medium- to fine-grained gray, greenish-gray to buff sandstone, with beds of greenish-gray and red shales. This portion of the Dresbach formation is from 25 to 225 feet thick. It crops out in the vicinity of Dresbach, particularly at Mineral Bluff and at the village of Dakota. Several outcrops occur also at or near Taylors Falls, where the formation rests directly on the Keweenawan basalts. Its western margin of outcrop is concealed under the glacial drift in Chisago, Isanti, and Sherburne counties. From this catchment area the beds extend eastward to the valleys of the St. Croix and Mississippi rivers.

Several good water-bearing horizons occur in the Eau Claire member. They differ in their yield and the height to which the water will rise. For large yields of water it is advisable to drill completely through the Eau Claire and to tap the coarser Mt. Simon sandstone that lies below it.

Galesville Member. — This is the upper part of the Dresbach formation. It is a medium to coarse, yellow to white, poorly cemented sandstone, from nearly 0 to 50 feet in thickness. It crops out at numerous places along the lower portion of the Mississippi River bluffs from Winona southward. The beds in its stratigraphic position along the St. Croix valley at Taylors Falls are fossiliferous and very glauconitic.

This member is an important bearer of water, which is under sufficient artesian pressure to lift it above or nearly to the surface at various points in the lower St. Croix Valley.

FRANCONIA FORMATION

The Franconia formation contains the portion of the St. Croixian series that is highly glauconitic and is referred to as the greensand and green shale horizon. The formation is subdivided into four members which can be distinguished on the basis of the fossils they contain but are difficult to recognize from drill cuttings alone. Furthermore, the lithology of an individual member of the formation may vary greatly in different localities. This variation is found especially in the lower members of the formation, which are pink to green with glauconite in the southeastern counties of the state but white to buff in the region of Taylors Falls. The type section. is exposed along Lawrence Creek south of the village of Franconia.

Ironton Member.—The Ironton member is the bottom part of the Franconia formation. It is a medium to coarse, buff to brown, poorly sorted sandstone, which varies in thickness from 2 to 25 or more feet. Most of its sands represent a reworking and redeposition of sands derived from the top of the Dresbach formation. In compiling a log of a well from drill cuttings, it is very difficult to establish the contact between the bottom of the Ironton member of the Franconia and the top of the Galesville member of the Dresbach. However, in general, the Ironton is more fossiliferous, whereas the Galesville is more glauconitic and contains few shell fragments.

Taylors Falls Member.—The Taylors Falls member of the Franconia formation lies above the Ironton. It is a medium- to fine-grained, buff to pink sandstone, from 10 to 100 feet thick. In Washington and Chisago counties it attains a thickness of approximately 100 feet. A textural analysis of a series of channel samples taken at Taylors Falls is given in Figure 4.

Section of Franconia Sandstone along Highway Cut at Roadside Spring, One Mile Southwest of Taylors Falls

	THICKNESS (feet)
Drift	55.00
FRANCONIA SANDSTONE	
Sandstone, white with yellow streaks, massive, friable	25.00
Covered interval	6.80
Sandstone, yellow, thin-bedded to shaly	12.35
Sandstone, white with yellow stains, massive, medium to coarse	44.55
Sandstone, gray to brown, massive to thin-bedded, medium to fine, glauconitic,	

	THICKNESS (feet)
cross-bedded, and with streaks of greenish shale along some bedding planes. Some layers may be very much indurated	21.40
Total	110.10
DRESBACH FORMATION	
Shale and glauconitic sandstone. Elevation of roadside spring at contact, 747.7 ft. A.T.	15.00

Hudson Member.—The Hudson member of the Franconia formation lies immediately above the Taylors Falls member. It is well exposed at Hudson, Wisconsin, from which town it gets its name. It crops out extensively along the valley of the St. Croix River and along the lower courses of its major tributaries, where it consists of gray to buff or pinkish-green sandstones and gray siltstones, all more or less glauconitic. Some layers from 2 to 6 inches thick are nearly all glauconite.

Bad Axe Member.—The Bad Axe member is the top part of the Franconia formation. It is a sandy siltstone with some greensand. Natural outcrops of this member show numerous small burrows and worm trails

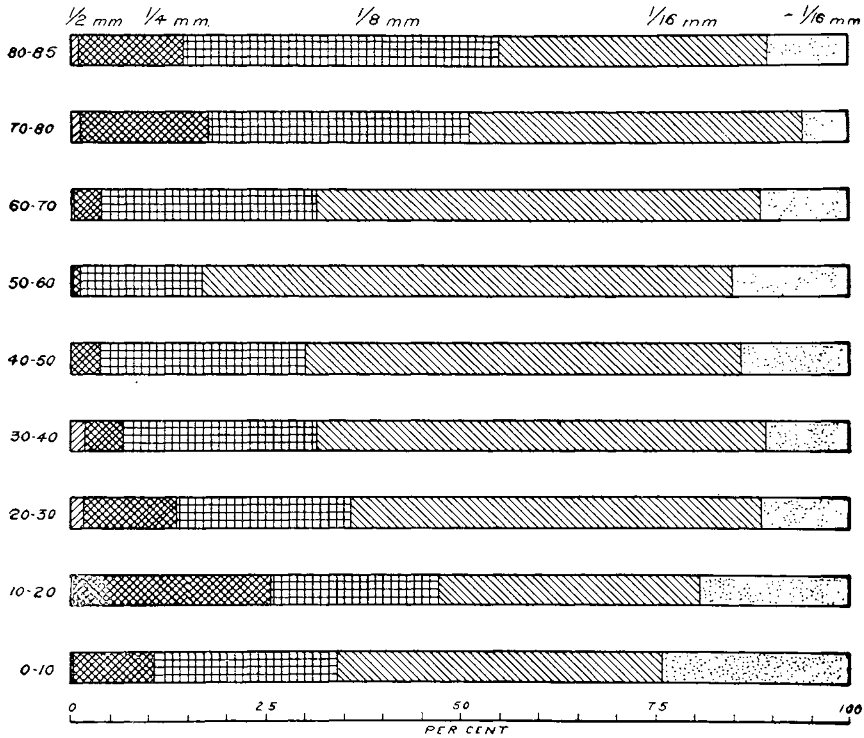

FIGURE 4.—Textural analysis of the Franconia sandstone from Taylors Falls, Minnesota.

made by organisms that inhabited the muds before they were lithified. Natural outcrops occur along the valley of the St. Croix River from Marine to Stillwater. (See the report on Chisago County.)

ST. LAWRENCE FORMATION

The St. Lawrence formation consists of glauconitic, buff, dolomitic sandstone. Several conspicuous beds of gray to buff, dolomitic siltstone occur near the base of the formation.[12]

Nicollet Creek Member.—The Nicollet Creek member is nearly all buff dolomitic sandstone, much of which is richly sprinkled with grains of glauconite. Most of the beds range from 2 to 6 inches in thickness, but some are much thicker. At its type locality north of Judson the Nicollet Creek is 35 feet thick. Several conglomerate beds with dolomitic pebbles in a highly glauconitic matrix occur near the base.

Lodi Shale Member.—The Lodi shale member of the St. Lawrence formation occurs between the dolomitic beds of the Nicollet Creek and the base of the buff to white Jordan sandstone. This member includes a stratigraphically important yellowish to ash-colored siltstone that is traceable over all the central and southeastern part of Minnesota. The siltstone contains a remarkable trilobite and graptolite fauna.

Neither member of the St. Lawrence formation is important as a source of ground water. The chief value of these members lies in their function as confining strata under the Jordan sandstone aquifer.

JORDAN FORMATION

The Jordan sandstone is a loosely cemented, medium- to coarse-grained, white sandstone, which becomes yellow or brown by oxidation along its outcrops and jointing planes. It ranges from 75 to nearly 125 feet in thickness and is exposed in the valleys of the St. Croix River and tributary streams and in the lower part of the bluffs of the Mississippi and its branches from near Hastings southward to the Iowa state line. Elsewhere it is deeply buried beneath younger rock.

The Jordan sandstone is made up of two members, the Norwalk below and the Van Oser above. The upper Van Oser member is the coarser. It consists of friable gray, white, pink, or brown sand grains, many of which have the faces of the crystals partly or completely restored. Its textural characteristics are shown in Table 2.

The coarseness of grain, uniformity of size of grain, and lack of cementing material make the Jordan sandstone an excellent aquifer. Except in the areas adjacent to its outcrops it is saturated with water which is under pressure and is yielded freely. It is believed that the formation will yield all the water it is called upon to furnish for a long

[12] The term St. Lawrence, as used by Hall, Meinzer, and Fuller in Water-Supply Paper 256 of the United States Geological Survey, included the Bad Axe and Hudson members of the Franconia formation. A similar classification was used by Schwartz in Bulletin 27 of the Minnesota Geological Survey.

TABLE 2. — SUMMARY OF THE TEXTURAL CHARACTERISTICS OF THE JORDAN SANDSTONE
(Long Lake well, Minnetonka project)

Stratigraphic Position (feet from top)	Textural Characteristics				
	Median Diam. (mm.)	Coef. of Sorting	Coef. of Skewness	Effective Size (mm.)	Uniformity Coef.
0–10	0.37	2.02	1.14	0.08	4.12
10–20	0.38	1.68	1.33	0.131	3.23
20–30	0.38	1.69	1.31	0.113	3.12
30–40	0.39	1.55	1.33	0.142	3.04
40–50	0.47	1.50	1.22	0.141	1.21
50–60	0.16	2.04	1.30	0.071	3.23
60–70	0.15	2.01	1.29	0.084	1.02
70–80	0.17	1.46	1.08	0.078	1.14
80–90	0.14	1.73	0.97	0.084	1.28
90–100	0.18	2.30	1.33	0.069	2.01
100–110	0.06	1.93	1.66	0.038	1.24
110–120	0.07	1.93	1.65	0.039	1.32
120–130	0.08	1.73	1.12	0.031	1.14
Average	0.23	1.81	1.28	0.084	2.08

time to come. Temporary steep depression cones have developed where the wells are closely spaced, but the recharge is rapid when pumping is halted.

ORDOVICIAN SYSTEM

The St. Croixian series is overlaid by rocks commonly referred to as the Ordovician system. Where the contact between these two systems of formations is exposed along the bluffs of the St. Croix River, the change is gradual and has been interpreted by some geologists as a transition without interruption from the sandy sediments of the Cambrian to the dolomites of the Ordovician.

Kasota Sandstone.—The oldest rock lying at the base of the Ordovician is the Kasota sandstone. It is known only at Kasota and St. Peter along the Minnesota River. It varies from a few inches to 6 feet in thickness and is composed of white, medium to coarse, well-rounded sand grains. Its sands were apparently derived from the underlying Jordan sandstone. The Kasota cannot be distinguished from the Jordan except for the presence in the Kasota of certain fossils that are quite foreign to any belonging in the Jordan.[13]

Blue Earth Siltstone.—The Blue Earth siltstone is a thin bed of white to pale green, very fine-grained, silty shale that lies above the Kasota sandstone and spreads out beyond it horizontally in the region of St. Peter and Mankato. It seldom exceeds 2 feet in thickness and is usually thinner, except as a filling in cavities or nearly vertical fissures.

[13] Powell, L., A study of the Ozarkian faunas of southeastern Minnesota: Science Museum of the St. Paul Institute, Bull. 1, 1935.

This layer served as an impervious and insoluble floor for the caves and channels that developed in the lower part of the overlying Oneota dolomite.[14]

Oneota Dolomite.—The Oneota dolomite is thick-bedded, drab to buff, and in places pink, and may be sandy or shaly. The upper part may be cherty and in many localities is porous to cavernous. Many of the cavities and joints are lined with quartz crystals, and huge calcite-lined pockets are common. In the southeastern counties, where the dolomite is strongly developed in the bluffs of the Mississippi and its tributaries, there are extensive solution channels, some of which reach the dimensions of caves penetrable for some distance.

At the Soo Line drawbridge over the St. Croix River the dolomite is 100 feet thick. At Mankato it is about 45 feet, at Minneapolis about 70 feet, at Stillwater 60 feet, at Faribault 110 feet, at Winona 130 feet, and at Dresbach 150 feet. Even greater thicknesses occur in the region of Albert Lea and Austin.

Small quantities of water are found in the upper and more porous portion of the Oneota formation, but great volumes are contained in the larger solution passages, which represent enlarged joints, bedding planes, or other lines of easy circulation. The formation yields little water to wells except from the solution passages. These passages yield freely, but it is always uncertain when or where they will be penetrated by the drill.

Soo Line Drawbridge, Washington County, Section at Falls West of Water Tank and Drawbridge
(Measured by C. R. Stauffer)

	THICKNESS (feet)
15. Drift	67.0
SHAKOPEE DOLOMITE	
14. Dolomite, buff, irregularly bedded, arenaceous	1.9
13. Sandstone, coarse, brown	1.1
ONEOTA DOLOMITE	
12. Dolomite, gray tinged with pink, irregularly bedded, thick to thin	85.0
11. Dolomite, gray to buff, even-bedded. Small quartz geodes common	11.0
10. Dolomite, buff to pinkish gray, sandy, thin, and irregularly bedded	5.0
9. Dolomite, gray to buff, sandy, with rounded pebbles of well-cemented sandstone at base	1.0
JORDAN SANDSTONE	
8. Sandstone, white, massive, ripple-marked, mostly well cemented	1.5
7. Sandstone, white to buff, coarse, rough, broken, poorly cemented, containing rounded, flat pebbles of well-cemented sandstone	1.5
6. Sandstone, white to brown, coarse, massive. Weathered surface is case-hardened, but interior is friable. Complexly jointed or cracked, upper part with small anastomosing veins	19.8
5. Sandstone, white, poorly cemented, heavy-bedded, fine-grained, but with some large, clear quartz grains. Contains a few poorly preserved trilobite fragments	3.0

[14] Graham, W. A. P., Petrology of the Cambrian-Ordovician contact in Minnesota: Jour. Geol., vol. 41, pp. 468–486, 1933.

	THICKNESS (feet)
4. Sandstone, white to yellow or brown, massive, poorly cemented, fine-grained. Complex cross-bedding and color-banding common	34.0
3. Sandstone, like that above, but mostly covered	15.5
ST. LAWRENCE FORMATION	
2. Shale, sandy, buff, with argillaceous blue partings, irregularly bedded. Contains fragments of inarticulate brachiopods	1.1
1. Shale, sandy, buff to blue, similar to that above, exposed along the river about 100 feet from No. 2. To level of St. Croix River (682 ft. A.T.)	25.0

Root Valley Sandstone.—In the southeastern counties of Minnesota there is a sandstone, 30 to 40 feet in thickness, lying between the upper cherty portion of the Oneota and below the Shakopee dolomite. In the older geologic literature this horizon was known as the New Richmond sandstone. From the abundant fine exposures of this sandstone in the valley of the Root River it has been renamed the Root Valley sandstone. It is typically exposed along the highway west of Lanesboro, along the river bluffs at Preston, in Whitewater State Park, and in many other places in that part of the state. The formation becomes thinner toward the north and west. In the southeastern part of Chisago County it is represented by about one foot of sandstone. It is often more or less cemented by carbonates and consequently is difficult to distinguish, in wells, from the dolomite above and below.

In spite of its thinness the Root Valley sandstone is a very persistent water-bearing bed, always yielding water except where drained by adjacent valleys. Its water probably enters chiefly through joints and other openings in the associated limestones. In the more calcareous facies the water occurs in what are termed "fissures" by the drillers, but what are actually local sandy zones from which the cement has been dissolved, leaving layers of nearly pure sand.

Shakopee Dolomite.—The Shakopee dolomite overlies, and its base is interbedded with, the Root Valley sandstone. It is much less dolomitic than the Oneota. Its basal beds are sandy and in many places the succeeding layers are thin-bedded. Much of the formation is a massive, drab, dolomitic limestone with cavities filled with white calcite. Calcareous oölites may be found throughout the Shakopee and much of the flint that is common in this formation is also oölitic.

A few farm wells end in the Shakopee, but the supplies it yields are very small. Most of the wells either stop in the overlying sandstone or penetrate to a lower formation.

St. Peter Sandstone.—The St. Peter sandstone is one of the most widely recognized formations of the central part of the United States. In Minnesota it underlies the greater part of the area between the Minnesota and Mississippi rivers and much of Ramsey, Washington, Anoka, and Hennepin counties to the north. It varies from 75 to 175 feet in thickness and consists of a medium- to fine-grained, friable, white to yellow sandstone, with beds of siltstone and shale in the lower part of the formation. It is thickest in the Minneapolis-St. Paul area, where an average of 57 well logs show a thickness of 158 feet. Southward from the Twin City basin it becomes thinner as the dolomite beds below it thicken.

Texturally and mineralogically the St. Peter sandstone is remarkably uniform, indicating that its sands were well sorted before and during deposition. Most of the quartz grains are from one-eighth to one-half of a millimeter in diameter.[15] It will all pass through a screen with 1 mm. openings. (See Table 3.) The sandstone is poorly cemented and consequently has a high porosity. A number of porosity determinations have been made, showing an average of approximately 28 per cent for the upper half of the formation. Because of the small size of its quartz grains, the formation is not highly permeable.

TABLE 3. — SUMMARY OF THE TEXTURAL CHARACTERISTICS OF THE ST. PETER SANDSTONE

Geographic Location	Textural Characteristics				
	Median Diam. (mm.)	Coef. of Sorting	Coef. of Skewness	Effective Size (mm.)	Uniformity Coef.
Caledonia	0.241	1.39	1.02	0.165	2.12
Castle Rock	0.192	1.31	1.17	0.106	1.64
Chatfield	0.239	1.42	1.01	0.124	2.39
Chimney Rock	0.309	1.45	1.26	0.107	2.24
Decorah, Iowa	0.233	1.45	0.99	0.117	2.34
Mendota	0.235	1.41	1.09	0.142	1.99
N. Minneapolis	0.235	1.48	0.96	0.107	2.65
St. Paul Park	0.178	1.32	1.20	0.119	2.28
Zumbrota	0.201	1.32	1.06	0.114	2.00
Preston	0.225	1.47	0.97	0.119	2.23
S. Minneapolis	0.219	1.55	0.94	0.098	3.02
Rochester	0.207	1.38	1.12	0.121	2.00
St. Paul	0.197	1.37	1.07	0.121	1.92
Washington Co.	0.281	1.27	1.11	0.175	3.66
Blue Mound, Wis.	0.235	1.33	1.04	0.125	2.38
Average	0.228	1.39	1.07	0.124	2.32

The greater part of the water in the St. Peter sandstone enters through its outcrops. This is true also where it lies immediately below the glacial drift, which serves as an excellent feeder. North of the Twin Cities and along the western margin of outcrop of the formation, the sandstone is covered with drift. The formations of the Upper Ordovician do not occur in the area covered by this report.

[15] Thiel, G. A., Sedimentary and petrographic analysis of the St. Peter sandstone: Geol Soc. Am. Bull., vol. 46, pp. 559–614, 1935.

MESOZOIC ROCKS

Cretaceous System

Most of the western half of Minnesota is covered by clastic sediments that lie between the glacial drift and the crystalline pre-Cambrian rocks. They are both marine and fresh-water deposits consisting of clays, silts, sands, and conglomerates that spread out over a wide area. Here and there swampy conditions prevailed and thin beds of impure lignite were formed which are found interbedded with the clays and shales. A study of the fossil plants from the shales at Springfield and from the sandstone along the Big Cottonwood River south of New Ulm has led to their correlation with the Dakota sandstone, but in north-central Minnesota the Cretaceous beds are of marine origin and carry a typical Benton fauna. They are well exposed in the walls of the open-pit mines in Itasca County.

Dakota Formation.—In the south-central counties the Dakota formation is composed of thick beds of clastic bluish-gray shale and thinner beds of white sand and pebbly sandstone. The shales are referred to by the well drillers as "soapstone." In some localities they attain a thickness of nearly 500 feet. The sandstone beds, which form only a small portion of the total thickness, occur chiefly near the bottom and near the top of the series. Those near the bottom often have a white quartz grit bed, with scattered pebbles of angular quartz, resting directly over the residual clays that cap the pre-Cambrian granites of that area. Locally the sands and pebbles are cemented by iron oxides into hard, resistant, ferruginous sandstones and conglomerates. A general characteristic of both the sand and the gravel is their yellow color, due to iron oxides that coat and cement the grains. Owing to this characteristic the name "orange gravels" is often applied to them. This unit of the Dakota formation is classified as the Ostrander member. The accompanying section occurs at the type locality.

Section at Carthog Gravel Pit at South End of Village of Ostrander
(Measured by C. R. Stauffer)

	THICKNESS (feet)
8. Loess and soil	2.0
7. Drift, with a few boulders	2.0
DAKOTA FORMATION	
Ostrander Member	
6. Sandstone, brown, coarse, pebbly, iron-stained and iron-cemented, very hard	2.5
5. Sand, coarse and sandy yellow gravel. The pebbles are smooth, rounded to ellipsoidal, pink and white quartz, together with subangular flint and chert pebbles about one-eighth to one-half an inch thick	10.0
4. Sandstone, brown, pebbly, hard, and in part a real conglomerate	1.5
3. Gravel, yellow, medium to fine, pebbles of flint and quartz as throughout the formation	1.5

The fossiliferous marine sedimentary rocks of Cretaceous age occur as a mantle on the uneven surface of the pre-Cambrian rocks. They are exposed in the walls of some of the open-pit mines from Coleraine eastward across the Mesabi Range as far as Virginia. A basal conglomerate composed of fragments of oxidized ferruginous chert, iron ore, and porphyry pebbles indicates that the sediments were derived largely from the local underlying iron formation and other pre-Cambrian rocks. This coarse basal conglomerate grades vertically through a somewhat glauconitic, fine-pebble conglomerate or grit, which in turn grades upward into ferruginous sandstone and shale. The grit and sandstone beds are very fossiliferous with an abundant molluscan assemblage. Many of the fossils are oysterlike pelecypods. All these fossiliferous strata are a part of the Coleraine formation, which, on the basis of the invertebrate fauna, is considered the age equivalent of the lower Benton in the Colorado Series of the Great Plains. The accompanying section is typical of the formation.

Exposure 1928 in South Face of Hill Annex Mine, Calumet,
NW¼, Sec. 16, T. 56 N., R. 23 W.
(Measured by C. R. Stauffer)

	THICKNESS (feet)
PLEISTOCENE	
12. Drift, sands, gravels, and boulder beds	125.0
CRETACEOUS (COLORADO SERIES)	
Coleraine Formation	
11. Iron ore, redeposited, red and gray, soft, massive, with fine pebbles. Fossils common	9.0
10. Conglomerate, red pebbles in a gray matrix	6.3
9. Iron ore, redeposited, red to gray, gritty, with fragments of wood at some places. At other places this same horizon carries an abundant molluscan fauna	3.0
8. Conglomerate, coarse, pebbly, unassorted	0.5
7. Iron ore, redeposited, green, gritty, with occasional pebbles of chert and iron formation	4.0
6. Conglomerate, gray, coarse pebbles cemented by a green iron sand	0.7
5. Conglomerate, very coarse, with polished black pebbles, chert, taconite, paint rock, hematite, slate, quartz, and other pebbles and cobbles up to 8 inches in diameter	8.2
PRE-CAMBRIAN	
Biwabik Formation	
4. Paint rock and slaty red taconite with white bands	8.0
3. Iron ore, deep red, cherty, gritty, with altered taconite	16.0
2. Iron ore, laminated, blue, cherty, with sandy beds and unaltered taconite	20.0
1. Iron ore, blue, hard, massive, cherty, laminated to bottom	28.0

CENOZOIC ROCKS

UNCONSOLIDATED SURFACE DEPOSITS

Nearly all of Minnesota was covered by a mantle of glacial deposits, but subsequent stream erosion removed or modified the deposits along many of the major valleys. Likewise, some Tertiary stream deposits were not completely removed by the Pleistocene glaciers. Thus the

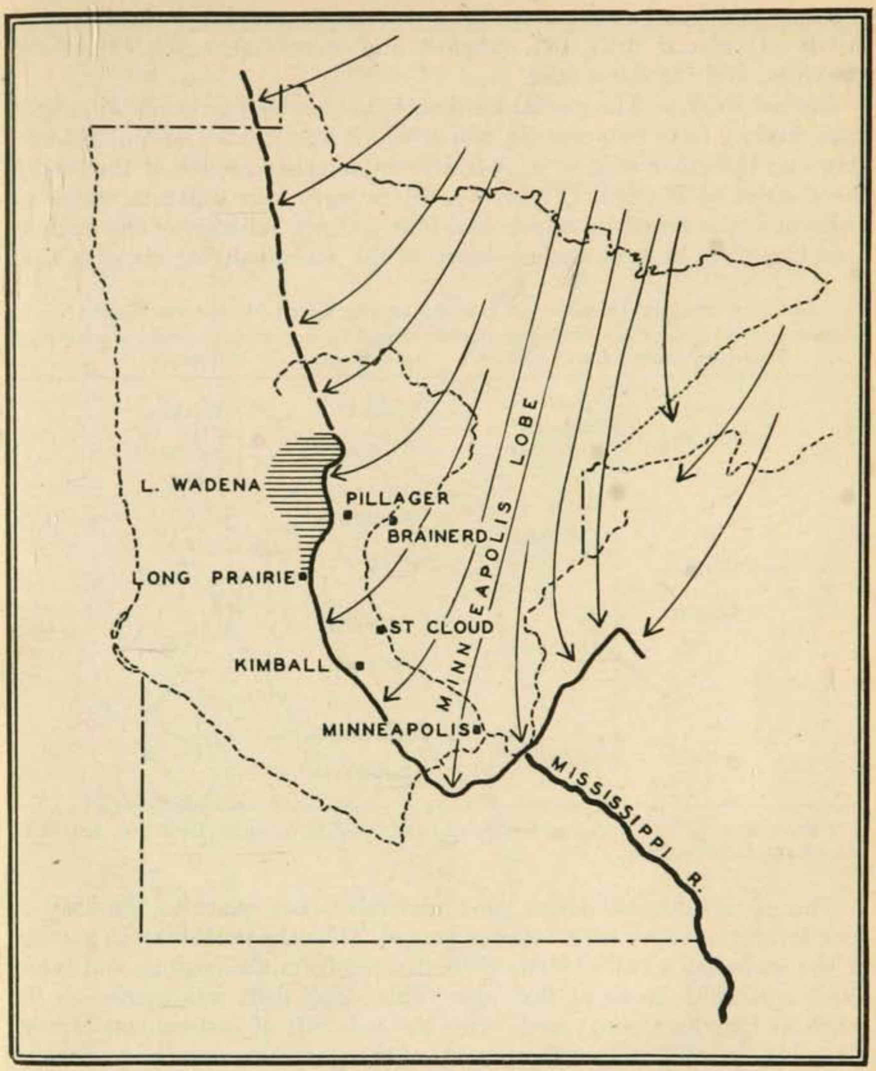

FIGURE 5. — Patrician glaciation in the upper Mississippi Valley at its maximum extent. After Cooper.

pre-Pleistocene sediments of Tertiary age cannot be readily differentiated. All unconsolidated surface deposits are treated as one unit in this report. This unit includes glacial drift and all associated water and wind deposits, as well as the alluvium laid down in the valleys outside the drift-covered area. From the standpoint of water supplies it is not so much the age of the deposit that is important as the texture and composition of the material and its topographic distribution. In discussing the unconsolidated surface mantle the following subdivisions are recognized: (1) glacial drift, (2) outwash and terrace deposits, (3) recent alluvium, and (4) dune sand.

Glacial Drift. — The glacial ice sheets that covered most of Minnesota came mainly from two centers, one of which was located east of Hudson Bay and the other west of it. A lesser center existed south of the bay in the district of Patricia (Figure 5). There were four separate stages of glaciation, the fourth of which had four distinct substages. The various invasions have been named as shown in the accompanying classification.

CLASSIFICATION OF PLEISTOCENE HISTORY IN THE UPPER MISSISSIPPI VALLEY *

Period (System)	Epoch (Series)	Ages (Stages)	Substages
Pleistocene or Glacial	Eldoran	Recent	
		Wisconsin	Mankato Cary Tazewell Iowan
	Centralian	Sangamon	
		Illinoian	
	Ottumwan	Yarmouth	
		Kansan	
	Grandian	Aftonian	
		Nebraskan	

* From Kay, G. F., Pleistocene history and early man in America: Geol. Soc. Am. Bull., vol. 50, pp. 453–464, 1939.

The glacial deposits show some variations that relate to the kind of rock formations over which the ice passed. Thus the northeastern portion of the state has a rather stony drift derived from the igneous and other hard, crystalline rocks of that area. This stony drift was carried as far south as Dakota County and forms the red drift of east-central Minnesota. The western and southern parts of the state have a large amount of clayey drift with many limestone pebbles imbedded in it. This material was gathered by the ice as it passed over the shales and limestones of southern Manitoba and moved southeastward into the area of granites and other crystalline rocks of west-central Minnesota. These clayey and limy deposits form what is known as the young gray drift of late Wisconsin or Mankato age (Figure 6).

The bulk of the glacial drift deposits consists of a matrix of clay in which are imbedded pebbles and boulders of various sizes and compositions, the whole forming an impervious mass known as till. Intermingled

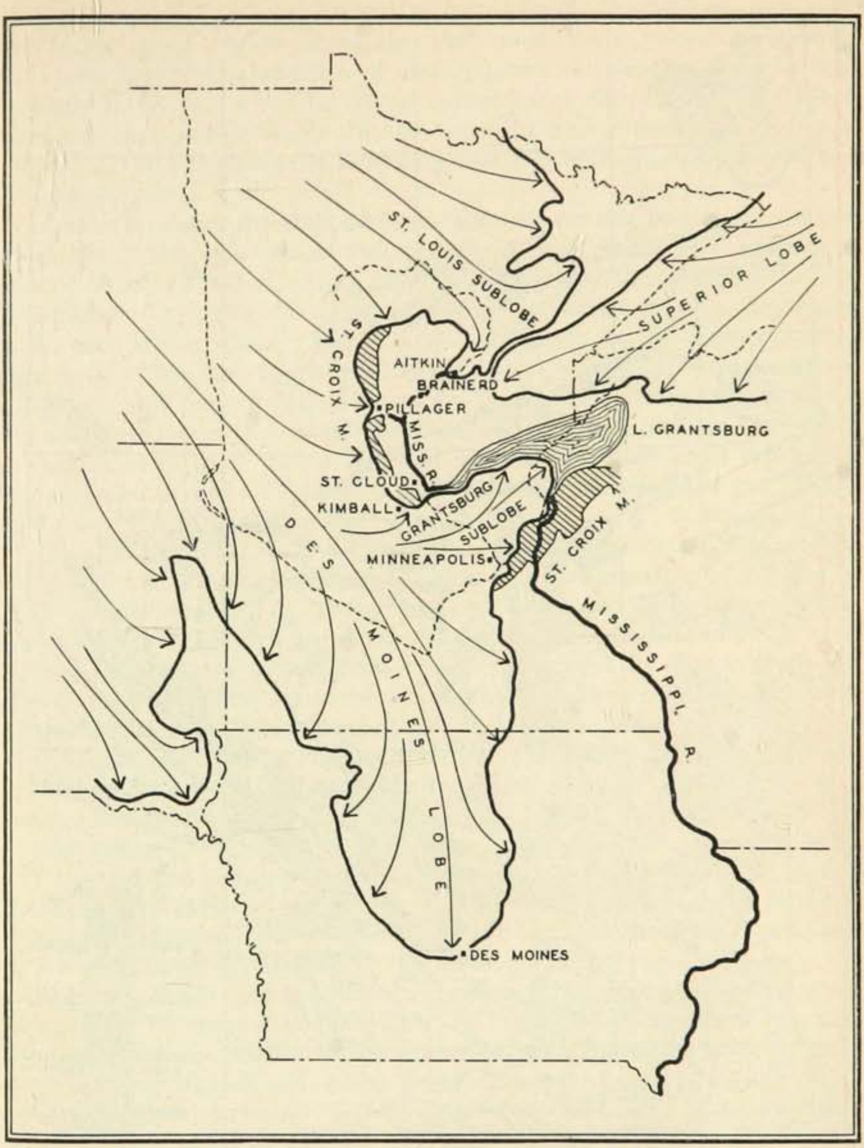

FIGURE 6. — Late Wisconsin (Mankato) glaciation in the upper Mississippi Valley at its maximum extent. After Cooper.

and interbedded with the till are beds of porous, water-laid sands and gravels, which constitute the water-bearing members of the drift. In some places such water-bearing beds lie between two drift sheets of distinctly different age. From the hundreds of wells drilled into the drift it is evident

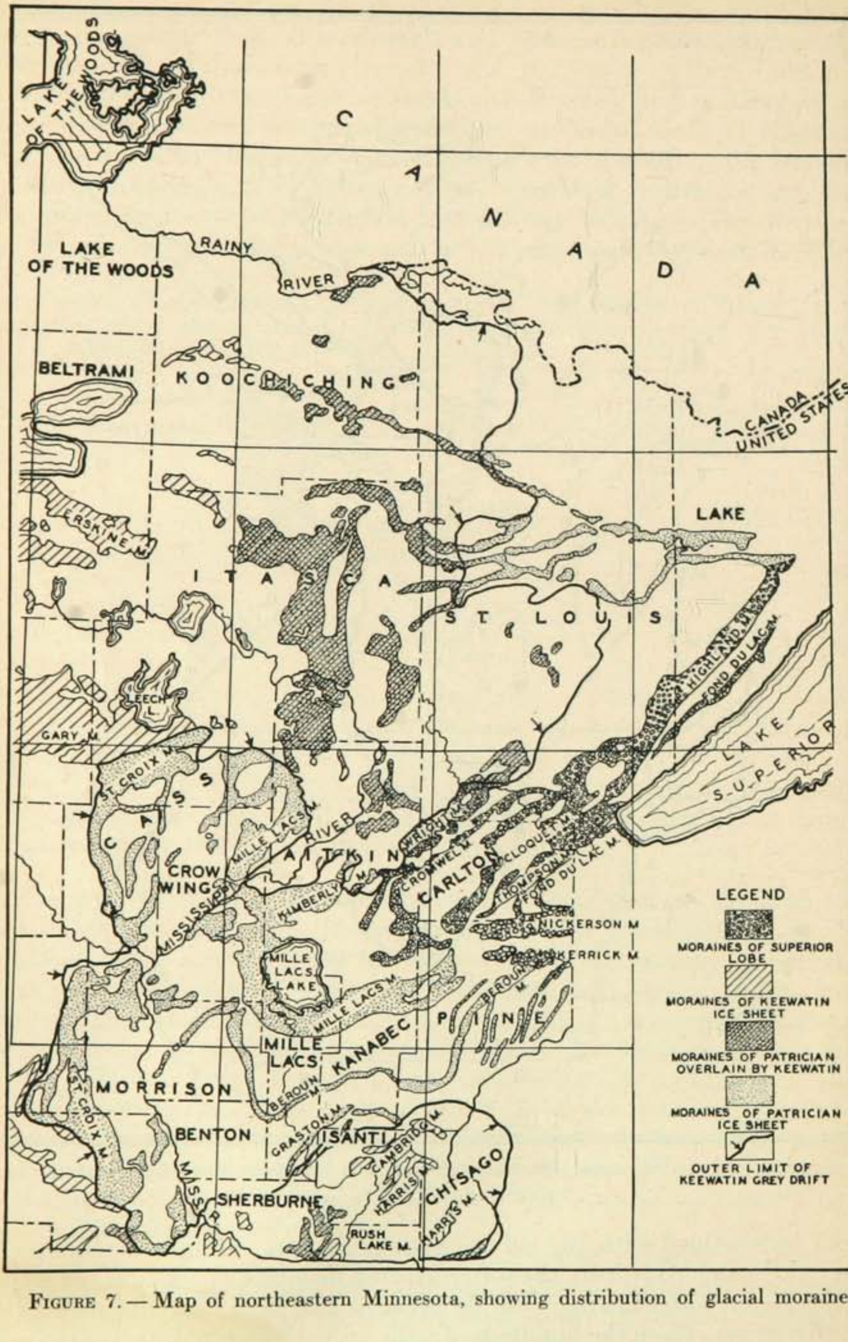

FIGURE 7. — Map of northeastern Minnesota, showing distribution of glacial moraines.

that such porous beds exist in nearly every locality. A comparison of well logs in any given region shows also that most of the porous beds vary widely in thickness, coarseness of material, and the depth at which they lie. Only rarely can a bed be traced definitely by means of well sections for more than a few miles. In the terminal and recessional moraines (Figure 7) the percentage of sand and gravel is much higher than in the ground moraine.

In most localities the drift has a dark gray color due to the unoxidized condition of the iron it contains, but at or near the surface there is a mantle of buff to yellow, partly oxidized drift that averages about 15 feet in thickness. Owing to the presence of soluble iron compounds, the water in the drift is almost everywhere charged with iron. In the upper oxidized zone most of the iron has been changed to the relatively insoluble ferric condition, and consequently less occurs in the near-surface waters. The distinction between the red northeastern and the gray northwestern drift is very clear in some places, and the mineral composition of the water can often be predicted through a knowledge of the source of the glacial drift from which it is derived.

The drift varies greatly in thickness. In some localities it is nearly 500 feet thick. It is thickest in the rugged terminal moraines of Wisconsin drift and thinnest in the rocky areas of Lake and Cook counties. In some localities the rock formation immediately beneath the drift is so similar in character to the drift itself that drillers do not differentiate clearly between them. In such regions the true thickness of the glacial deposits has not been determined.

Outwash and Terrace Deposits.—Since glacial rivers were of great volume, their deposits are generally composed of sandy and gravelly material somewhat coarser than that carried by the present rivers. Such glacial streams were loaded with debris, some of which was deposited well beyond the margins of the drift proper, especially where the glacial floods entered pre-existing valleys and rapidly filled them with fluvatile sediments. More recently the streams have cut into this filling, and they now flow at lower levels, leaving the remnants as terraces.

Outwash sands and gravels occur in many portions of east-central Minnesota. Terraces are found mainly in the valleys of the St. Croix and Mississippi rivers. Other valley deposits not connected with present drainage lines include old, filled, pre-glacial valleys.

Most terrace sands are saturated with water nearly to the surface. They are recharged by rainfall and by springs that issue from the valley walls. Where they are underlaid by impervious clays and the region remains undissected by stream erosion, terraces yield water freely to dug or driven shallow wells. Many cities along the major valleys in the state have abandoned their old deep wells and are obtaining their supply of water from a group of shallow terrace wells. One reason for the change is the lower mineral content of the terrace waters.

Recent Alluvium.—Recent stream deposits are restricted to the valleys and are therefore of limited area. They are present, however, in greater or less amounts in all the valleys of eastern and central Minnesota. The water in the alluvium is derived in part directly from the rainfall on the flood plains, in part from the run-off from the valley slopes, and in part from the river during its flood stages. When the water level in the stream rises faster than the ground water level in the alluvium, the direction of movement of the water underground is reversed and the river water flows into the alluvium on each side of the stream. Alluvial sands and gravels yield their water freely, but clayey sediments, though they contain much water, hold it firmly and little or none flows into a well.

Dune Sand.—Well-developed belts of dune sand occur in Isanti, Sherburne, and Mille Lacs counties, where the sand derived from the glacial outwash has been blown into dunes, but these dunes occupy a relatively small percentage of the so-called Anoka sand plain. Cooper states that "from north Minneapolis an almost continuous belt of dunes extends northwestward for eighteen miles. It lies parallel to the line of division between sand plain and valley train and is nowhere more than two miles distant from it. The maximum width is two miles, the total area about seventeen square miles."[16] The dunes are a poor source of water.

MAJOR SUBSURFACE STRUCTURES OF NORTHEASTERN MINNESOTA

The subsurface structure of the major portion of northeastern Minnesota is a monoclinal dip to the southeast toward the axis of the Lake Superior geosyncline. This structure is conspicuous in the Huronian rocks from Remer in eastern Cass County, northeast to Pigeon Point. The Keweenawan rocks on the north shore of Lake Superior show a similar dip.

The metamorphic rocks north of the Giants Range are complexly folded slates and schists that represent the roots or stumps of the Algoman mountains. These intensely folded strata have been intruded by the Vermilion and Giants Range batholiths. Northeastward from Lake Vermilion the folding is still more complex and the rocks included in the folds are recrystallized more completely. The general strike of the folds is N. 65° E. and many of the closed, isoclinal folds have their axial plane inclined toward the southeast.

A similar, complex, folded and intruded relationship occurs between the slates, schists, and granites in central Minnesota in Crow Wing, Morrison, and Mille Lacs counties. There the field relations indicate that the granites are younger than the schists. The iron-bearing strata of the Cuyuna Range are folded into isoclinal anticlines and synclines trending northeast-southwest. The dip of the limbs of the folds is usually nearly vertical and may be either to the southeast or to the northwest, the former dip predominating.

[16] Cooper, W. S., The history of the Upper Mississippi River in late Wisconsin and postglacial time: Minn. Geol. Survey Bull. 26, p. 46, 1935.

II. CHEMICAL QUALITIES OF THE WATERS OF NORTHEASTERN MINNESOTA

In the compilations of data for this report no chemical analyses of water were made. However, numerous analyses by the Minnesota State Board of Health are included with the reports on individual counties. The following discussions of the chemical quality of the waters is a summary based on these analytical results.

Variations According to Geologic Source

A somewhat arbitrary division of northeastern Minnesota into four general provinces makes it possible to bring out chemical relations in the waters from the various glacial drifts. The southeastern province of this area is underlaid by the late Wisconsin (Mankato) gray drift. This includes the greater parts of Chisago, Isanti, and Sherburne counties. The south-central province extends from the southern part of Cass County into northern Sherburne County and thence eastward to the St. Croix River, and from there northward to Duluth. This province was last glaciated by the Patrician ice sheet and is underlaid by the young red (Cary) drift. The northeastern province includes Cook and Lake counties and the eastern part of St. Louis County. In this province the mantle of drift is thin and large areas of pre-Cambrian igneous and metamorphic rocks are exposed at the surface. The northwestern province extends northward from the northern part of Aitkin County and westward from the western part of St. Louis County. This province has a thick mantle of young gray (Mankato) drift and its northernmost portion is covered with lacustrine and bog sediments that accumulated on the floor of glacial Lake Agassiz.

The underground waters of the two northern provinces show a pronounced increase of salinity from east to west. The low salinity in the Arrowhead region of the northeastern counties is attributed to the high permeability of the sandy and stony drift and to the fact that the drift was abraded chiefly from areas of crystalline rocks. Farther westward in Itasca and Cass counties the drift was derived from the Cretaceous sedimentary rocks that underlie the northwestern part of the state and adjoining regions of Canada. These rocks are composed of calcareous shales and thin beds of limestone, both of which contain soluble sulphates and carbonates. Northwestward from the village of Cook the salinity is much greater than the average for the young gray (Mankato) drift. This is undoubtedly due to the sluggish underground circulation in the silts and clays which were deposited on the floor of glacial Lake Agassiz.

The two southern provinces are distinguished mainly by the character of their glacial deposits. The waters in the red drift of the south-central province are ordinary bicarbonate solutions of moderate salinity.

TABLE 4. — AVERAGE HARDNESS OF WATERS FROM WELLS IN GLACIAL DRIFT *
(Calculated as parts of $CaCO_3$ per million)

County	Depth in Feet	
	0–100	100–200
Red drift		
Benton	209	...
Carlton	110	...
Crow Wing	140	170
Kanabec	...	132
Mille Lacs	175	190
Morrison (eastern)	110	225
St. Louis (eastern)	45	27
Average	132	149
Gray drift		
Aitkin	...	226
Cass	230	300
Chisago	245	...
Isanti	...	280
Itasca	...	275
Koochiching	...	507
Pine	...	210
St. Louis	280	310
Sherburne	...	210
Average	250	290

* Data from State Board of Health Laboratory.

TABLE 5. — AVERAGE HARDNESS OF WATERS FROM STREAMS AND LAKES OF NORTHEASTERN MINNESOTA *
(Calculated as parts of $CaCO_3$ per million)

Source	Hardness
Carlton County, Otter Creek	71
Koochiching County, Rainy River	51
Koochiching County, Barrett Lake	95
Mille Lacs County, Rum River	114
Morrison County, Mississippi River	190
St. Louis County	
Burntside Lake	19
Cedar Island Lake	71
St. Mary's Lake	77
Sagawa Lake (Ely)	46
Lake Superior	32
Lake Vermilion	17
Average	71

* Data from State Board of Health Laboratory.

Table 6. — Percentage of Soluble Carbonates in Various Types of Glacial Deposits

Red Drift		Gray Drift	
Sample No.	% $CaCO_2$	Sample No.	% $CaCO_2$
1	4.29	11	14.66
2	1.69	12	13.28
3	5.53	13	18.10
4	3.98	14	10.65
5	5.23	15	7.36
6	2.41	16	8.00
7	11.52	17	16.34
8	19.85	18	11.15
9	.98	19	6.48
10	1.89	20	8.11
Average	5.73	Average	11.41

Description of Samples *

RED DRIFT

1. Red drift from fresh road cut east of Cedar Lake, Aitkin County. A sandy clay with calcium carbonate cementing fissures. Classified as morainic sand.

2. Clayey red drift from pit east of Pelican Lake, Crow Wing County. Classified as coarse sandy outwash.

3. Red drift from road cut through hill that borders large marl deposit near Clearwater. Classified as coarse sandy outwash.

4. Red sandy clay from road cut on west shore of Mille Lacs Lake about 3 miles south of Garrison. Classified as morainic sand.

5. Gravel from ridge a mile south of Pillager. Classified as outwash.

6. Sand from pit near the road along the east shore of Lake Edward, Crow Wing County. Classified as outwash sand.

7. Clayey red drift from cut through a hill 3 miles northeast of Swanville. Classified as till clay.

8. Fine sand from cut through a hill a mile north of Princeton. Classified as till clay.

9. White sand from pit on the east shore of Pelican Lake, Crow Wing County. Classified as outwash sand.

10. Red sandy drift from cut through hill about 5 miles west of Mora, Kanabec County. Classified as red till.

GRAY DRIFT

11. Drift from cut through hill near Richmond, Stearns County. Classified as outwash sand.

12. Drift from road cut, about 4 miles north of Elk River, in Sherburne County. Classified as morainic sand.

13. Drift from cut on east shore of Wautab Lake, Stearns County. There is a thick marl bed in the lake. Drift classified as sandy moraine.

14. Gray laminated clay west of the Mississippi River in Minneapolis. Classified as clayey moraine.

15. Gray laminated clayey drift near Albert Lea, Freeborn County. From area of clayey moraine.

16. Fine-grained silty swamp clay, Freeborn County. Area of clayey moraine.

17. Clayey glacial silt from near Grand Forks in the Red River valley. Classified as glacial lake sediments.

18. Same region as Sample 17.

19. Loess clay from the old gray drift sheet of Steele County.

20. Fine-grained gray drift clay from Freeborn County.

* Based on classifications by Leverett and Sardeson.

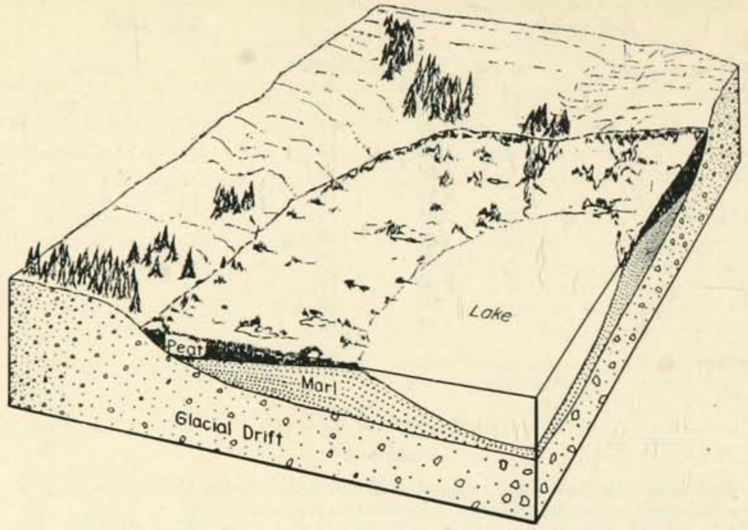

FIGURE 8. — Diagram of section of a lake basin showing marl that was precipitated from calcium bicarbonate in the lake water.

The amounts of sulphate and chloride in solution are generally low. The southeastern province is mostly covered with outwash sands and silts derived from the Grantsburg lobe of the late Wisconsin glacier. Because of their greater permeability, the waters in these sediments do not contain as great a concentration of dissolved mineral matter as the clayey gray tills of Itasca and Cass counties.

HARDNESS

The hardest waters occur in the deeper wells in the gray drift. Table 4 shows a maximum of 507 parts per million in Koochiching County and a minimum of 27 parts per million in eastern St. Louis County. The average hardness calculated from all analyses of waters from the red drift is 140 parts per million, whereas the average for waters in the gray drift is 270 parts per million.

The waters of the streams and lakes are generally softer than the underground waters. Table 5 gives the averages of a group of analyses compiled over a period of more than ten years. Vermilion Lake and Burntside Lake have the softest water; the hardness of the Mississippi River at Little Falls is more than three times as great as that of Rainy River at International Falls.

The influence of the permeability of the glacial drift on the leaching and transportation of calcium bicarbonate, which is the chief cause of the temporary hardness of underground waters, is strikingly shown by the distribution of calcium carbonate deposits in the lakes and bogs of northeastern Minnesota. These deposits, commonly called marl beds (Figure 8), are more numerous and far more extensive in the areas of red drift than in the areas of gray calcareous glacial sediments. This apparent discrepancy is undoubtedly due to the difference in texture of the drift, which in turn influences the rate of circulation of underground water.

Table 6 shows an average of 11.41 per cent of calcium carbonate in the gray drift and only 5.73 per cent in the red glacial deposits.[1]

Correlation of Marl Deposits with Texture of Drift Sheets

Glacial drift is deposited in a number of characteristic topographic forms. The most widespread are the hilly moraines, outwash plains, till plains, coarse outwash plains, and fine-grained sandy outwash plains. The majority of the marl beds that have been discovered in the state are located in areas of outwash gravels and in sandy and stony moraines. Their occurrences with respect to the texture of the glacial deposits are summarized in Table 7.

Table 7. — Number of Marl Beds Occurring in the Several Types of Glacial Deposits

County	Sandy Moraines	Clayey Moraines	Outwash	Till Plains	Total
Aitkin	18		5	1	24
Benton			3		3
Carlton	1	1			2
Cass	5			2	7
Chisago			1	2	3
Crow Wing	5		76		81
Isanti	2			1	3
Itasca		7	6		13
Mille Lacs		1	2		3
Morrison	4		2	1	7
St. Louis	2	1			3
Sherburne	1		22	2	25

Iron

The waters of northeastern Minnesota all contain small amounts of dissolved iron (Tables 8 and 9). Lake waters having access to the air for oxidation contain very little, but water in the deeper wells may contain several parts per million. Water that contains much iron is objectionable because of its turbid appearance after exposure to the air and because of the stains it makes on white porcelain or enamelware, and on clothing and other fabrics washed in it.

Table 8 shows that the waters in the ferruginous red drift contain less dissolved iron than those in the limy gray drift. This difference is due to the chemical state of the iron-bearing minerals in the two drifts. The red drift is red in color because the iron is oxidized and in that form it is quite insoluble. Even the waters in the iron ore bodies are low in dis-

[1] Stauffer, C. R., and Thiel, G. A., The limestones and marls of Minnesota: Minn. Geol. Survey Bull. 23, pp. 93–97, 1933.

TABLE 8. — AVERAGE IRON CONTENT OF WATERS FROM THE GLACIAL DRIFT OF NORTHEASTERN MINNESOTA *

Source	Iron in Parts per Million
Red Drift	
Benton County	.28
Carlton County	1.19
Crow Wing County	1.33
Kanabec County	.26
Mille Lacs County	.51
Morrison County	1.41
Average	.83
Gray drift	
Cass County	3.00
Chisago County	2.50
Itasca County	1.20
Koochiching County	4.20
Average	2.72

* Data from State Board of Health Laboratory.

TABLE 9. — AVERAGE IRON CONTENT OF WATERS FROM STREAMS AND LAKES OF NORTHEASTERN MINNESOTA *

Source	Iron in Parts per Million
Carlton County, Otter Creek	1.40
Koochiching County, Rainy River	.22
Koochiching County, Barrett Lake	.70
Mille Lacs County, Rum River	.60
Morrison County, Mississippi River	6.00
St. Louis County	
Burntside Lake	.05
Cedar Island Lake	.60
St. Mary's Lake	.06
Sagawa Lake	.06
Lake Superior	.10
Lake Vermilion	.10
Average	1.10

* Data from State Board of Health Laboratory.

solved iron. In the gray drift, however, most of the iron occurs as ferrous iron carbonate, which is taken into solution as iron bicarbonate.

CHLORINE

The average chlorine content of the waters of northeastern Minnesota is summarized in Table 11. In most areas the amount is small for both the surface waters and waters in the drift and bedrock formations. The higher figures for some of the counties are undoubtedly due to pollution from the surface, facilitated by the shallowness of the wells and the open texture of the materials.

Some of the wells that penetrate the lava rocks which occur along the North Shore of Lake Superior contain water with a high concentration of chlorides. This is especially true in the region of Hovland, where the deeper water contains more than 2000 parts per million of chlorine. Similar conditions exist in the flows of eastern Pine County where some waters contain nearly 4000 parts per million. Most of these waters are rich also in sulphate ions.

Sulphates

The waters of only a few localities contain an excessive amount of sulphates. Water in the lacustrine silts and fine sands of Koochiching County contains as much as 120 parts per million, but most of the water in the glacial drift has less than 50 parts per million of the SO_4 radical, and the surface lakes and streams average less than 10 parts per million. The highest concentration of sulphate ions is found in the waters of the deep wells drilled into the lava rocks in Lake and Cook counties. There the sulphates are associated with the chlorides referred to above. The average sulphate content of all waters analyzed is summarized in Table 11. Variations in individual formations are shown in Table 10.

TABLE 10. — AVERAGE CHEMICAL CHARACTER OF WATERS FROM VARIOUS STRATIGRAPHIC HORIZONS

	1	2	3	4	5
Hardness	242	113	169	178	171
Alkalinity	240	121	160	176	160
Iron	.66	.63	.70	.57	.19
Manganese	.70	.14	.03	.11	.04
Chlorine	16.2	.17	4.5	5.9	294
Fluorine	.06	.05	.05	.02	.14
SO_4 radical	9	9.6	23.8	70	155
pH value	7.90	7.50	7.40	7.45	8.40

1. Cambrian sandstones.
2. Hinckley sandstone.
3. Biwabik iron formation.
4. Iron ore bodies.
5. Keweenawan lava flows.

Drinking Water Standards[2]

"PHYSICAL AND CHEMICAL CHARACTERISTICS. 4.1. Physical characteristics. — The turbidity of the water shall not exceed 10 p.p.m. (silica scale), nor shall the color exceed 20 (standard cobalt scale). The water shall have no objectionable taste or odor.[3]

"4.2. Chemical characteristics. — The water shall not contain an excessive amount of soluble mineral substance, nor excessive amounts of

[2] United States Public Health Service Drinking Water Standards, adopted September 25, 1942: U.S. Public Health Reports, reprint no. 2440, vol. 58, no. 3, Jan. 15, 1943.

[3] Odor-symbols and values: a, aromatic; c, free chlorine; d, disagreeable; e, earthy; f, fishy; g, grassy; m, moldy; n, musty; p, peaty; s, sweetish; S, hydrogen sulphide; v, vegetable; 1, very faint; 2, faint; 3, distinct; 4, decided; 5, very strong; 0, none.

TABLE 11. — AVERAGE CHLORINE AND SULPHATE CONTENT OF WATERS FROM DIFFERENT SOURCES IN NORTHEASTERN MINNESOTA *

Source	Parts per Million	
	Chlorine	SO_4 Radical
Red drift		
Benton County	17.0	21
Carlton County	9.9	34
Crow Wing County	3.8	72
Kanabec County	1.8	10
Average	8.1	34
Gray drift		
Cass County	6.1	12
Chisago County	40.3	10
Isanti County	3.5	11
Itasca County	4.9	8
Koochiching County	6.1	58
Average	12.2	20
Bedrock formations		
Aitkin County	6.6	31
Chisago County	0.9	10
Isanti County	2.7	8
Lake County	14.0	
Mille Lacs County	23.0	35
Pine County (southern)	1.9	
St. Louis County	4.7	38
Average	9.4	24
Surface waters		
Otter Creek, Carlton County	1.1	...
Rainy River, International Falls	1.2	...
Barrett Lake, Koochiching County	2.7	...
Lake Superior, Two Harbors	1.6	...
Rum River, Milaca	0.0	...
Mississippi River, Little Falls	1.7	18
Vermilion Lake	1.1	5
Cedar Island Lake, Gilbert	7.0	...
Ely Lake, Gilbert	3.9	5.5
Sagawa Lake, Ely	2.6	...
Burntside Lake	2.1	...
St. Mary's Lake, Eveleth	1.8	2
Average	2.2	7.4

* Data from State Board of Health Laboratory.

any chemicals employed in treatment. Under ordinary circumstances, the analytical evidence that the water satisfies the physical and chemical standards given in sections 4.1 and 4.21 and simple evidence that it is acceptable for taste and odor will be sufficient for certification with respect to physical and chemical characteristics.

"4.21. The presence of lead (Pb) in excess of 0.1 p.p.m., of fluoride in excess of 1.0 p.p.m., of arsenic in excess of 0.05 p.p.m., of selenium in excess of 0.05 p.p.m., shall constitute ground for rejection of the supply. These limits are given in parts per million by weight and a reference to the method of analysis recommended for each determination is given in section 4.31. Salts of barium, hexavalent chromium, heavy metal glucosides, or other substances with deleterious physiological effects shall not be allowed in the water supply system.

"Ordinarily analysis for these substances need be made only semiannually. If, however, there is some presumption of unfitness because of these elements periodic determination for the element in question should be made more frequently.

"4.22. The following chemical substances which may be present in natural or treated waters should preferably not occur in excess of the following concentrations where other more suitable supplies are available in the judgment of the certifying authority. Recommended methods of analysis are given in section 4.3.

Copper (Cu) should not exceed 3.0 p.p.m.
Iron (Fe) and manganese (Mn) together should not exceed 0.3 p.p.m.
Magnesium (Mg) should not exceed 125 p.p.m.
Zinc (Zn) should not exceed 15 p.p.m.
Chloride (Cl) should not exceed 250 p.p.m.
Sulfate (SO_4) should not exceed 250 p.p.m.
Phenolic compounds should not exceed 0.001 p.p.m. in terms of phenol.
Total solids should not exceed 500 p.p.m. for a water of good chemical quality. However, if such water is not available, a total solids content of 1,000 p.p.m. may be permitted.

"For waters softened by the lime soda process the total alkalinity produced should not exceed the hardness by more than 35 p.p.m. (calculated as $CaCO_3$).

"For chemically treated waters the phenolphthalein alkalinity (calculated as $CaCO_3$) should not be greater than 15 p.p.m. plus 0.4 times the total alkalinity. This requirement limits the permissible pH to about 10.6 at 25° C.

"For chemically treated waters the normal carbonate alkalinity should not exceed 120 p.p.m. Since the normal alkalinity is a function of the hydrogen ion concentration and the total alkalinity, this requirement may be met by keeping the total alkalinity within the limits suggested when the pH of the water is within the range given. These values apply to water at 25° C.

pH *Range*	*Limit for Total Alkalinity* (p.p.m. *as* $CaCO_3$)	pH *Range*	*Limit for Total Alkalinity* (p.p.m. *as* $CaCO_3$)
8.0 to 9.6	400	10.1	210
9.7	340	10.2	190
9.8	300	10.3	180
9.9	260	10.4	170
10.0	230	10.5 to 10.6	160

III. DESCRIPTIONS BY COUNTIES

Surface Features, Unconsolidated Surface Mantle, Rock Formations, Municipal Water Supplies, Farm Water Supplies, Analyses of Waters

AITKIN COUNTY

SURFACE FEATURES

Aitkin County lies mainly in the southwestern part of the northeastern quarter of Minnesota. Nearly all the county is within the Mississippi River drainage basin; only a few square miles in the northeastern corner are tributary to Lake Superior through the St. Louis River. Much of the county is poorly drained and more than 800 square miles are swampy. Lakes are numerous and part of Mille Lacs Lake, the second largest lake in the state, lies in the southwestern corner of the county. A temporary glacial lake, commonly referred to as Lake Aitkin, covered much of the township of Aitkin and extended northeastward across the northwestern part of Spencer Township and northeastward across most of Morrison Township. This area was occupied by a sublobe of the St. Louis lobe of the Keewatin ice sheet. Morainic tracts occur in the northern part of the county and in an east-west belt between Aitkin and Mille Lacs Lake, but a large part of the county is a smoothly undulating till plain.

The morainic hills in the northwestern townships reach elevations of 1400 to 1450 feet, while the lowlands along the Mississippi River are about 1200 feet above sea level. The divide that serves as the watershed between the tributaries of the Mississippi River and those of the Snake River stands at about 1350 feet. The surface of Mille Lacs Lake shows seasonal fluctuations, but its average elevation is about 1250 feet above sea level.

UNCONSOLIDATED SURFACE MANTLE

All of Aitkin County is covered with a mantle of glacial drift or with postglacial alluvial sediments. Local areas have thick deposits of peat underlaid by beds of marl. Three Wisconsin drifts — Patrician, Keewatin, and Superior — are present. The Patrician, which is the oldest of the three, is at the surface in the western part of the county and underlies the other drifts in the remainder of the county. The Keewatin drift covers most of the northern half and extends in places a few miles into the southern half of the county. It does not, however, cover the Patrician drift in an area of high land in the northwestern part of the county south and west of the Willow River. The Superior drift covers several townships in the southeastern townships, where it forms several conspicuous moraines.

The Patrician ice sheet deposited a series of moraines across the county, but those of the northern half of the county were overridden by the St. Louis lobe of the Keewatin ice sheet. As a result of this overriding, the surface has in many places been rendered smoother. The areas of morainic topography are underlaid by gravel, sand, and very stony glacial till. In such areas the drift yields large quantities of water. The till plains of Keewatin (Mankato) drift, however, are composed mainly of impervious boulder clays. In such areas the specific yield of drift wells is small. The drift has an average thickness of between 150 and 200 feet. Table 12, compiled from exploratory drilling records, shows the variations in thickness.

TABLE 12.— DEPTH TO BEDROCK IN AITKIN COUNTY

Location	Depth (feet)
SE ¼, NE ¼, Sec. 25, T. 44 N., R. 23 W.	56
SE ¼, NE ¼, Sec. 25, T. 44 N., R. 23 W.	67
SW ¼, NW ¼, Sec. 26, T. 44 N., R. 23 W.	72
SW ¼, NW ¼, Sec. 5, T. 45 N., R. 25 W.	16
SW ¼, NW ¼, Sec. 28, T. 46 N., R. 25 W.	20
SW ¼, NW ¼, Sec. 12, T. 47 N., R. 26 W.	95
SW ¼, NW ¼, Sec. 3, T. 47 N., R. 27 W.	110
SW ¼, NW ¼, Sec. 35, T. 48 N., R. 26 W.	80
SW ¼, NW ¼, Sec. 18, T. 48 N., R. 26 W.	237
SW ¼, NW ¼, Sec. 26, T. 50 N., R. 26 W.	260
SW ¼, NW ¼, Sec. 6, T. 50 N., R. 25 W.	185
SW ¼, NW ¼, Sec. 7, T. 50 N., R. 25 W.	200
SE ¼, SW ¼, Sec. 8, T. 50 N., R. 25 W.	270
SW ¼, NW ¼, Sec. 20, T. 50 N., R. 25 W.	290
NE ¼, NE ¼, Sec. 23, T. 51 N., R. 23 W.	208
SW ¼, NE ¼, Sec. 25, T. 52 N., R. 23 W.	202
NW ¼, SW ¼, Sec. 10, T. 52 N., R. 22 W.	150

ROCK FORMATIONS

PRE-CAMBRIAN

There are only a few known areas of outcrops of bedrock formations in Aitkin County. Gneissic granite crops out near the southern county line along the Snake River in Williams Township (T. 43 N., R. 23 W.) and southwest of McGrath in the northeastern sections of Idun Township (T. 43 N., R. 24 W.); a pink augen-gneiss crops out on both sides of the east-west road between Sections 1 and 12 and westward between Sections 2 and 11 (Figure 9). Granite exposures occur also in Sections 34 and 35 in Millward Township (T. 45 N., R. 22 W.) south of Arthyde. Petrographic analyses indicate that all the granites are of Algoman age.

Basic, hornblendic gneiss crops out both east and west of Long Lake in Glen Township (T. 46 N., R. 25 W.). Winchell correlated these basic rocks with the Keewatin recrystallized schists of the Coutchiching

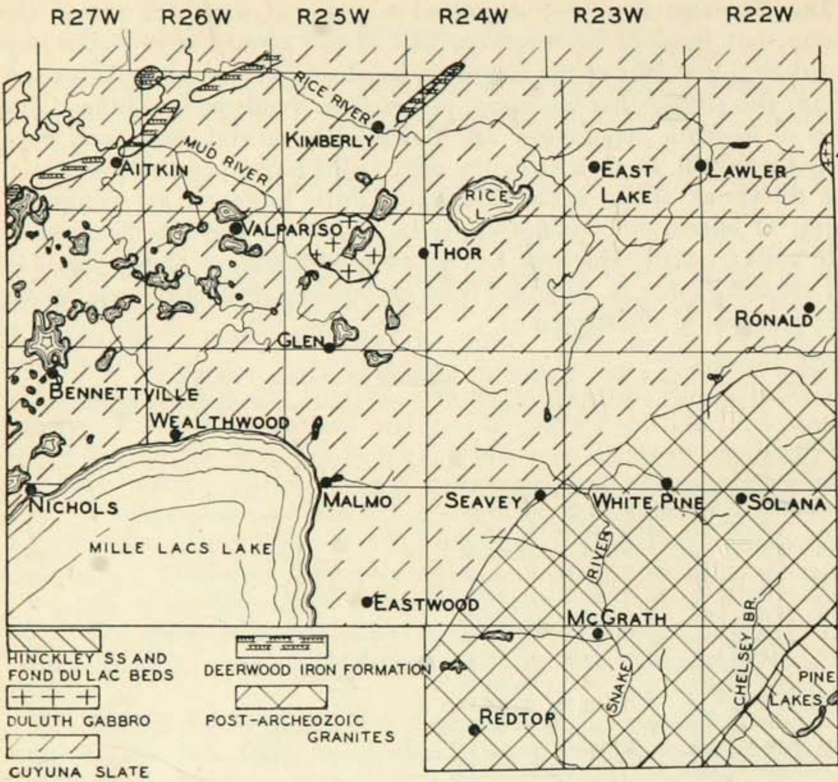

FIGURE 9. — Geologic map of southern Aitkin County.

area.[1] More recent studies indicate, however, that they are of Proterozoic age.

Quartzitic rocks occur at and near the surface along the west side of Dam Lake in Kimberly Township (T. 47 N., R. 25 W.). It crops out along the shore of the lake for a distance of about 240 feet and rises 4 or 5 feet above the level of the lake. The rock is massive, coarse-grained, and of uneven texture. Winchell considered these quartzites as the equivalent of the Pokegama quartzite of the Mesabi Range.[2]

Exploratory drilling for iron ore has demonstrated the presence under the drift of ferruginous cherts interbedded with slates and schists in a zone from the west county line near Aitkin northeastward toward Sandy Lake (Figure 10). To the north and east of this zone most of the bed-

[1] Winchell, N. H., The geology of Minnesota: Final Rept., Minn. Geol. and Nat. Hist. Survey, vol. 6, plate 57, 1901.

[2] Winchell, N. H., *op. cit.*

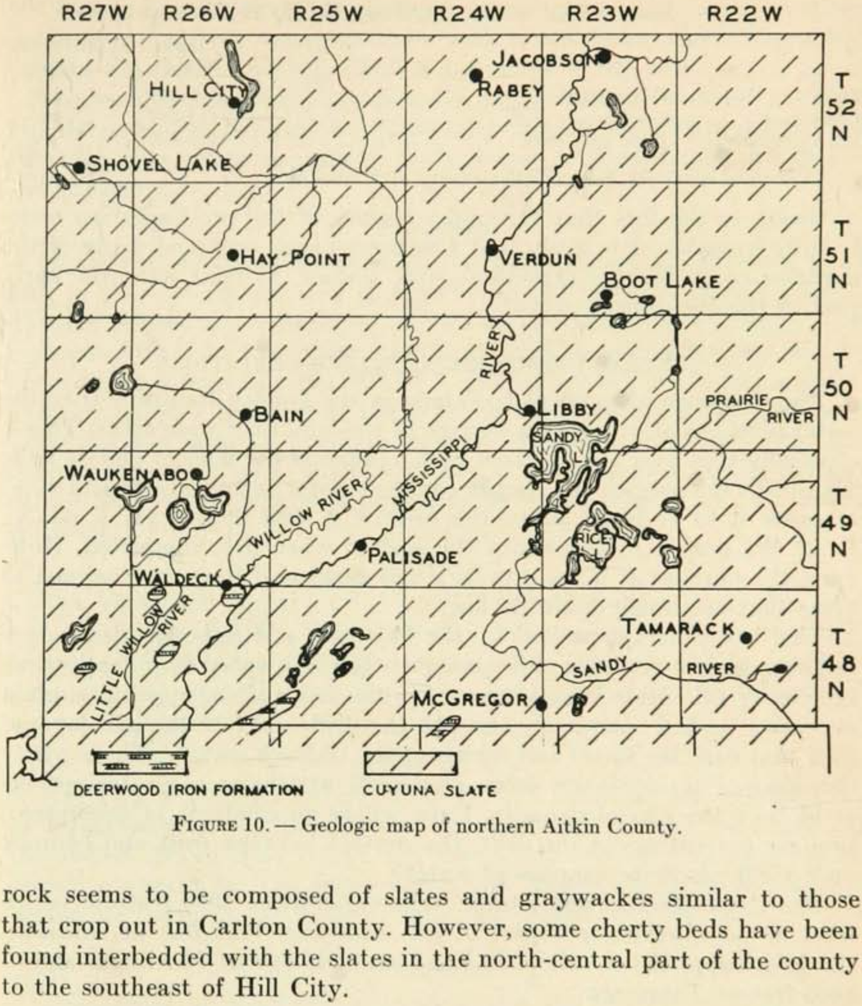

FIGURE 10. — Geologic map of northern Aitkin County.

rock seems to be composed of slates and graywackes similar to those that crop out in Carlton County. However, some cherty beds have been found interbedded with the slates in the north-central part of the county to the southeast of Hill City.

MESOZOIC

CRETACEOUS SYSTEM

No Cretaceous rocks are known to crop out in Aitkin County, but the clayey blue-gray glacial till with fragments of lignite indicates that Cretaceous sediments were mingled with the drift. Furthermore, exploratory drilling in the north-central part of the county has demonstrated fossiliferous, marine, Cretaceous strata in places under the glacial drift. The accompanying log gives a typical section.

Hole Drilled in Sec. 23, T. 50 N., R. 27 W.*

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–212	212
Cretaceous	Gray, sandy shale	212–372	160
Pre-Cambrian	Dark gray slate	372–429	57

* Compiled by G. M. Schwartz, University of Minnesota.

Owing to the fact that the upper surface of the pre-Cambrian rocks is quite irregular, it is likely that Cretaceous beds occupied many of the depressions on the old crystalline rock surface, at least until the early part of the Pleistocene period.

GENERAL UNDERGROUND WATER CONDITIONS

The existence of extensive swamps in the county indicates that the water level lies at or near the surface of the land over wide areas. This is especially true over the flat area that represents the floor of glacial Lake Aitkin. In that region the deeper confined water is under sufficient head to cause it to be lifted above the surface. A well in Sec. 14, T. 47 N., R. 27 W., flowed 15 feet above the surface when first completed. However, the number of flowing wells is not great and they are confined to areas that are topographically low.

The drift sheets deposited by the Patrician and Superior glaciers are in general more pervious and consequently yield water more freely than the clayey till of late Wisconsin age. In the areas of clayey till it is often necessary to drill completely through the drift and into the decomposed rock that caps the slates and schists of the bedrock surface. These partly decomposed residuals are more permeable and have a greater specific yield than the glacial deposits. Even where no products of decomposition are present under the drift, the contact between drift and bedrock may yield adequate supplies of water.

The static level in water-table wells varies from 1300 feet above sea level in the northwestern part of the county to 1200 feet at Aitkin in the Mississippi River valley. It stands at 1225 feet at McGregor and at 1260 feet at Tamarack.

MUNICIPAL WATER SUPPLIES

AITKIN [3]

The city of Aitkin obtains water for its public supply system from a group of shallow wells 20 to 30 feet deep. Well No. 1 is 30 inches in diameter and 22 feet deep. It is pumped at the rate of 90 gallons per minute. Well No. 2 is 10 inches in diameter and 20 feet deep. It is pumped at the rate of 125 gallons per minute. Well No. 3 is 8 inches in diameter and 27 feet deep. Well No. 4 was drilled to a total depth of

[3] Data from Mr. Fuller, Superintendent, Light and Water Department.

360 feet. It encountered slaty bedrock at a depth of 150 feet. The slates produced very little water and the well is not being used. The static level in the shallow wells is about 10 feet below the surface.

The well at the Aitkin creamery is 4½ inches in diameter and 154 feet deep. It was pumped 60 gallons per minute with little drawdown. However, fine silt in suspension in the water renders it unfit for use in the creamery.

McGregor

McGregor is located on an extensive sandy plain that covers a large area in the east-central part of the county. The surface of the plain is about 1230 feet above sea level. A well for the public water supply system was drilled in 1932. The well is 3 inches in diameter and 80 feet deep. When pumped at the rate of 5 gallons per minute it has a drawdown of 10 feet.[4] A well near the depot of the Northern Pacific Railway Company is 8 inches in diameter and 120 feet deep. It yields 85 gallons per minute with slight drawdown from a bed of gravel at the bottom of the well. When not being pumped, its static level is 10 feet below the surface.

Tamarack

The village of Tamarack lies east of the McGregor sand plain and near the south end of a glacial swamp that gives the village its name. There is no public water supply system. The Northern Pacific Railway Company has a well 43 feet deep in typical boulder till. The static level is near the surface.

Hill City[5]

Hill City is situated to the northwest of a morainic hill that reaches an elevation of more than 100 feet above the level of the tributaries of the Willow River. The village has a well 245 feet deep in impervious, clayey, glacial drift. The water is pumped from a sandy layer near the bottom of the well. No bedrock formations were penetrated.

Kimberly

The village of Kimberly is located near the margin of a Patrician moraine that was partially overridden by the Keewatin ice sheet. Thus there is an area of red drift to the south and younger gray drift to the north of the village. There is no public water supply system in the village. A well at the schoolhouse is 117 feet deep. It penetrates 115 feet of glacial drift and 2 feet of gray slate. Water enters the well at the contact between the drift and the slate.[6] The well on a farm half a mile west of the village encountered slaty bedrock at a depth of 80 feet.

[4] Data from Frank Hiller, driller.
[5] Data from R. Corbett, driller, Aitkin.
[6] Data from Hasskamp Brothers, drillers, Aitkin.

McGrath

McGrath is located in the southeastern part of the county in Williams Township, at the north margin of the Mille Lacs moraine of the Patrician ice sheet. The water supply for the village is taken from a well 84 feet deep that terminates in the glacial drift.[7]

Malmo

Malmo is a village on the northeastern shore of Mille Lacs Lake. The well at the tourist resort is 80 feet deep and terminates in the glacial drift. Another private well a short distance from the resort reached granite at a depth of 112 feet.

Arthyde, Bain, Palisade, Shovel Lake, Swatara, Washburn

These villages have no public water supply systems.

FARM WATER SUPPLIES

In the areas where the regional water table is near the surface, dug and bored wells are common. In the outwash tracts along the Willow and Mississippi rivers, driven and dug shallow wells yield generous supplies of water. In the moraines and till plains digging or drilling is

Table 13. — Flowing Artesian Wells near Aitkin, T. 47 N., R. 27 W.

Location	Thickness of Drift	Total Depth (feet)
Sec. 12	265	270
Sec. 13	230	237
Sec. 14	211	281
Sec. 20	160	160

continued until the hole penetrates an enclosed layer or pocket of sand or gravel from which water may enter the well freely. The extent, thickness, depth, porosity, and yield are different for each pocket or lens of sand. Few holes penetrate the drift completely without encountering one or more of them, although some are too thin, too small, or too fine to yield adequate supplies of water. On the morainic hills the upper sand layers may be dry and it is then necessary to drill deeper to get below the water level.

In Aitkin Township (T. 47 N., R. 27 W.) a number of farm wells flow at the surface. In the flowing wells listed in Table 13 the surface elevation is about the same, but the irregularity of the bedrock surface is shown by the variations in the thickness of the glacial drift.

[7] Data from Mr. Dahl, driller, Isle.

TABLE 14. — ANALYSES OF WATERS OF AITKIN COUNTY *

	1	2	3	4
Depth (feet)	100	250	250	360
Hardness	273	210	163	260
Alkalinity	292	272	204	270
Iron	.3	...	.1	.25
Manganese	...	...	...	.2
Chlorine	1	6	4	10
Fluorine	...	...	...	0
SO_4 radical	...	...	...	31
Turbidity	3	3	3	.4
Color	15	50	5	10
Odor	0	0	0	...
pH value	...	...	...	7.7

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon=17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Hill City, drilled well, 1922.
2. Aitkin, drilled well, May 1921.
3. Aitkin, drilled well, September 1921.
4. Aitkin, drilled well, August 1942.

BENTON COUNTY

SURFACE FEATURES

A large part of Benton County is occupied by a red drift till plain. The only moraine occurs as a narrow zone in a northwest-southeast direction across the northeasternmost township. A sharp sand and gravel ridge that may be an esker extends from Ronneby southwestward, passing just south of Foley and extending as far as the north-central part of St. George Township (T. 36 N., R. 29 W.). A broad outwash plain parallels the valley of the Mississippi River and extends eastward along the southern border of the county to the valleys of the Elk and St. Francis rivers.

The amount of relief is not great. The plain along the Mississippi River stands at an elevation of about 950 feet and the highest elevations occur in the moraine east and northeast of Foley where some of the drift knolls reach an elevation of 1175 feet. Some of the granite knobs that are exposed in the central and northeasternmost townships are as much as 1100 feet above sea level.

The drainage is all to the Mississippi River, but only a small strip along the river drains directly into it. The drainage tends to take courses that parallel the Mississippi rather than flow toward it. The western part drains through the Elk River southeastward across Sherburne County, while the southeastern townships drain southeastward into the Rum River, which enters the Mississippi at Anoka.

UNCONSOLIDATED SURFACE MANTLE

The upper surface of the mantle rock layer is the red drift deposited by the Patrician glacier. These glacial sediments rest on an older gray drift of Kansan or Nebraskan age that is exposed along the crests of some of the drift ridges. Over parts of the till plain in the central part of the county, the interglacial valleys cut into the old gray drift are only partially filled with Patrician red till, and many farm wells penetrate a dark gray, clayey drift under the red sandy and stony glacial deposits. Early postglacial alluvial sediments are deposited over the drift along the valley of the Mississippi River, and lacustrine silts of glacial Lake Grantsburg are present in the southeastern townships. A westward extension of the Anoka sand plain with local areas of dune sands crosses the central part of the county.

In the southeastern part of the county a gritty, white clay occurs beneath the drift and above the granite. Well drillers refer to the clayey material as "marl." It is rather a kaolinite clay formed as a residual deposit by the weathering of the underlying granite.

The drift varies in thickness from 0 to 175 feet. Marked local variations in thickness are due to the abrupt irregularities in the upper surface of granite. This is shown typically at Sartell, where the granite is exposed in knoblike outcrops a short distance north of the village, whereas a well in the village penetrated 150 feet of drift before encountering the top of the granite.

ROCK FORMATIONS

Pre-Cambrian

Pre-Cambrian igneous and metamorphic rocks occur directly beneath the drift over most of Benton County (Figure 11). They are exposed in a broad zone along the Mississippi valley from Watab to East St. Cloud. Areas of groups of outcrops occur along the Elk River and its tribu-

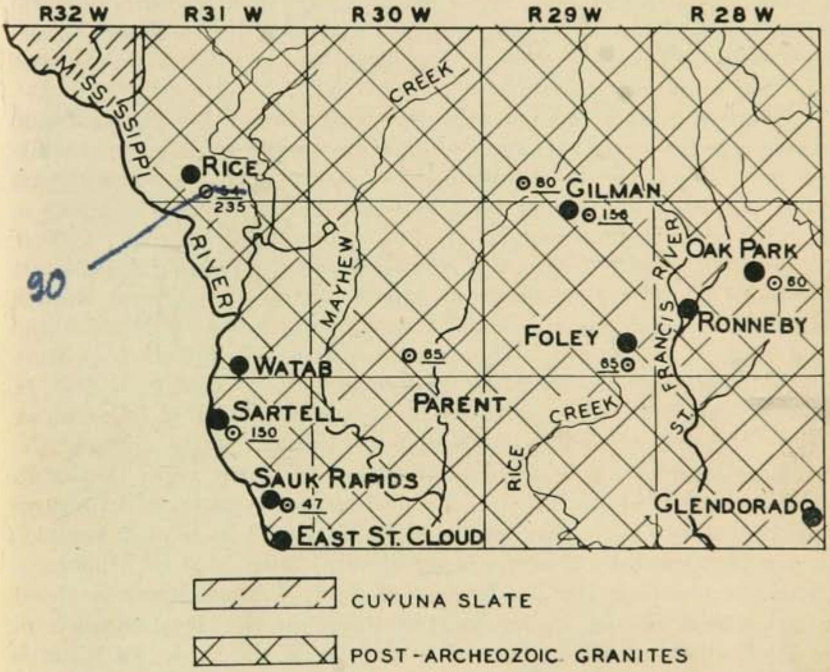

Figure 11. — Geologic map of Benton County. The small circles indicate drill holes that reached bedrock at the depth shown by the upper figure. The lower figures show the total depth of the wells.

taries in the west-central part of the county and along the tributaries of the Rum River in the northernmost township. The pink and red granites are of Middle Keeweenawan age and the gray granites and diorites are Algoman. Harder and Johnson give the following descriptions of the rock exposures:

"Most of the outcrops occur in groups, but isolated, scattered outcrops are also abundant. The most northerly of the groups of outcrops is that south of Watab on the east side of the Mississippi River. Three rocky knolls are found here between the tracks of the Northern Pacific Railway and the river. The knolls consist principally of a dark, fine-grained hornblende rock, probably a diorite. Locally between the knolls fine to medium-grained pink granite which appears to be intrusive in the diorite crops out. In the knoll farthest east near the railroad a quarry occurs in the pink granite, in which several phases are shown.

"From Watab southward to Sauk Rapids exposures of diorite and pink and gray granite occur at frequent intervals. Most of them are found from 1 to 3 miles east of Mississippi River, but west of the river there are also scattered outcrops. About 1½ miles north of Sauk Rapids and 2 miles east of the river, are situated a number of quarries. Several different types of granite are taken from these, including medium coarse-grained pink hornblende granite and light to dark gray biotite and hornblende granite.

"At Sauk Rapids a number of outcrops are found. On the east side of Mississippi River are exposures of dark gray hornblende granite, while on the west side below the bridge is an exposure of coarsely porphyritic rhyolite porphyry containing both feldspar and quartz phenocrysts in a gray, finely crystalline matrix. . . .

"A group of granite outcrops of considerable extent is found northeast of the Saint Cloud region along the upper courses of the West Branch of Rum River and Saint Francis River in northeastern Benton and western Mille Lacs counties. The outcrops on the West Branch of Rum River both in Benton and Mille Lacs counties are said to consist of remarkably uniform, coarse-grained, reddish syenite. They occur along the river through an extent of about 2 or 3 miles. Many different exposures are found, most of them small ledges occurring along the banks or in the channel of the stream. The westernmost group of exposures is a short distance above the mouth of Stony Brook in Benton County, while the easternmost exposures occur about 3 miles west of Milaca.

"The outcrop near the headwaters of Saint Francis River is about four miles west of the westernmost outcrop on the West Branch of Rum River in the northern part of section 20, T. 38 N., R. 28 W. It is reported to be about 25 rods long by 15 rods wide and to consist of reddish syenite cut by an east and west trap dike. The dike is from a foot to a foot and a half wide and has fine-grained syenite on the north side and coarse-grained syenite on the south side."[1]

The bedrock surface is the highest in the northeastern part of the county, where the granite outcrops along the West Branch Rum River are at an elevation of 1135 feet. In the south-central townships granite is encountered at a depth of about 75 to 100 feet or at an elevation of 975 feet above sea level. A short distance east of the southeasternmost

[1] Harder, E. C., and Johnson, A. W., Geology of East Central Minnesota: Minn. Geol. Survey Bull. 15, pp. 38–40, 1918.

township pre-Cambrian rocks crop out along Estes Brook at an elevation of 1060 feet. Table 15 shows the major variations.

TABLE 15. — ELEVATIONS OF THE BEDROCK SURFACE, BENTON COUNTY

Location	Elevation above Sea Level (feet)
Along West Branch Rum River	1135
Gilman	1095
Oak Park	1070
Foley	1060
Estes Brook	1060
Rice	975
Sauk Rapids	960

GENERAL UNDERGROUND WATER CONDITIONS

The yield of water from the drift varies greatly. If, however, a layer of porous sand or gravel is penetrated at a depth of 50 to 150 feet below the surface, a moderate yield may be expected. Since several drift sheets are present, yellow clays and sands may be expected under the red Patrician till. These oxidized zones yield softer water than the bluish-gray drift that lies directly above the granite. The yellow color is due to the oxidation that penetrated from the surface downward while the clays and sands were near the surface, before the last drift sheet was deposited over them.

The outwash sediments and alluvial deposits along the Mississippi valley are saturated with water, but near the stream the exposed edges do not retain much water. Elsewhere they may yield large quantities.

In general the yield of water from the drift depends upon the thickness and depth of the sand and gravel beds associated with it. The supplies from shallow beds are generally meager, but the yield of the deeper zones is generous and permanent. The yields of individual wells are given in the discussion of the supplies of the various cities and villages in the county.

The head of the water varies with the relief of the region. In some localities the water is under sufficient pressure to lift it near the surface. Along the valleys some wells in the drift flow at the surface, but the yield is not great.

MUNICIPAL WATER SUPPLIES

FOLEY

The city of Foley is located in the south-central part of the county in Sec. 26, T. 37 N., R. 29 W. It is situated on the till plain at an elevation of 1130 feet, about 2 miles west of the St. Francis River. In this region granite bedrock lies from 50 to 75 feet below the surface.

The public water supply is taken from a well 56 feet deep that terminates in the glacial drift. A well near the courthouse reached granite at

96 feet and one near the depot struck the bedrock at 60 feet. The creamery well obtains its water at the drift-granite contact at a depth of 65 feet.

A farm well 3½ miles east of the city entered granite at a depth of 47 feet and a well in Sec. 34, T. 37 N., R. 29 W., about 1½ miles to the southwest, penetrated 65 feet of bluish-gray till over the granite.

Rice

The private wells in the village of Rice are mostly dug and driven to a depth of 30 to 60 feet. The Northern Pacific Railway Company's well at the depot is 70 feet deep in sand and gravel. The water rises to a static level about 25 feet below the surface. It is pumped at the rate of 8 gallons per minute. South of the village in Sec. 32, T. 38 N., R. 31 W., a farm well encountered granite at a depth of 90 feet, or 978 feet above sea level.[2]

A well at Jansky's potato warehouse in the village penetrated the following formations.

Well at Jansky's Potato Warehouse, Rice *

		DEPTH (feet)	THICKNESS (feet)
Drift	Sand and gravel	0–40	40
	Brown, stony hardpan	45–54	9
	Sand and clay	54–93	39
Pre-Cambrian	White clay	93–98	5
	Sticky red and white clay	98–185	87
	Greenish red and white clay	185–235	50
	Granite	entered	

* Data from G. Nugent, Sauk Rapids.

The well produced very little water, but a small yield was developed in the sands and clays from 65 to 95 feet below the surface. The residual clays over the granite were too impervious to allow water to reach the drilled hole.

Sauk Rapids

The city of Sauk Rapids is situated on the east bank of the Mississippi River near the southeast corner of the county. It adjoins East St. Cloud in Sec. 26, T. 36 N., R. 31 W. Many granite exposures occur in this vicinity and the mantle of glacial drift is thin. Therefore, all wells must be shallow and of large diameter if a moderately large volume of water is required.

The city has several wells. One is a drilled well 10 inches in diameter and 47 feet deep. The yield from this well is not sufficiently great to supply the demands of the population. Consequently, a well 16 feet in diameter was dug to a depth of 40 feet. The static level is about 25 feet below the surface.[3]

[2] Data from Frank Long, driller, Sauk Rapids.
[3] Data from Kernan and Long, drillers, St. Cloud.

Sartell

This village has no public water supply system. A well at the Watab Paper Company is 12 inches in diameter and 85 feet deep. It is pumped at the rate of 1000 gallons per minute and continues to give a satisfactory yield. A test hole near the well site reached granite at a depth of 150 feet.[4]

Gilman

The village of Gilman is located at the north boundary of Gilmanton Township east of the Elk River. In this area the upper surface of the granite is quite irregular, varying from 75 to 150 feet below the surface. Both the bluish-gray and the younger red drift sheets are found over the bedrock surface.

The village has no public water supply system, but private wells obtain abundant supplies above the granite. Most wells are dug or bored, but the deeper wells are drilled. One drilled well penetrated 156 feet of drift before reaching granite. The creamery well is 108 feet deep and has a static level 25 feet below the surface. A farm well across the road from the creamery struck granite at a depth of 88 feet. It produced a very limited yield of water.

East of Gilman in Sec. 32, T. 38 N., R. 28 W., on the farm of William Seemers, a well penetrated 80 feet of bluish-gray till and obtained water at the contact zone between drift and granite. South of the village in Sec. 9, T. 37 N., R. 29 W., the drift is impervious clay and wells from 75 to 100 feet in depth yield only enough water for the most restricted requirements.

Oak Park

The water supply for the village of Oak Park is taken from private wells. The granite bedrock lies from 50 to 60 feet below the surface and consequently all wells are shallow. The water for the creamery is supplied by three wells dug to the top of the granite. Small diameter wells yield very little water.

East St. Cloud

In the region of East St. Cloud a layer of residual white kaolinite clay has formed from the weathering of the upper part of the granite. This clay underlies 40 to 60 feet of alluvial sands and glacial till. Shallow private wells obtain satisfactory supplies of water for domestic use from the sediments above the clay. West of the river in St. Cloud there are a number of flowing wells, varying in depth from 40 to 100 feet, from which the water rises about 15 feet above the level of the Mississippi River. They are situated on a terrace below the level of the outwash plain.

The public supply of water for East St. Cloud is pumped from the Mississippi River.

[4] Data from Frank Long, driller, Sauk Rapids.

FARM WATER SUPPLIES

The general underground water conditions for the county are outlined above. The following descriptions are of typical farm wells.

A farm well in Sec. 14, T. 37 N., R. 31 W., is 90 feet deep and terminates in glacial till. No bedrock was encountered and the static level of the water is 30 feet below the surface.

A farm well in Sec. 15, T. 37 N., R. 30 W., has a total depth of 75 feet. It penetrates a bluish-gray glacial drift that has occasional thin layers of sand and gravel. The well does not reach the bedrock surface and its static level varies slightly.

A farm well east of Little Rock Lake in Sec. 2, T. 37 N., R. 31 W., passes through 85 feet of clayey till and hardpan and obtains water from a sand layer 2 feet in thickness that yields water freely.

Other farm wells that reach the bedrock surface are described above, in the discussions of the water supplies of the various villages.

TABLE 16. — ANALYSES OF WATERS OF BENTON COUNTY *

	1	2	3	4
Depth (feet)	49	47	48	59
Hardness	208	227	170	230
Alkalinity	192	171	160	150
Iron	.4	.2	.47	.05
Manganese	...	...	.42	.12
Chlorine	6	7	17	36
Fluorine	...	...	.25	.3
SO_4 radical	...	...	19	24
Turbidity	8	5	.4	...
Color	52	9	28	...
Odor	Gas 2	0	...	...
pH value	...	...	7.6	8.0

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Sauk Rapids, three drilled wells, 1923.
2. Sauk Rapids, dug well, 1926.
3. Sauk Rapids, dug well, 1943.
4. Foley, drilled well, 1943.

CARLTON COUNTY

SURFACE FEATURES

Carlton County is located at the southwest end of Lake Superior. Owing to the gorge of the St. Louis River, which approaches the level of Lake Superior in the northeastern township, the county has a maximum relief of about 750 feet. The highest area is in Sec. 3, T. 49 N., R. 16 W., northeast of Cloquet, where the morainic hills reach an elevation of 1400 feet above sea level. Another high area occurs along the morainic divide between the headwaters of the Kettle River and the tributaries of the St. Louis River to the north of Cromwell. There are six distinct moraines which were developed on the northwest border of the Superior lobe of the late Wisconsin ice sheet in Carlton County and the adjacent part of St. Louis and Aitkin counties (Figure 7). On the south side of the ice lobe in southern Carlton County and northern Pine County, the moraines are combined into two morainic belts, with the Fond du Lac moraine banked against the Nickerson moraine in the southeastern part of the county and eastward into Wisconsin. The Fond du Lac moraine at the west end of the ice lobe was laid down in ponded waters of glacial Lake Nemadji and was later covered by the waters of glacial Lake Duluth.

There were three glacial lakes in Carlton County, formed like Lake Agassiz by the waters that resulted from the melting of the glaciers being dammed in by the contour of the land while the lower outlet was closed by the glacier. One of these was Lake St. Louis; its outlet 523 feet above Lake Superior was through Otter Creek and across Mahtowa Township, uniting with the Moose River valley near Barnum. The second has been named Lake Nemadji and its outlet was across T. 46 N., R. 18 W., at a height of 468 feet above Lake Superior. The third was glacial Lake Duluth, which extended southwestward across the county beyond the city of Moose Lake. The uppermost beach of Lake Duluth stood 1070 to 1076 feet above sea level in the vicinity of its outlet at the Brule Valley in Wisconsin.

"The shore lines of Lake Duluth show marked northeastward differential uplift throughout their extent. Near the west end there is a rise of about 60 feet between the altitude of the south shore line and that at Duluth, though the intervening space is only about 24 miles. The highest shore line appears to extend eastward only into southwestern Lake County, Minnesota, where it has an altitude of 1,165 feet. The shore lines that continue into the northeast corner of Minnesota show that the lake there covered ground that is now 1,300 feet above sea level, or 700 feet above Lake Superior. The upper limit on the Keweenaw Peninsula near Calumet, Michigan, is similar, being 1,305 feet. A comparison of altitudes of beaches on the north and south shores of Lake

Duluth indicates that over much of its area the direction of the line of maximum tilting is about N. 32° E. Data bearing on this matter are given in a recent report."[1]

UNCONSOLIDATED SURFACE MANTLE

All the county with the exception of a part of the northwesternmost township is covered with red glacial drift from the Superior lobe of the late Wisconsin ice sheet. Since the Patrician ice had melted away from its moraines before the Superior ice advanced over them, there are two drift sheets from the same direction, one superimposed on and intermixed with the other.

The drift is mainly loose-textured, sandy, and stony, but in places it consists of heavy impervious clay. That of the Superior lobe is generally a brighter red than that deposited by the Patrician ice. The pebbles consist largely of sandstone and of basic volcanic rocks from the borders of the Lake Superior basin. However, in the western and south-central part of the county slate and graywacke pebbles are most prominent.

There is a thin deposit of sand over the part of the bed of glacial Lake Nemadji beyond the Thomson moraine, but inside the Fond du Lac moraine the lake bed is a stiff, heavy clay. A thick deposit of calcareous clay in the vicinity of Wrenshall may be referable to the drainage from glacial Lake St. Louis, which received its sediments from the St. Louis sublobe of the Keewatin glacier. These clays are conspicuously laminated or varved, indicating that they were deposited from ponded waters.

There is a broad zone of outwash sands and gravels extending in a northeast-southwest direction from Moose Lake to Carlton. These deposits are sufficiently thick so that the regional water table keeps the lower portion of the sediments saturated. Their coarser texture makes them highly permeable and consequently they yield water generously.

ROCK FORMATIONS

PRE-CAMBRIAN

Igneous and metamorphic rocks of pre-Cambrian age crop out in widely separated areas over the northwestern three-fourths of Carlton County (Figure 12). Most of the exposures occur along the St. Louis River between Cloquet and Fond du Lac, and from the city of Carlton southwesterly along an old valley where the glacial lakes of the Superior basin overflowed into the Kettle River drainage area.

In the region of Carlton, Thomson, Scanlon, and Cloquet, exposures

[1]Leverett, Frank, Quaternary geology of Minnesota and parts of adjacent states: U.S. Dept. of Interior Prof. Paper 161, p. 55, 1932. The report referred to in the last sentence is Leverett, Frank, Moraines and shore lines of the Lake Superior basin: U.S. Geol. Survey Prof. Paper 154, pp. 57–63, 1929.

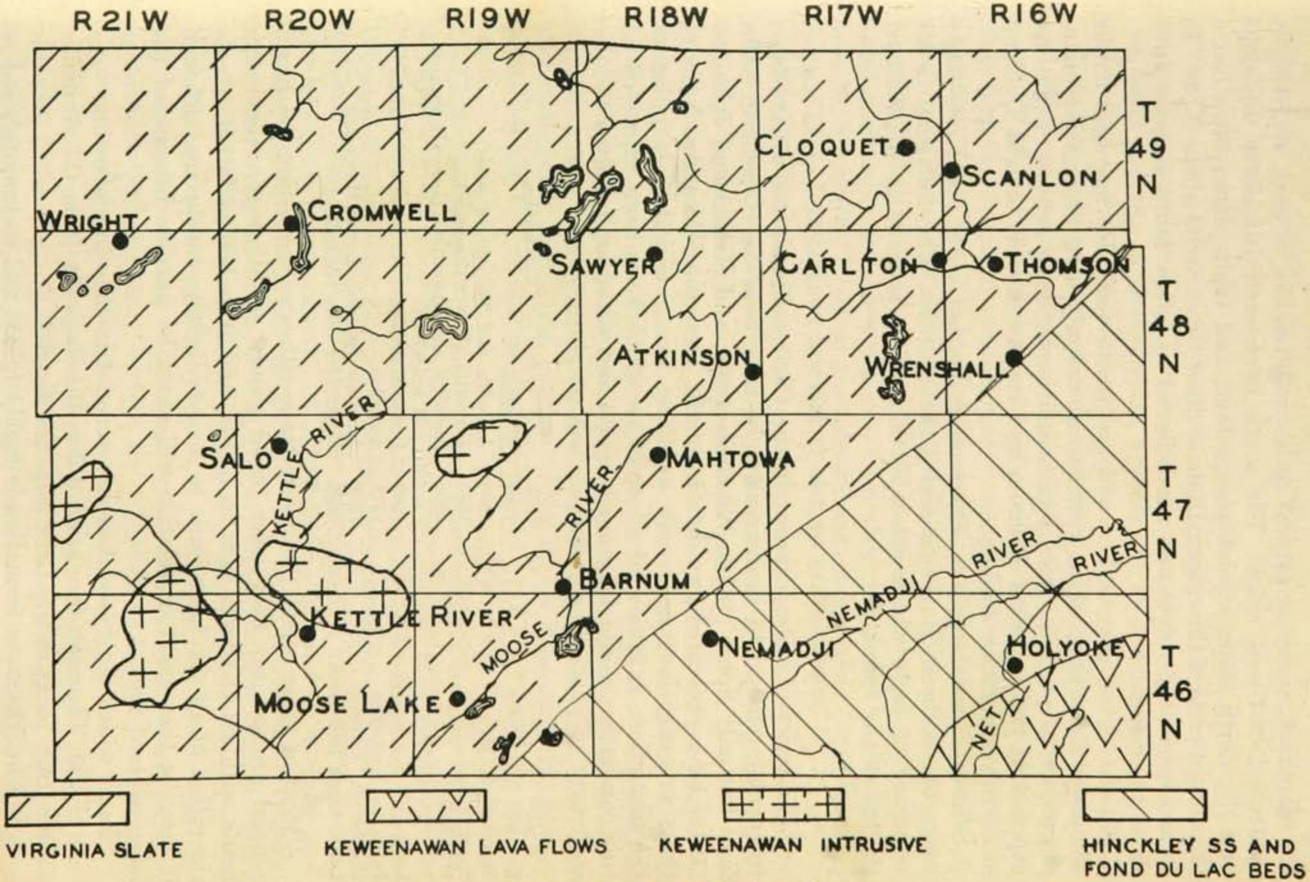

FIGURE 12. — Geologic map of Carlton County.

are abundant, many as typical roches moutonnées in long, structurally controlled east-west ridges. The south is characteristically a dip slope and the north slope a joint plane. Joint and fault planes often mark the abrupt ends of the ridges. Diabase dikes which trend about N. 30° E. form gaps in the ridges and are believed to follow faults because they offset the ridges.

All the slates, graywackes, and graywacke-slaty are members of the Thomson formation, which varies southwesterly with progressive metamorphism to phyllite, mica schist, and garnet-mica schists. These are exposed in the region of Barnum and southwestward toward Denham in northwestern Pine County.

Schwartz correlates the Thomson formation with the Knife Lake series of northern St. Louis and Lake counties. The following is his summary of facts which must be taken into account in determining the age of the formation.

"CORRELATION OF THE THOMPSON FORMATION"

"The series of slates exposed in the Carlton-Cloquet area have been frequently referred to in discussions of Lake Superior correlation problems but only Spurr (1894), Winchell (1899), and Harder and Johnston (1918) have presented any details on the Thomson formation. None of these investigations undertook anything like a complete mapping of the formation. A review of all opinions which have been expressed on this correlation would take much space, and accordingly only a tabular statement of previous correlations will be given.

Author	*Date*	*Correlation*
Irving	1883	Animikie
Winchell, N. H.	1890	Animikie and Taconic (2 series)
Spurr	1894	Keewatin (Lower Huronian)
Winchell	1898	Animikie and Keewatin (Lower Huronian) (2 series)
Leith	1903	Lower Huronian
Leith and Van Hise	1911	Animikie
Harder and Johnston	1918	Animikie (possibly Lower Huronian)
Leith, Lund, and Leith	1935	Upper Huronian (Animikie)

"Most of these correlations were made either as suggestions on broad general grounds, or they were based purely on lithology. None were made with all the facts now available, and it is believed that a consideration of all the facts leads to a more definite conclusion, although it may be that exact correlation will never be possible because of the large covered areas.

"Facts which must be taken into account include the following:

"(1) The Thomson formation differs lithologically from the Animikie sedimentary rocks of the Lake Superior district.

"(2) The Thomson formation is highly folded and metamorphosed so that the lowest grade has excellent slaty cleavage. In this respect it resembles the Knife Lake series of the Vermilion district and not the Animikie Virginia slate.

"(3) The strike of the beds, cleavage, and axial planes of the folds is predominantly east-west. This is at an angle of about 35° to the prevailing regional structure of younger beds related to the north limb of the Lake Superior geosyncline. At Duluth the two structures strike at about right angles to each other.

"(4) The Thomson formation is separated from the Lower Keweenawan by a pronounced angular unconformity.

"(5) The Keweenawan rocks overlying the Thomson partake of the same regional structure as the Animikie beds of the north shore of Lake Superior — that is, a strike generally northeast and a dip of 10° SE. A pronounced structural discordance, therefore, exists between Animikie-Keweenawan beds and the beds of the Thomson formation. No structural discordance is known between Animikie and Lower Keweenawan beds in Minnesota but a disconformity evidently exists in the Grand Portage region.

"(6) The Thomson has suffered progressive regional metamorphism with low-grade rocks in the Carlton-Cloquet area and high-grade metamorphics to the south near the granite contact.

"(7) The granites of central Minnesota have recently been tentatively correlated (Tyler and others, 1940), on the basis of accessory-mineral studies, with granites of Algoman age. Seven additional samples of granites collected in 1941 from scattered points from Little Falls to Denham all show accessory minerals characteristic of Algoman granites. The only batholithic Minnesota granite which shows Keweenawan characteristics is the red granite of the Milaca and St. Cloud areas far to the south.

"These facts lead to certain interpretations: The Thomson formation of Carlton and Pine counties is pre-Animikie in age and should not be correlated with the Virginia slate, because (1) The structure of the Thomson formation is discordant with the regional Lake Superior geosynclinal structure as developed in late Keweenawan time. The Animikie and Keweenawan are in practical structural accordance in northeastern Minnesota (Grout and Schwartz, 1933). (2) The Thomson and Virginia formations differ in the nature of the original sediments and in metamorphism. (3) The Thomson formation is greatly metamorphosed in the southern part of its extent by granites which are correlated with the Algoman granite on the basis of accessory minerals and general correspondence of other characteristics; the Thomson is therefore older than Algoman, whereas the Animikie rocks are younger.

"As to the correlation of the Thomson formation with other pre-Animikie rocks, there is little direct evidence. On the basis of lithology, metamorphism, and deformation, the formation compares well with some of the Knife Lake series, and reference to the recent summary of Lake

Superior correlations (Leith, Lund, and Leith, 1935, p. 10) leaves no other logical choice. This is not a new choice but was suggested by Spurr (1894), Leith (1903), and others. The difficulty is that the position of the Knife Lake series in the lower pre-Cambrian is somewhat doubtful and the series is complicated in itself (Gruner, 1941).

"In any event the Thomson formation is Lower Huronian or older. Its character and metamorphism correspond well with what might be expected in a Lower Huronian formation. The possibility of the Thomson formation and Knife Lake series being the equivalent of formations classified as Archean in Canada is not excluded."[2]

The Lower Keweenawan is represented by the sandstone and conglomerate of the Puckwunge formation, which rests unconformably over the Thomson slates. This relationship may be seen in an outcrop in the channel of the St. Louis River in Sec. 15, T. 48 N., R. 16 W. Winchell described other exposures of the conglomerate and sandstone very near the slate and the Upper Keweenawan sediments.[3]

The Middle Keweenawan volcanic flows are not exposed in Carlton County, but there may be erosion remnants of the lower flows under the drift in the northeasternmost township of the county. Furthermore, some of the diabasic and basaltic dikes, sills, and larger intrusive masses in the Thomson formation in the Carlton area and in the region west of Moose Lake may be of Middle Keweenawan age. Basic lava flows are present also under the drift in the southeasternmost township to the southeast of Holyoke.

The Upper Keweenawan sandstones are exposed along the valley of the St. Louis River west of Fond du Lac in the northeastern part of T. 48 N., R. 16 W. The location of the outcrops is shown in Figure 12. The lithological characteristics are given in detail by Grout and Thiel in a study of the accessory minerals in pre-Cambrian rocks.[4] The sandstone strata represent part of the type section of the red, clastic Fond du Lac beds of the Lake Superior series and may be the equivalent of the lower part of the Orienta formation of the south shore of Lake Superior in Wisconsin.

The Fond du Lac beds occur directly beneath the drift along a zone about 10 miles wide from the St. Louis valley at Fond du Lac southwestward to Nickerson in northeastern Pine County.

Winchell has mapped a small outlier of Hinckley sandstone along the west bank of the Kettle River in the southwestern part of the county (Sec. 16, T. 46 N., R. 20 W.) to the west of the slate outcrops of the

[2] Schwartz, G. M., Correlations and metamorphism of the Thomson formation, Minnesota: Geol. Soc. Am. Bull., vol. 53, pp. 1001–1020, 1942.

[3] Winchell, N. H., The geology of Minnesota: Final Rept., Minn. Geol. and Nat. Hist. Survey, vol. 4, p. 13, 1899.

[4] Tyler, S. A., Marsden, R. W., Grout, F. F., and Thiel, G. A., Studies of the Lake Superior pre-Cambrian by accessory-mineral methods: Geol. Soc. Am. Bull., vol. 5, pp. 1429–1538, 1940.

Moose Lake region.[5] He suggests that this light-colored sandstone and its basal conglomerate may be Cretaceous in age.

Cretaceous System

No bedrock of Cretaceous age has been positively identified in Carlton County. From the presence of numerous kidney iron-ore balls and limonitic crusts in the glacial drift, Winchell inferred that the Cretaceous probably extended over the region, but that it has been destroyed by the severity of the glacial abrasion.

GENERAL UNDERGROUND WATER CONDITIONS

Since most of the county is underlaid by pre-Cambrian crystalline rocks, the supplies of ground water must be obtained from the glacial drift. In the area from Carlton and Cloquet southwestward toward Moose Lake the drift is thin and the regional water table may lie below the bedrock surface. In such areas surface or near-surface waters must be relied upon for public and domestic supplies. Locally adequate supplies for limited uses may be obtained from joints and fractures in the slates and graywackes or from the contact zone between the slates and the drift. Several wells drilled 200 feet or more into the slates yielded an ample volume of water, but it was charged with sulphurous gases and the wells were abandoned.

In the glacial moraines of the southeastern part of the county, the drift is as much as 300 feet thick and is underlaid by Upper Keweenawan sandstone. In that area the water in sand and gravel layers near the base of the drift or in the sandstone under the drift has a static level within 50 feet of the surface.

In Wrenshall Township (T. 48 N., R. 16 W.) many of the wells in the intermoraine zones flow at the surface. The wells vary in depth from 120 to 225 feet and terminate in sand and gravel layers in the glacial drift.[6] A flowing well at the Kelley Brickyard in Wrenshall at an elevation of about 1030 feet penetrates 312 feet of drift and 10 feet of reddish sandstone.

Along the St. Louis River the static level of the ground water is influenced by the pools back of the dams at Thomson and at Scanlon. The Thomson pool is at an elevation of 1067.7 feet and that at Scanlon stands at a normal level of 1120.9 feet.

MUNICIPAL WATER SUPPLIES

Carlton

The city of Carlton is built in the midst of numerous outcrops of slates and graywackes. The drift is thin and therefore the source of

[5] Winchell, N. H., *op. cit.*, p. 16.
[6] Data from Mr. Hogal, driller, Carlton.

ground water is limited. The city well is 8 inches in diameter and 28 feet deep. The static level is 4 feet below the surface. The well is developed with a screen 7 inches in diameter and 12 feet long. It is pumped at the rate of 300 gallons per minute. A number of years ago the city drilled a well into the slates to a total depth of 1100 feet. No satisfactory yield of water could be developed.

Cloquet

The city of Cloquet gets the water for its public supply system from a group of wells and springs south of the city in Secs. 26 and 27, T. 49 N., R. 17 W. A glacial basin rimmed by high sandy and gravelly moraine hills is fed by a series of springs. The springs have been connected by pipe lines that discharge in a concrete reservoir constructed in the center of the basin. The reservoir is 20 feet in diameter and extends 20 feet below the surface. This glacial basin has a catchment area of about 160 acres. Another spring 1¼ miles west is pumped to a storage reservoir also. Several wells in the drift are pumped and the water added to the spring water in the big reservoir. One well is one-fourth of a mile west of the reservoir. The well is 8 inches in diameter and 110 feet deep. It was tested at 200 gallons per minute.

There are many shallow private wells dug or bored to the bedrock surface. A number of wells have been drilled into the slates but most of them prove to be quite unsatisfactory.

A private well on the hill between Cloquet and Scanlon obtains water from the slate. The well penetrates 80 feet of drift and 33 feet of slate. There is a small flow of water from a fracture at a depth of 5 feet into the slate. The well produces no more than 2 gallons per minute.

Moose Lake

The city of Moose Lake has a dug well 20 feet in diameter and 35 feet deep. Several points and screens are driven 10 to 15 feet at the bottom of the dug hole. The static level is about 30 feet below the surface.[7]

The well at the creamery is 6 inches in diameter and 38 feet deep in outwash sands and gravel. It yields 60 gallons per minute.

A farm well 2½ miles west of the city obtains water from the slates. It penetrates 25 feet of drift, 16 feet of hard slate, and 4 feet of soft slate. Water seeps through fractures in the soft slate.

Barnum

Water for the public supply system at Barnum is taken from a well 10 inches in diameter and 40 feet deep. The well is near the bank of the Moose River.

[7] Data from Mr. Anderson, driller, Moose Lake.

The private wells in the city of Barnum are shallow and obtain water from the outwash sediments along the Moose River. The slates and schist lie from 20 to 75 feet below the surface. A well at the depot of the Northern Pacific Railway Company penetrated 20 feet of sand and gravel and 173 feet of slate and schist. No adequate supply of water could be developed in the slaty bedrock.

West of the city the bedrock surface is exposed in many places as low flat outcrops. In this area it is often difficult to locate adequate supplies of water for domestic use. Locally small yields are obtained at the contact of the drift and the slates.

A few miles east of the city the drift is as much as 200 feet thick and generally contains layers of sand and gravel that yield water freely.

A farm well in Sec. 10, T. 46 N., R. 18 W., penetrates 315 feet of drift and the upper part of the Keweenawan sandstone. The static level is 50 feet below the surface. The accompanying log gives the subsurface relations.

Farm Well, Sec. 10, T. 46 N., R. 18 W. (elevation 1095 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Tight, red clay	0–315	315
Fond du Lac	Light red sandstone	315–387	72

WRENSHALL

The village of Wrenshall has no public water supply system. The well at the depot at an elevation of 1030 feet penetrated 186 feet of drift. Its static level is 76 feet below the surface. The accompanying log gives the nature of the glacial sediments.

Well of Northern Pacific Railway Company at Wrenshall

		DEPTH (feet)	THICKNESS (feet)
Drift	Yellow clay	0–28	28
	Blue clay	28–62	34
	Red sand and clay	62–76	14
	Quicksand	76–89	13
	Red sand and clay	89–107	18
	Sand and gravel	107–115	8
	Quicksand	115–155	40
	Red clay	155–178	23
	Sand and gravel	178–186	8

Many of the farm wells north of the village flow above the surface. These wells are from 120 to 225 feet in depth and do not reach the bedrock surface.

CROMWELL

The village of Cromwell is located on the west shore of Island Lake, in the northwestern part of the county, in the morainic topography of the second moraine of the Superior lobe.

The well at the depot is 4 inches in diameter and 75 feet deep. It terminates in a gravel layer in the drift. Its static level is 5 feet below the surface or 1300 feet above sea level.

Black Hoof

In this region the glacial drift is from 250 to 300 feet thick. The well at the village schoolhouse is 250 feet deep in clayey glacial till. The static level is 25 feet below the surface.

Table 17. — Analyses of Waters of Carlton County *

	1	2	3	4	5	6	7	8
Depth (feet)	...	...	...	...	...	...	40	35
Hardness	80	58	140	93	160	150	190	150
Alkalinity	68	74	74	97	140	130	170	97
Iron	tr.	2	.18	.07	.48	.17	2.4	.03
Manganese	...	...	...	...	.1	.08	.7	.2
Chlorine	1	7.7	17	2.5	4.8	7	20	2.7
Fluorine	...	3.2	.3	.05	0	.15	0	0
SO_4 radical	...	...	...	...	97	39	24	24
Turbidity	1	10	.4	.2	5	.1	10	0
Color	5	50	2	1	45	30	15	1
Odor	0	...	...	...	...	...	...	...
pH value	...	6.9	7.65	8.35	7.3	7.25	7.5	7

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Cloquet, spring, 1924.
2. Cloquet, Well No. 3, 1944.
3. Cloquet, Well No. 4, 1942.
4. Cloquet, Well No. 5, 1942.
5. Carlton, Well No. 1, filtered, 1942.
6. Carlton, Well No. 2, filtered, 1943.
7. Barnum, drilled well, 1939.
8. Moose Lake, dug well, 1938.

NORTHEASTERN CASS COUNTY

Only that part of Cass County north of Crow Wing County is included in this report. The geology of the western part of the county is included in Bulletin 22 of the Minnesota Geological Survey, *The Geology and Water Resources of Northwestern Minnesota* by I. S. Allison.

SURFACE FEATURES

The most impressive surface features of Cass County are its large lakes. Leech Lake has an area of about 175 square miles and Lake Winnibigoshish about 75 square miles. Leech Lake (raised somewhat by a dam) lies about 1300 feet above sea level.

South of the Mississippi River and Winnibigoshish Lake is an outwash plain of sandy gravel which extends south a short distance beyond the track of the Great Northern Railway. South of this is a great till plain. The area south of Leech Lake is a rolling moraine, which loses its ruggedness toward the east where it consists of scattered groups of knolls bordered by areas of clayey ground moraine. In the southeastern townships, south of Remer, rugged moraines of Patrician drift extend in a north-south direction as far south as Whitefish Lake in Crow Wing County.

UNCONSOLIDATED SURFACE MANTLE

The contact between the red Patrician and gray Keewatin drift sheets crosses this portion of Cass County in Twps. 140 and 141 N. A northeasterly extension of the St. Croix moraine, which is the terminal moraine of the Patrician ice sheet, enters the area south of Leech Lake and extends to within a short distance south of Bay Lake. The four southeasternmost townships are within the area of the Mille Lacs moraine, a recessional moraine of the same ice sheet. These are areas of red sandy moraine in which the red color is due to iron-bearing minerals brought in by the ice from the iron ranges. Drilling reveals that deposits of "old gray" Kansan drift from the Keewatin center of glaciation underlie the red drift. The red glacial sediments are generally from 50 to 150 feet or more in thickness.

The conspicuous Altamont and Gary moraines of the late Wisconsin glacier are welded into one moraine zone that extends in an east-west direction south of Leech Lake. Its hills, as much as 200 feet above the plain areas, constitute the highest land in the county. The gray drift outwash extends beyond the moraine, over the low areas of the red drift to the south, covering so much of it in some places that only the morainic hills rise like islands above a sea of outwash sand and gravel.

A broad zone of sand and gravel outwash parallels the Mississippi from Bemidji southeastward across Cass County. In the area southwestward from Ball Club toward Leech Lake much of the outwash is covered with lake and swamp sediments.

Variations in the the thickness of the drift are shown in Table 18.

TABLE 18. — DATA ON DRILLINGS TO BEDROCK IN CASS COUNTY

Location	Kind of Rock	Elevation of Surface	Depth to Rock
Federal Dam	......	1300	234
Near Walker (T. 142 N., R. 31 W.)	......	1375	350
Near Cyphers (T. 141 N., R. 31 W.)	......	1350	230
Sec. 31, T. 137 N., R. 32 W.	......	....	330
Sec. 16, T. 138 N., R. 29 W.	Basic intrusive	....	...
Sec. 9, T. 138 N., R. 29 W.	Acid intrusive	....	...
Pequot (Crow Wing County)	Black slate	1275	95
Near Jenkins (Crow Wing County)	Mica schist	1270	200
At Remer (T. 141 N., R. 26 W.)	Slate	....	224
At Pine River (T. 137 N., R. 29 W.)	Granite	1300	200
T. 134 N., R. 31 W.	Gray granite	....	115
T. 140 N., R. 26 W.	Granite	....	...
T. 142 N., R. 25 W.	Granite	....	...

WATER CONDITION IN THE DRIFT

Supplies of ground water in Cass County must be obtained from the glacial sediments. The large areas of sand and gravel are saturated with water to within a short distance of the surface, and they yield water generously to numerous shallow wells, many of which are dug or driven. The areas of red clayey till contain numerous lenses of sand and gravel which supply water for domestic purposes and for small industries. The smallest yields are obtained from the clayey gray till areas where veins of sand and gravel are less common.

The regional water table is near the level of the water in the lakes and streams, and in the extensive outwash areas the static level is generally from 10 to 25 feet below the surface. In the hilly moraines the water table stands as much deeper as the height of the hills. So free is underground circulation that the raising or lowering of lake levels by means of dams affects the water level in the shallow wells. This is especially true in the area near Lake Winnibigoshish. In the clayey gray moraine the water table stands at a higher level, and in this region numerous hillside springs discharge into the lake basins. This condition is common in the area south of Leech Lake.

ROCK FORMATIONS

Data on bedrock formations in this part of Cass County are very meager. H. V. Winchell and G. H. Griffin refer to an outcrop of bedrock "about one or two miles below the mouth of Boy Lake, in the north edge

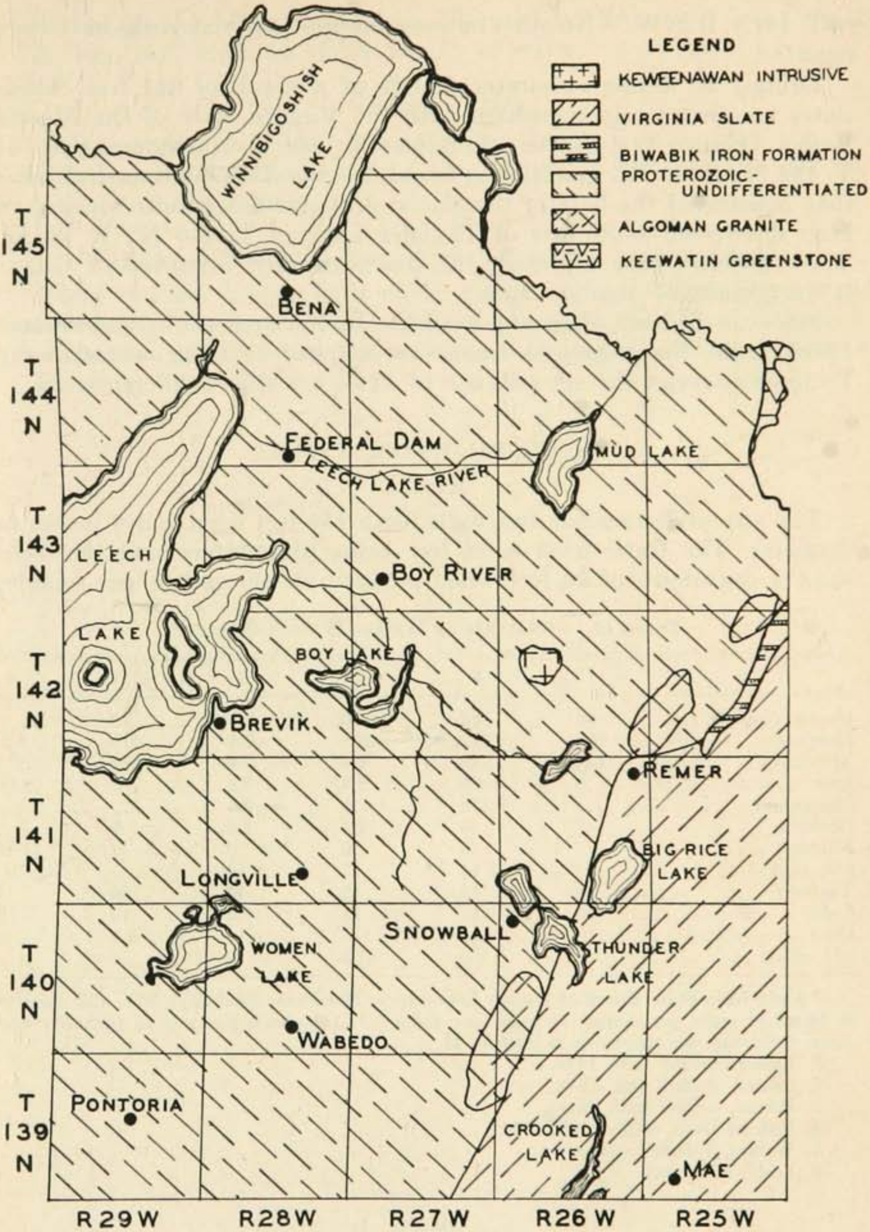

FIGURE 13. — Geologic map of northeastern Cass County.

of T. 142N, R.27W."[1] No other outcrops of pre-Cambrian rocks have been reported.

Drilling at Remer encountered slate at a depth of 224 feet. These slates are tentatively correlated with the Virginia slate of the Mesabi Range (Figure 13). North of Remer in the southwestern part of T. 142 N., R. 25 W., granite was found in several exploratory drill holes that penetrated the base of the glacial drift. Similar granite rocks have been discovered southwest of Thunder Lake in T. 140 N., R. 26 W. These granites may represent the southwestward extension of Giants Range granite of Algoman age.

Since no bedrock data are available in the area south and east of Leech Lake, that region is commonly mapped as being underlain by Proterozoic rocks, the age relations of which are still undifferentiated.

MUNICIPAL WATER SUPPLIES

Remer

The city of Remer has two wells, both 150 feet deep and 6 inches in diameter. The static level is 18 feet below the surface and the wells show a drawdown of 20 feet when pumped at 350 gallons per minute.

Table 19. — Analyses of Waters of Cass County *

	1	2	3	4	5	6
Depth (feet)	65	65	70	117	70	...
Hardness	261	230	200	300	210	142
Alkalinity	272	260	260	350	212	155
Iron	.8	5.6	2.4	3.2	2	tr.
Manganese	...	.12	.5	.05	...	...
Chlorine	1	9	7.5	6.6	2	...
Fluorine	...	0	0	0	...	...
SO_4 radical	...	14	17	10	...	...
Turbidity	15	15	10	16	40	4
Color	15	11	18	5	10	10
Odor	0	...	...	...	d-1	...
pH value	...	7.5	7.3	8	...	...

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon=17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Remer, drilled well, 1925.
2. Remer, drilled well, 1942.
3. Remer, drilled well, 1942.
4. Federal Dam. drilled well, 1944.
5. Walker, 3 drilled wells.
6. Leech Lake, raw.

Bena

This village has no public water supply system, but there are a number of private driven and dug wells in the vicinity. The static level is

[1] Winchell, N. H., The geology of Minnesota: Final Rept., Minn. Geol. and Nat. Hist. Survey, vol. 4, p. 65, 1898.

less than 20 feet below the surface. The well at the hotel is less than 50 feet deep and yields an ample supply of water.

Federal Dam

In the region of Federal Dam the glacial drift is more than 200 feet thick. A private well was drilled to a depth of 234 feet and did not reach the bedrock surface.

Wabedo, Longville, Boy River, Pontora, and Snowball

None of these villages have public water supply systems. The private wells obtain water from lenses or veins in the glacial drift. Most of the wells are less than 200 feet deep and none reach the upper surface of bedrock.

CHISAGO COUNTY

SURFACE FEATURES

Chisago County is located on the eastern border of the state, with the gorge of the St. Croix River forming its eastern boundary. The surface elevation ranges from less than 700 feet on the bottomland in the southeastern corner of the county to more than 1050 feet in the morainic hills of the northwesternmost townships. In the region south of Taylors Falls the St. Croix valley is from 250 to 300 feet below the adjoining uplands. Much of the sandy plain in the central part of the county is at an elevation of about 900 feet above sea level. A series of terraces are well developed along the St. Croix River, the uppermost standing 125 feet above the stream.[1]

From Franconia southward the St. Croix valley has been deeply channeled by lines of glacial drainage from the outlets of glacial Lake Duluth, and at Arcola, a few miles beyond the southern county boundary, the valley fill is nearly 120 feet thick. Upstream from the region of Osceola some of the small tributaries within the limits of the county have step rocky gorges with waterfalls that have receded from the bluffs of the St. Croix valley.

There are many lakes in the south-central part of the county, some of which seem to be along the zones of partly filled valleys. Rush Lake, in the northwesternmost township, occurs in an area of clayey glacial till.

UNCONSOLIDATED SURFACE MANTLE

With the exception of the rock outcrops along the gorge of the St. Croix River, the entire county is covered with a mantle of glacial drift, dune sand, and stream alluvium. Three drift sheets are represented. The oldest is a deeply weathered, dark gray till, which may be seen in the deep gullies formed by the tributaries of the St. Croix River. This is overlaid and partly admixed with the red drift deposited by the Patrician glacier. The red drift is exposed on the ridges and knolls in the eastern townships, and excellent sections are artificially exposed in the road cuts both west and south of Taylors Falls. The youngest drift sheet is a gray till that was deposited by the Grantsburg lobe of the late Wisconsin (Mankato) glacier. The gray drift forms a moraine along the east side of Sunrise River and another in the northwestern part of the county. Outwash deposits are extensively developed in the northeastern townships along the St. Croix River. These sediments range in thickness from 25 to 75 feet. Where they have been deposited over

[1] The terraces and the general geology of the region of Taylors Falls were studied in detail by Dr. C. P. Berkey in the *American Geologist*, vol. 20, pp. 346–383, 1897, and vol. 21, pp. 139–155, 270–294, 1898. For a summary of the geologic history of the St. Croix valley the reader is referred to Bulletin 26, 1935, and Bulletin 27, pp. 68–70, 1936, of the Minnesota Geological Survey.

older, impervious glacial clays, water is retained in the coarser porous material.

The terrace sands and gravels were laid down by streams flowing at distinctly higher elevations than those of the present rivers. In places the upper level stands more than 200 feet above the level of the St. Croix River and the deposits are more than 100 feet thick. Such sediments are porous, but the water level is low at most points near the outer margins of the terraces.

The dune sands represent a reworking of outwash sands by wind action. They occur locally in the area that is part of the Anoka sand plain, which enters the county from the southwest and extends from Forest Lake northward to Harris and eastward to a short distance beyond the Sunrise River.

ROCK FORMATIONS

Pre-Cambrian and early Paleozoic rocks crop out extensively along the valley of the St. Croix River (Figure 14). Downstream a short distance from Franconia and southward, the bluffs along the river are capped by the Oneota dolomite, below which exposures of the Cambrian formations may be observed. At Franconia and northward toward Taylors Falls the Franconia sandstone forms conspicuous cliffs along the valley of the St. Croix River and its tributaries. At Taylors Falls the lowest formation of the St. Croixian series is seen overlapping the Keweenawan lava flows. There are no outcrops of bedrock in the upland areas beyond the St. Croix valley.

PRE-CAMBRIAN

Pre-Cambrian igneous rocks are represented by the Keweenawan basic lava flows that are exposed in the Taylors Falls region. This area of outcrops is surrounded by Cambrian sandstones which overlap older pre-Cambrian sediments. The upper surface of the lavas slopes in all directions. At Taylors Falls they reach an elevation of more than 1000 feet, at Franconia they are exposed in the St. Croix valley at an elevation of about 725 feet, and at Stillwater they were encountered at a depth of 3120 feet or about 2300 feet below sea level. In the northern part of the county, at Rush City, the flows lie 100 feet below the surface or 800 feet above sea level.

The lithology and structure of the flows are described by Berkey.[2] He mapped seven flows at the Upper Dalles at Taylors Falls, where each flow is accessible throughout its entire thickness. Their thickness varies between 30 and 60 feet and the dip is toward the south at an angle of 10° to 15°. The massive flows have several sets of joints that are closely spaced and tend to break the rocks into irregular, angular blocks, some of which stand as isolated columns along the walls of the St. Croix valley. The upper part of the lava rocks may contain some water in joints and

[2] C. P. Berkey, *op. cit.*

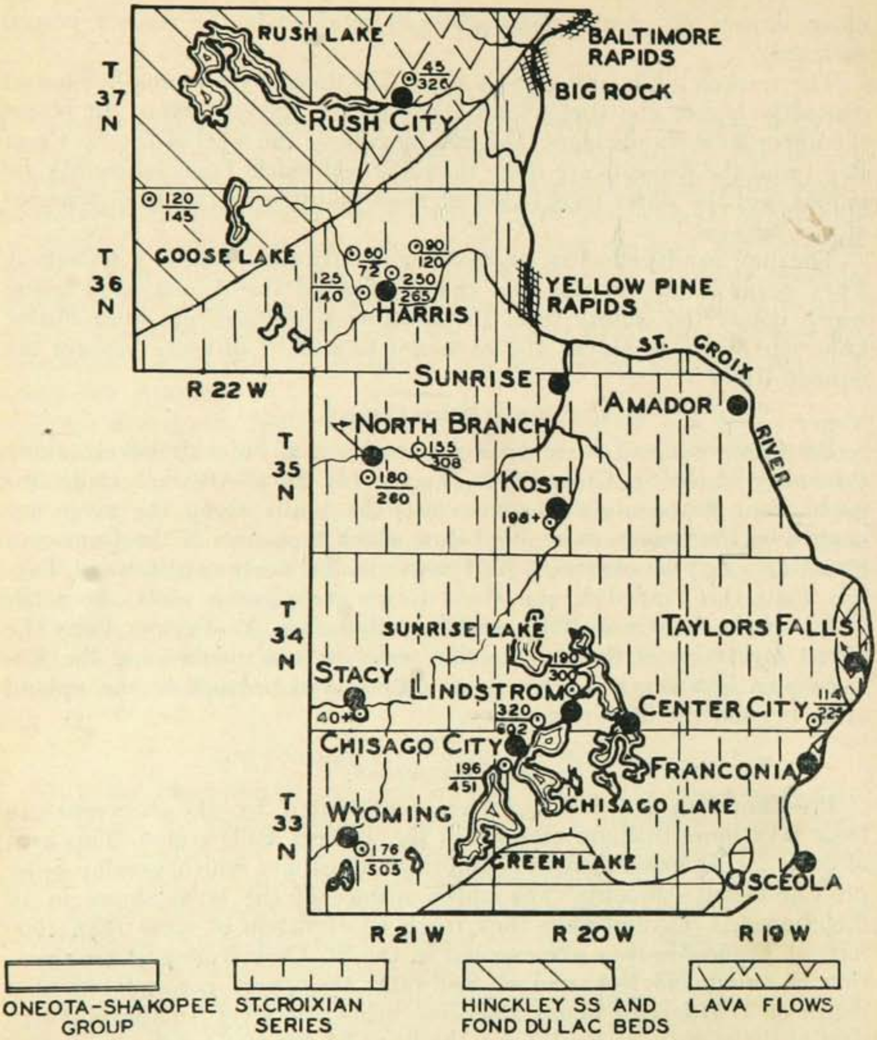

FIGURE 14. — Geologic map of Chisago County. The small circles indicate drill holes that reached bedrock at the depth shown by the upper figures. The lower figures show the total depth of the wells.

fractures, but their yield is insignificant compared with that of the overlying sandstones.

Pre-Cambrian sedimentary rocks are not exposed in Chisago County nor has drilling penetrated strata that can be positively identified as belonging to the Hinckley formation or to the red Fond du Lac beds. Some of the white sandstone encountered under the drift in the northwesternmost townships may belong to the Hinckley formation, but the presence of fossiliferous Dresbach sandstone at Braham, a few miles west of the northwest corner of Chisago County, indicates that the Keweenawan sediments, if present, are overlain by Cambrian formations.

Since the upper surface of the flows slopes steeply southward from Taylors Falls, it is reasonable to assume that the Keweenawan sediments wedge out against the flows somewhere in the southern part of Chisago County or in the northern part of Washington County. This interpretation is given credence by the presence of more than 2000 feet of sediments of pre-Cambrian age in the old deep well at Stillwater.

In the northern part of the county the contact between the lava flows and the pre-Cambrian sedimentary rocks is along the Douglas fault that crosses Douglas County, Wisconsin, in an east-west direction south of Lake Superior and then changes its trend to a southwesterly direction across Carlton, Pine, and Chisago counties. In the central part of Chisago County the fault is deeply buried under Cambrian rocks and its presence cannot be detected with a magnetometer.[3] The downthrow component of the fault is to the northwest of the fault plane. The Upper Keweenawan sedimentary rocks have been eroded from the upthrow block east of the fault plane (Figure 33).

Cambrian System

All the formations of the upper Cambrian or St. Croixian series are represented in Chisago County. Structurally, they are part of the monocline that dips southward at a low angle. Their lithological characters and stratigraphic relations are shown in the accompanying measured section.

The Dresbach formation is well exposed along the St. Croix River both upstream and downstream from Taylors Falls. The lowest or Mt. Simon member may be seen in the northeasternmost corner of the county at Baltimore Rapids. The middle or Eau Claire member, which is highly fossiliferous, crops out along Rush Creek, southeast of Rush City, and further south along the valley of the St. Croix River. It overlaps the lava rocks at Taylors Falls, where its basal conglomeratic beds contain large basalt boulders with a fossiliferous sandy matrix. Shaly beds with abundant fossils may be seen in the river bank on both sides of the river a short distance downstream from St. Croix Falls. The upper or Galesville sandstone member is poorly developed in this region and if present is a marine facies with brachiopod fossils.

The Franconia formation has its type section in this county. (See the accompanying tabulation.) Its various units are well exposed in the road cut south of Taylors Falls and along Lawrence Creek south of Franconia Station. It is predominantly a sandstone sprinkled with minor amounts of green glauconite grains. The green shales and silts of the Bad Axe and Hudson members were not well developed near the islands and reefs of basaltic rocks of the Taylors Falls area. The Taylors Falls

[3] Frey, Gordon, unpublished thesis, University of Minnesota, 1939.

member is an excellent aquifer and supplies water to many wells in the east-central part of the county.

Franconia, Chisago County, Type Section of the Franconia Sandstone, Lawrence Creek
(Measured by C. R. Stauffer)

	THICKNESS (feet)
24. Drift, covered to Franconia railroad station (915 ft. A.T.)	78.5
FRANCONIA FORMATION	
Taylors Falls Member	
23. Sandstone, white to yellow and brown, thick-bedded, medium-grained	22.0
22. Sandstone, buff, fine-grained, massive to thin-bedded, lower part very ferruginous. Trilobites common in lower 4 feet are *Conaspis perseus, Taenicephalus bipunctatus,* and *Wilburnia* sp.	8.8
21. Sandstone, yellow to buff, partly covered	2.0
20. Sandstone, fine-grained, micaceous, buff to tan	3.0
19. Sandstone, fine-grained, thin-bedded to shaly, buff to brown	2.0
18. Sandstone, fine-grained, massive, white to tan. Contains fragments of small brachiopods and trilobites	2.5
17. Sandstone, fine-grained, thin-bedded, tan to white, showing glauconite and patches of brown iron stain	1.5
16. Sandstone, fine-grained, white to tan, massive. Parts micaceous and glauconitic. Brachiopod fragments common	4.5
15. Sandstone, fine-grained, shaly, gray to buff, glauconitic, micaceous	0.5
14. Sandstone, fine-grained, white to massive	2.0
13. Sandstone, mostly covered	2.0
12. Sandstone, fine-grained, buff to tan, thin-bedded, micaceous	8.0
11. Sandstone, mostly covered	17.0
10. Sandstone, fine- to medium-grained, thin-bedded, glauconitic, interstratified with thin layers of buff shale	6.5
Ironton Member	
9. Sandstone, medium-grained, white to gray, massive, cross-bedded, glauconitic, with occasional thin layers of gray shale. Occasional quartz pebbles. *Dicellomus* sp., *Camaraspis hemisphericus,* and fragments of other fossils	11.7
8. Sandstone, fine-grained, white to gray, with much greenish shale and locally streaks of iron stain	1.5
7. Sandstone, fine- to medium-grained, friable, white to gray and brown, in part glauconitic. Gray-green shales alternate with thin, lenticular layers of sandstone, especially in lower part. *Dicellomus* abundant, especially in the upper part	5.8
6. Sandstone, mostly covered	3.5
5. Shales, gray to bluish gray, arenaceous, alternating with thin layers of sandstone	2.8
4. Glauconite, sandy, green	1.5
3. Covered interval	2.5
2. Sandstone, medium to coarse, poorly sorted, fossiliferous	6.0
KEWEENAWAN	
1. Massive diabase and flows to level of St. Croix River	30.0

The St. Lawrence formation, which is from 50 to 60 feet thick, consists essentially of somewhat glauconitic, calcareous sandstone and buff to bluish-gray siltstone and shale. Its sandy layers carry small quantities of water, but the supply is far less than in the Jordan sandstone above and the Franconia sandstone below. Its lithological and stratigraphic relations are shown in the exposures at the west end of the Osceola Bridge.

Osceola Bridge, Chisago County, Section along Highway at West End of Bridge
(Measured by C. R. Stauffer)

	THICKNESS (feet)
22. Drift	25.0
JORDAN SANDSTONE	
Van Oser Member	
21. Sandstone, thin-bedded, yellow to brown, ferruginous, weathered	18.0
20. Sandstone, massive, white to yellow, fine- to medium-grained, thin-bedded at top	32.0
19. Sandstone, brown, heavily impregnated with iron	0.5
Norwalk Member	
18. Sandstone, thick-bedded, yellow to brown, with scattered fossils	10.5
17. Sandstone, thin-bedded, vermicular, brown, containing a few fossils	2.5
16. Sandstone, cross-bedded, laminated, brown, not well separated from that above, but containing two thin, edgewise conglomerates	1.5
15. Sandstone, massive, laminated, cross-bedded, brown, full of characteristic Norwalk fossils	5.3
14. Covered interval	16.0
13. Sandstone, thin-bedded, medium-grained, brown, with Norwalk fossils	2.5
12. Covered interval	3.0
ST. LAWRENCE FORMATION	
Lodi Member	
11. Sandstone, thin-bedded, fine-grained, glauconitic; with some gray-green shales. Ripple-marked and mud-cracked; worm trails common	4.0
10. Shale, gray to greenish, with streaks of fine sand	0.7
9. Dolomite, sandy, gray, glauconitic, with pebbles at the base	1.5
8. Shale, green, in layers, alternating with fine-grained, laminated glauconitic sandstone; some layers are very glauconitic. *Dikelocephalus minnesotensis* fauna	4.0
7. Shale, gray to green, with sandy glauconitic lenses. Some layers are a fine siltstone. Ripple marks, mud cracks, and worm trails common	8.0
Nicollet Creek Member	
6. Conglomerate, flat pebble	0.5
5. Shale, blue clay, soft, sticky	0.3
FRANCONIA FORMATION	
Bad Axe Member	
4. Sandstone, fine-grained, poorly cemented, glauconitic	10.7
3. Shale or shaly sandstone, fine-grained, glauconitic, vermicular	5.0
2. Sandstone, massive, white, medium-grained, poorly cemented	8.0
1. Covered interval to level of St. Croix River (684 ft. A.T.)	10.7

The Jordan sandstone crops out along the St. Croix valley in the southeastern part of the county. A good exposure may be seen in the cut along the road leading down into the valley at the west end of the bridge at Osceola. The Jordan is about 90 feet thick and yields large supplies of water back from the valley walls, especially where covered by the Oneota dolomite.

ORDOVICIAN SYSTEM

The Oneota dolomite underlies parts of the southernmost townships of the county. It crops out and caps the bluffs along the St. Croix valley from near Franconia southward into Washington County. It is not an important source of water and in general its yield is no greater than that from the glacial drift.

GENERAL UNDERGROUND WATER CONDITIONS

Owing to the fact that the pre-Cambrian lava rocks crop out and underlie the glacial drift in widely separated parts of the county, the underground water conditions are exceedingly variable. In the northernmost townships, in the region of Rush City, water must be obtained from the glacial drift. The same is true in the area west of the outcropping igneous rocks of the Taylors Falls region. The margins of the sandstones that overlap the igneous flows have not been mapped in detail. Therefore, test drilling is recommended in the above areas if a large yield of water is required.

Where the Hinckley sandstone or either of the Cambrian sandstones occurs beneath the drift, ample supplies of water for small industries and for domestic uses may be expected. Near the major valleys, however, the sandstones discharge water into the streams and deeper wells are required. The outwash sediments and glacial tills contain ample supplies for domestic use.

MUNICIPAL WATER SUPPLIES

Taylors Falls

For a number of years the city of Taylors Falls obtained water for the public supply system from a group of springs at the base of the hill, near the north edge of the city. The springs are tapped by pipe lines 800 feet and 1500 feet in length respectively. With a gravity flow the water is collected in a series of reservoirs and finally pumped to an underground tank on the top of the hill. This pump has a capacity of 75 gallons per minute.

In 1942 a drilled well was added to the system. This well is located on the upland west of the city. It is 16 inches in diameter and 189 feet deep. Its static level is 106 feet below the surface and when pumped at the rate of 100 gallons per minute it has a drawdown of 24 feet. The accompanying log gives the geologic succession.

Log of City Well, Taylors Falls *

		DEPTH (feet)	THICKNESS (feet)
Drift	Yellow clay	0–30	30
	Sand and gravel	30–140	110
Franconia	Sandstone	140–169	29
Dresbach	Bluish shale	169–189	20

* Compiled by the McCarthy Well Company, St. Paul.

A farm well one mile southwest of Taylors Falls on the farm of G. B. Lane near the center of Sec. 35, T. 34 N., R. 19 W., penetrates the following geologic strata.

		DEPTH (feet)	THICKNESS (feet)
Drift	Sand with basalt pebbles	0–68	68
	Sand and clay	68–114	46
Franconia	Gray to white, medium-grained sandstone	114–169	55
	White glauconitic sandstone	169–225	56

Center City

Center City is located on the east side of Chisago Lake in Secs. 34 and 35, T. 34 N., R. 20 W. The water for the city is pumped from a privately owned well 4 inches in diameter and 120 feet deep that terminates in the glacial drift. The static level is about 85 feet below the surface or 870 feet above sea level.

A deep well in the city reaches bedrock at a depth of 155 feet. The accompanying log gives the geologic succession.

Mr. Powers' Well, Center City *

		DEPTH (feet)	THICKNESS (feet)
Drift	Sand and gravel	0–155	155
Franconia	White sandstone	155–228	73
	Brown shale	228–274	36
	White sandstone	274–308	34

* Data from the Keys Well Company, St. Paul.

Chisago City

Chisago City is located at the north end of Green Lake and the southwest bay of Chisago Lake. Water for the city supply is taken from a well 8 inches in diameter and 451 feet deep. The static level is 46 feet below the surface and when tested at 150 gallons per minute the well showed a drawdown of 30 feet. The accompanying log gives the geologic succession.

Chisago City Public Well (elevation approximately 925 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Clay and silt	0–20	20
	Fine muddy quicksand	20–97	77
	Sand and gravel	97–99	2
	Hardpan	99–149	50
	Clayey sand and gravel	149–196	47
Franconia	White sandstone	196–231	35
Dresbach	Bluish-green and yellow shale	231–273	42
	Glauconitic sandstone	273–360	87
	Shale and silt	360–451	91

The well at the Dahl House is 410 feet deep and terminates in the Dresbach shales. No detailed log is available.

A test well drilled by the county is located about half way between Chisago City and Lindstrom. This well penetrated 320 feet of drift and alluvium before entering bedrock. The great thickness of sand and gravel suggests an interglacial valley now filled with drift and alluvium. The well is 12 inches in diameter and 602 feet deep. The static level is 39 feet below the surface and when tested at 928 gallons per minute it showed a drawdown of 42 feet.

Lindstrom

The village of Lindstrom is located on a point of land between the two elongated bays of Chisago Lake. The elevation of the railroad grade is 940 feet above sea level. The village obtains water for the public supply system from a well 4 inches in diameter and 300 feet deep. The static level is 50 feet below the surface or 890 feet above sea level. No detailed log of the well is available.

A well half a mile south of the village penetrates 190 feet of sand, gravel, and hardpan but does not reach bedrock at that depth.

Wyoming

The village of Wyoming does not have a public water supply system. An old well of the Northern Pacific Railway Company is 505 feet deep and terminates in white sandstone. The accompanying log gives the formations penetrated.

Northern Pacific Railway Company Well at Wyoming (elevation 895 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Sand and silt	0–15	15
	Red clay	15–109	94
	Sand and clay	109–169	60
	Sand and hardpan	169–176	7
Franconia and Dresbach	Brown and white sandstone and shale	176–284	108
	White sandstone	284–330	46
	Brown sandstone	330–355	25
	White sandstone and shale	355–375	20
	White sandstone	375–505	130

Creamery Well, Wyoming

		DEPTH (feet)	THICKNESS (feet)
Drift	Sand and silt	0–22	22
	Red clay	22–139	117
	Hardpan	139–203	64
	Sand and clay	203–211	8
Franconia and Dresbach	Shale	211–227	16
	Soft sandstone	227–251	24
	Sandstone	251–368	117
	Shale	368–376	8

Rush City

Rush City is located about half way between Rush Lake and the St. Croix River near the northern boundary of the county. In this region the Douglas fault is buried under the Cambrian sandstones that overlap Keweenawan sediments and rest unconformably on the lava flows. Only the basal 15 to 25 feet of white Cambrian sandstone remain in place over the flows.

The city has a number of wells, some dug and others drilled. The dug wells are 25 feet deep and the two drilled wells reach a depth of about 100 feet. They penetrate 80 feet of glacial drift and 15 to 20 feet of white sandstone.[4]

A well at the creamery was drilled through the upper decomposed portion of the lava flows and into fresh igneous rock to a total depth of 326 feet. The accompanying log gives the geologic succession.

Creamery Well, Rush City, Drilled 1944 (elevation approximately 925 feet) *

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–45	45
Dresbach	White sandstone	45–100	55
Keweenawan	Decomposed trap rock	100–275	175
	Fresh trap rock	275–326	51

* Compiled from samples submitted by the Keys Well Company, St. Paul.

North Branch

This village is located on the north branch of the Sunrise River in the central part of the county at an elevation of about 900 feet. In this region the drift is from 175 to 200 feet thick. The log of a private well shows the following subsurface relations.

Well in Village of North Branch (elevation 900 feet; static level 30 feet below surface)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–180	180
Dresbach	Soft, white sandstone	180–250	70
	Bright red sandstone	250–260	10

A new well drilled for the village in 1947 reached a total depth of 760 feet. It penetrated red and grayish-green silt and shale from a depth of 250 feet to the bottom of the well.

Some drift wells in the valley flow from sandy layers that occur under an impervious hardpan at a depth of 175 to 195 feet below the surface. In the drained peat bog area northeast of the village, flowing wells may be obtained from the drift at a depth of 105 to 115 feet. This area lies about 75 feet lower than the elevation in the village. The accompanying log gives the nature of the glacial sediments in that area.

[4] Data from Mr. Forsberg, driller, Braham.

Well at Fish Hatchery, NE¼, Sec. 15, T. 35 N., R. 21 W. (elevation 830 feet)*

		DEPTH (feet)	THICKNESS (feet)
Drift	Sand and gravel	0–50	50
	Sticky clay	50–100	50
	Hardpan	100–108	8

* Data from O. Bjorklund, owner.

Harris

The village of Harris is located on Goose Creek in the north-central part of the county. Cambrian sandstones crop out along the St. Croix valley 4 miles east of the village. About 2 miles northeast of Harris Goose Creek flows in a wide, flat valley flanked by steep banks that stand 50 feet above the valley flats.

The village has no public water supply system. The private wells are driven, dug, or drilled into the sandy till to a depth of 35 to 50 feet. Deeper drilled wells encounter white Cambrian sandstone at a depth of 50 to 75 feet. One well a mile north of the village penetrated 250 feet of drift before encountering bedrock. A short distance from this well the sandstone was reached at a depth of only 90 feet. The deeper well penetrated coarse gravel and pebbles over the sandstone. These relations indicate a preglacial or interglacial valley in this region.

The accompanying log is typical of most of the region that lies around Harris.

Farm Well, SE¼, Sec. 17, T. 36 N., R. 21 W., Northwest of Harris *

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–60	60
Dresbach	Soft, white sandstone	60–72	12

* Data from Mr. Lufi, driller, Isanti.

Stacy

The village of Stacy is located on Middle Branch Sunrise River north of Wyoming. There is no public water supply system in the village. Most of the private wells are driven into the sandy drift from 15 to 40 feet, where satisfactory supplies of water are obtained. The stream at the south edge of the village maintained a constant flow during the drought seasons of 1933 and 1934.

Kost

The creamery well in this inland village flows at a surface elevation of 830 feet. The well is 198 feet deep. No log is available.

FARM WATER SUPPLIES

The general subsurface water conditions in Chisago County are outlined on page 82. However, a few logs of farm wells are given to illustrate the variations in subsurface relations.

A farm well in Sec. 6, T. 35 N., R. 19 W., northwest of Amador, was drilled to a total depth of 400 feet and terminated in glacial drift.[5] The school well at Almelund likewise penetrates more than 200 feet of glacial drift and the drift is nearly 200 feet deep in a well at the south end of Sunrise Lake. Such a great thickness of drift indicates the presence of a deep preglacial valley in this region.

Drilled farm wells in the region of Harris find ample supplies of water in the sandstone that occurs under 75 to 125 feet of glacial drift. (See the accompanying logs.)

Farm Well, SW¼, Sec. 15, T. 36 N., R. 21 W. (surface elevation 915 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–90	90
Dresbach	White sandstone	90–120	30

Farm Well, NE¼, Sec. 21, T. 36 N., R. 21 W. (surface elevation 905 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–125	125
Dresbach	Light gray sandstone	125–140	15

In the sandy moraine of the western part of the county the glacial drift is from 125 to 185 feet thick. If the quicksand layers in the drift do not yield the amount of water required for domestic and farm purposes, ample supplies are available in the white sandstones under the

TABLE 20. — ANALYSES OF WATERS OF CHISAGO COUNTY *

	1	2	3	4	5	6	7
Depth (feet)	...	...	20	169	100	450	292
Hardness	210	350	240	200	245	120	73
Alkalinity	190	320	170	200	220	130	80
Iron	0	.05	2	.05	tr.	.25	.8
Manganese	0	.3	.15	.05	...	.15	...
Chlorine	2	57	54	3.9	10	.28	...
Fluorine	0	.05	...	0	...	.15	...
SO_4 radical	5	15	...	4.9	...	0	...
Turbidity	.5	.3	15	.3	2	.9	0
Color	0	5	18	0	15	5	3
Odor	...	0	...	...	a-2	...	1–4
pH value	7.3	7.8	...	7.4	...	7.8	...

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon=17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Taylors Falls, spring, 1941.
2. Rush City, 1944.
3. North Branch, dug well, 1933.
4. Taylors Falls, drilled well, 1943.
5. Center City, private drilled well, 1938.
6. Chisago City, drilled well, 1936.
7. Lindstrom, drilled well, 1931.

[5] Data from F. Hoover, driller, Taylors Falls.

glacial deposits. The accompanying logs are typical of the region west of Fish Lake.

Farm Well, Sec. 6, T. 35 N., R. 22 W., near West Boundary of County

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–120	120
Dresbach	Light gray sandstone	120–145	25

Farm Well, Sec. 29, T. 36 N., R. 22 W.

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–70	70
Dresbach	Fine, light gray sandstone	70–180	110

COOK COUNTY

Cook County forms the extreme northeastern part of the state. It has a roughly triangular shape, being bounded on the west by Lake County, on the north by Canada, and on the southeast by Lake Superior. Its total length east and west is 72 miles and its width, 54 miles. The county is mostly unsettled and is traversed by few roads, the only ones of great length being the North Shore highway and the Gunflint Trail, which extends from Grand Marais northwestward to Gunflint Lake and from there north to Sea Gull and Saganaga lakes. Several roads enter the Superior National Forest and the Minnesota State Forest from the villages along the shore of Lake Superior, and one extends from Tofte to Sawbill Lake, which lies about 25 miles north of the village.

SURFACE FEATURES

The surface of Cook County is generally rough and hilly. The hills have a general northeastern direction in the southern part of the county, conforming to the Lake Superior shore, but farther north they extend nearly east-west. The land rises abruptly from the lake shore and within 1 to 4 miles from the shore hilltops rise several hundred feet above the lake. Among these hills near the lake are two prominent peaks, Mount Josephine and Carlton Peak. The former rises 703 feet above Lake Superior and the summit of the latter is 927 feet above the lake or 1529 feet above sea level. The highest point in the county is one of the Misquah Hills that reaches an elevation of 2234 feet.

Farther northward, to a line running from the Pigeon River a few miles south of South Fowl Lake to near Elephant Lake and thence west in Lake County, is an area that is rough but has no very marked isolated elevations. Still farther north in what is referred to as the Gunflint and Rove Lake district is a belt from 6 to 20 miles in width that is characterized by conspicuous east-west ridges. Here many of the parallel ridges are capped by diabase sills. The sills are responsible for the development of hogbacks, which have steep and frequently precipitous northern slopes, while the southern dip slopes are quite gentle. Farther eastward, in the vicinity of Pigeon Point, the ridges are steep on both sides, being formed by thick vertical diabase dikes instead of southward-dipping diabase sills.

The northwestern townships of the county have a massive granite range of hills that rise in places to more than 2000 feet above sea level. This high area slopes toward Saganaga Lake, which lies in a comparatively flat district along the international boundary.

Lakes are very abundant, especially in the northern half of the county. In the Gunflint and Rove Lake area the lakes have a marked east and west elongation, coinciding with the direction of the strike of the rock formations. Even in the central part of the county where massive gabbro rocks underlie the glacial drift, a number of the lakes also show an elongation in the same direction. Tucker, Winchell, Brule, and Devil Track lakes are typical examples.

The drainage divide between the Great Lakes and Hudson Bay is the height of land between North Lake and South Lake on the international border. By far the larger portion of the county drains eastward into Lake Superior. The courses of the streams are largely determined by the geologic structure, which is, in brief, a series of alternating hard and soft rocks dipping gently toward the south and southeast. Many streams flow in deeply cut, trough-like valleys which widen locally into rock-basin lakes that parallel the strike of the rock formations. Transverse valleys are not numerous, but there are a few that have important effects on the drainage. The lower parts of the streams flowing into Lake Superior have very high gradients and contain many waterfalls. The finest of these is the Pigeon River Falls.

Along the shore of Lake Superior many of the streams discharge their water back of conspicuous shingle beaches and storm bars. The waters from these streams enter the lakes by seeping through the shingle beaches. The beaches and bars are the products of wave action, a result of the rapid deepening of the water off the coast and the exposure of the lake without the protection of any breakwaters.

All along the Lake Superior shore, above the present level of the lake, are abandoned beaches of glacial Lake Duluth. These old beaches range in height from a few feet above the present storm beaches to more than 600 feet above the lake at Mount Josephine. At Wauswaugoning Bay an exceptionally distinct beach occurs 43 feet above the present level of the lake. Ancient strand lines are conspicuous also on the slope of Carlton Peak and in the region of Lutsen. The Poplar River near Lutsen cuts through a broad embankment of sand and gravel which mantles the rocky slope of this part of the coast for many miles. Similar beaches and wave terraces occur at Good Harbor Bay, Grand Marais, Horseshoe Bay, Double Bay, and Grand Portage.

Leverett states that "the beaches near Grand Marais lie at elevations of from 1,206 to 1,275 feet above sea level, or 604 to 623 feet above the present beach of the lake. A later glacial lake known as Lake Algonquin formed beaches near Grand Marais at 1,042 above sea level, and as the lakes drained off at several lower levels beaches are noted at 785, 760, 725, and finally 630 feet above sea level near Grand Marais. Since the beaches were formed the region has been tilted, with the result that around Pigeon Point they are a little higher than at Grand Marais; but several of these lower beaches are clearly visible at places on the 'Point' and back to Wauswaugoning Bay.

"From the Pigeon River Falls to its present mouth at Lake Superior the river is bordered on the south side by a low swamp which extends to Wauswaugoning Bay. When the lake was at a slightly higher stage this area was under water. Pigeon Point was an island, and the mouth of the river was just below the falls. There was no doubt a time when the river emptied into Wauswaugoning Bay. The swampy area is probably a delta deposit.

"Many of the valleys in the area are bordered with alluvium, particularly parts of the Pigeon River and the Stump River, a tributary in T.64N., R.3E. Some of the swampy lakes are rapidly filling with peat, but most of the larger lakes are in deep rock basins, and the levels fluctuate very little."[1]

UNCONSOLIDATED SEDIMENTS

There is only a very scanty drift covering about one-third of the area of Cook County. This is especially true in the northern part of the county and along a strip of rugged land known as the Sawtooth Mountains which occurs near the Lake Superior shore westward from Grand Marais. Several townships in the eastern end of the county are also only thinly covered with drift.

North of the steep slope leading to Lake Superior the rocks are more heavily covered by drift. This zone of morainic topography, which is prevailingly of the strong knob and basin type, is a part of the Highland moraine system that takes its name from Highland Station on the Duluth and Iron Range Railroad in the southwestern part of Lake County. It represents the outer moraine of the Lake Superior lobe of the late Wisconsin age. In the moraine ridges of drift rise abruptly from 25 to 75 feet or more above the basins and low ground areas. The glacial sediments are generally loose-textured and contain many cobblestones and small boulders. In most areas, however, there is enough clayey material in the matrix to produce a loamy soil at the surface.

Younger moraine zones formed during the recession of the Superior lobe are described by Leverett.

"The Highland morainic system is prevailingly of the strong knob and basin type, with knobs or ridges of drift rising abruptly to heights ranging from 25 to 75 feet or more above the intervening basins and low ground. Some of the basins and low swampy tracts are completely surrounded by higher land and have no drainage over the surface. Others are winding depressions through which drainage courses run. The lakes interspersed with the drift knolls and ridges of this morainic system are not so many nor so large as those found among the rock hills and ridges farther north, in Cook, Lake, and St. Louis Counties. Wild Rice Lake has an area of but little more than 2 square miles, and no others reach 2 square miles. The drift is generally loose textured and contains many cobblestones and small boulders.

[1] Leverett, Frank, Moraines and shore lines of the Lake Superior region: U.S. Geol. Surv. Prof. Paper 154, p. 59, 1929.

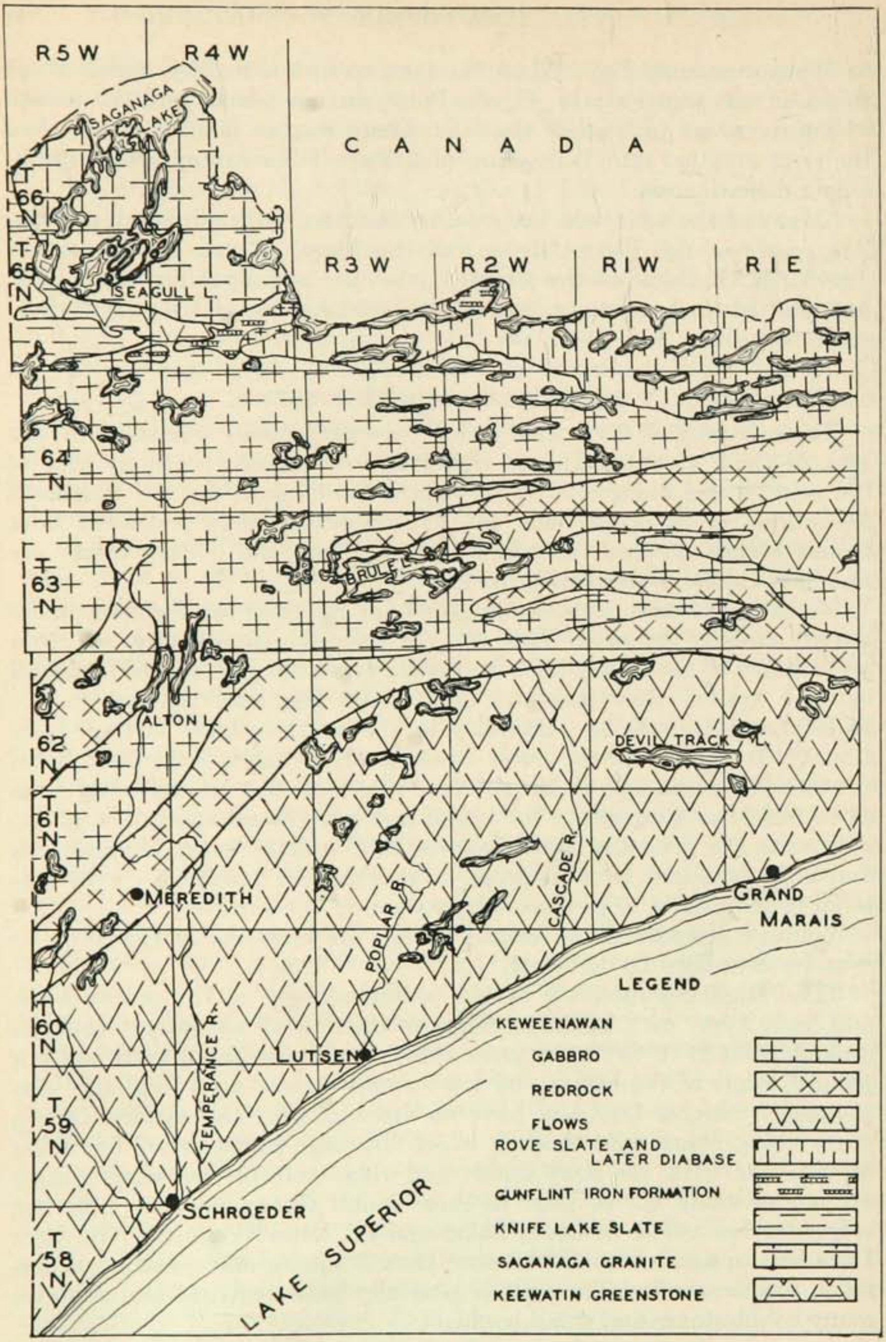

FIGURE 15. — Geologic map of western Cook County.

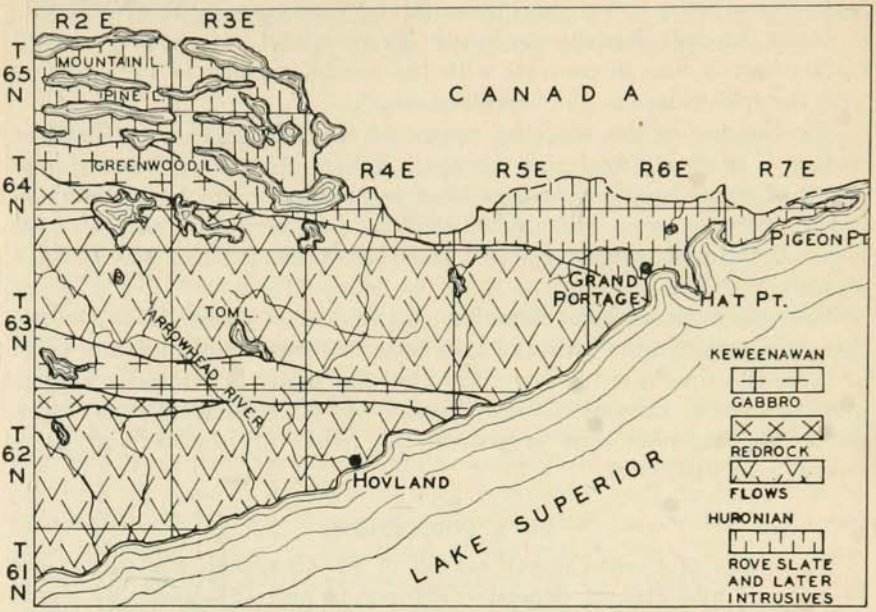

FIGURE 16. — Geologic map of eastern Cook County.

"A later moraine than that just noted sets in on the Lake and Cook County line, only 2 or 3 miles from the shore of Lake Superior, and leads northeastward beyond the meridian of Grand Marais, Minn. It is generally 6 to 10 miles back from the lakeshore and has a width of 1 to 2 miles. It passes along the north side of Devil Track Lake and was traced northeastward about 8 miles beyond this lake to Brule River. To the north of Brule River there is a rough rocky region in which it may be difficult to identify the moraine. This moraine lies back of the Sawtooth Range, in a district where the drift is heavy enough for the morainic features to stand out with some clearness. The drift is stony and loose textured and the area contains swamps of considerable extent and therefore has not been developed for agriculture.

"A still later moraine was traced from a point near the mouth of Cascade River northeastward for several miles. This is thought to continue across Cook County to the Canadian border, crossing Brule River in the southwestern part of T.63N., R.3E., and passing west of Toms Lake and coming to Pigeon River in T.64N., R.4E. After passing Devil Track River it follows the eastern edge of a prominent rocky area and marks the west limit of a district with considerable drift and much swamp land. Immediately above the place where, according to Elftman,[2] the moraine reaches the Canadian border there is a lowland extending

[2] Elftman, A. H., Am. Geologist, vol. 21, pl. 11, 1898.

back several miles west from Pigeon River, nearly across T.64N., R.3W., in which the drift deposits are heavy. This lowland has a nearly smooth surface and is thus in contrast with the knolly moraine to the east and with the rock ridges to the north and south.

"To the east of this moraine, in eastern Cook County, about half the surface is in rock ridges and the other half is in swamps and drift deposits of ground-moraine rather than terminal-moraine type. North of Grand Portage is an area in which lake clay occupies the low areas between the rock ranges, for it stands below the level of glacial Lake Duluth."[3]

Near the shore of Lake Superior, on the floor of glacial Lake Duluth, there are considerable bodies of lake beds and water-laid moraine. Chief of these is a tough, red, pebbly clay that fills many of the older valleys, and the present streams cut steep banks into it. These banks may show miniature landslides, but in general the banks are as steep as those eroded into solid rock.

ROCK FORMATIONS

The rocks of Cook County are all of pre-Cambrian age except the Pleistocene and Recent deposits (Figures 15 and 16). Table 21 shows their age relationships.

TABLE 21. — GEOLOGIC SUCCESSION IN COOK COUNTY

Recent	Alluvium and beaches
Pleistocene	Drift and beaches
Keweenawan	Duluth gabbro
	Logan sills and dikes
	Basalt flows, breccias, and tuffs
	Sandstone and conglomerate
Animikie	Rove formation
	Gunflint (iron-bearing) formation
Lower Huronian (or Archean)	Knife Lake slates
Archean (Laurentian)	Batholithic intrusives, mostly granite
Archean (Keewatin)	Ely greenstone

ARCHEOZOIC

KEEWATIN

The largest area of Keewatin greenstones occurs south of Seagull Lake in T. 65 N., R. 5 W. This zone lies between the Knife Lake slates to the south and the Saganaga granite to the north. It extends eastward into the southwestern part of T. 65 N., R. 4 W. A small area of outcrops occurs 3 miles to the west of the narrows between Gunflint Lake and Magnetic Bay. The greenstones are now largely chlorite schist, but the outlines of ellipsoidal structures and other features of lava flows may still be seen. Locally it has been intruded and altered to hornblende

[3] Leverett, Frank, Moraines and shorelines of the Lake Superior region: U.S. Geol. Survey Prof. Paper 154-A, pp. 28–29, 1929.

schist by the Saganaga granite. The formation is described in detail by Clements in his monograph on the Vermilion iron-bearing district.[4]

LAURENTIAN

The Saganaga batholith is the oldest intrusive granite in northeastern Minnesota. It is the only one that is older than the Knife Lake sediments and it is therefore assigned to the Laurentian. This granite area lies about 30 to 40 miles north of Lake Superior in the northwestern townships of Cook County and occupies a roughly oval area, about 100 square miles in Minnesota and nearly as much in Ontario. Although Seagull and Saganaga lakes occupy a high percentage of the area of the batholith, there are numerous exposures in the region between the lakes and along their shores.

The dominant rock of the Saganaga batholith is a pink to nearly white hornblende granite with conspicuous aggregates of quartz, many of which seem to be hexagonal grains one-eighth to one-half of an inch across. Over most of the area the rock is monotonously uniform in color and texture. A few small outcrops show inclusions and dikes, and some local variations occur in the midst of the granite area. The most important areas that differ petrographically from the main granite constitute a border, or zone, roughly a mile in width along the southeast and northeast sides of the batholith. Detailed petrographic descriptions and chemical analyses of the granite have been published by Grout.[5]

PROTEROZOIC

A small area of Knife Lake slate occurs in the western and southwestern part of T. 65 N., R. 5 W., and the easternmost extension of the slates of northeastern Lake County continue a mile or more into the southwestern part of T. 66 N., R. 5 W. Many slate areas are highly folded and metamorphosed to hornblende and mica schists, whereas others are dense and banded siliceous beds that are steeply inclined.

The Animikean rocks are represented by the Gunflint iron formation and the Rove slates. These rocks occur in a narrow east-west zone from west of Gunflint Lake to Pigeon Point. They rest with a distinct unconformity on the older Archeozoic and early Proterozoic formations. The break is marked by a basal conglomerate in the Gunflint formation and by a change in dip from nearly vertical in the older rocks to nearly horizontal in the later. Furthermore, they transgress a whole series of different older rocks that show a much higher degree of folding and metamorphism. Dikes and porphyries of Algoman age cut the Knife Lake slates, but pebbles formed by the erosion of such dikes are found in the conglomerate at the base of the Gunflint iron-bearing formation.

[4] Clements, J. Morgan, The Vermilion iron-bearing district of Minnesota: U.S. Geol. Survey, Monograph 45, pp. 130–169, 1903.

[5] Grout, F. F., The Saganaga granite of Minnesota-Ontario: Jour. Geol., vol. 37, pp. 562–591, 1929.

The Gunflint formation is 300 to 700 feet thick and is composed of iron-bearing cherts similar to those of the Biwabik formation with which it is correlated. Its metamorphism has been more intense than on the Mesabi Range, and more of its iron oxide is magnetite. The chief exposures of the Gunflint formation are on Gunflint and North lakes. The trend of these outcrops is north of east and their extension eastward crosses the international boundary into Ontario in T. 65 N., R. 2 W. The formation is not known to occur farther eastward in Cook County. The detailed lithology of these iron-bearing rocks has been described by Broderick.[6]

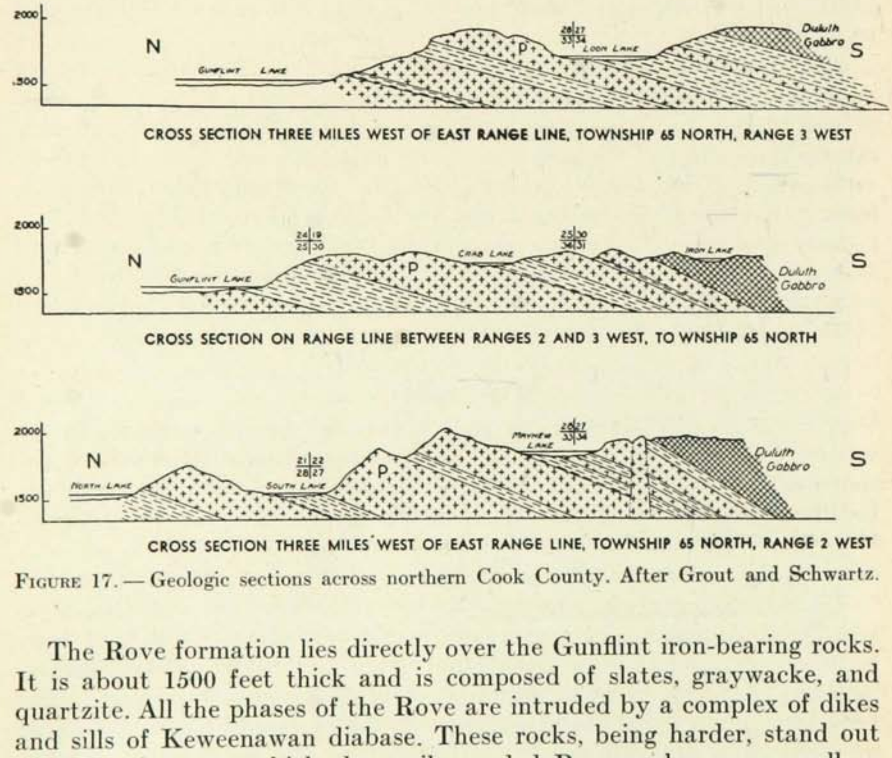

FIGURE 17. — Geologic sections across northern Cook County. After Grout and Schwartz.

The Rove formation lies directly over the Gunflint iron-bearing rocks. It is about 1500 feet thick and is composed of slates, graywacke, and quartzite. All the phases of the Rove are intruded by a complex of dikes and sills of Keweenawan diabase. These rocks, being harder, stand out as ridges, between which the easily eroded Rove rocks occupy valleys and lake basins (Figure 17). The best exposures of Rove formation are at the bases of cliffs in the north-facing escarpments of a series of sawtooth mountains.

The most common type of rock in the Rove is called slate because the thin beds are recrystallized to such an extent that the slabs do not slake down to clay as do the slabs of many shales. The graywacke and

[6] Broderick, T. M., Economic geology and stratigraphy of the Gunflint iron district, Minnesota: Econ. Geol., 15, pp. 422–450, 1920.

slates are dark gray to black in most fresh exposures, but at some places they are gray and green. The cherty and quartzitic varieties range from gray to nearly white, but near the intrusions they are reddened by feldspar grains. In old weathered outcrops nearly all varieties are lighter colored than in fresh exposures or drill cuttings. The average gray slate bleaches to a light gray with a brownish tint produced by the oxidation of iron-bearing minerals.

Most outcrops of the slates expose a thickness of less than 100 feet. For this reason no complete section of the formation is to be found, and consequently the succession within the formation must be generalized from scattered exposures. In general there is a sequence from the base of the formation to higher beds in the exposures from Gunflint Lake to Pigeon Point. In the west near the base most of the exposures are black and dark gray argillite. Those farther east have a higher percentage of quartzite. In most large exposures, however, the thin and thick beds of argillite and graywacke alternate irregularly and no satisfactory division of the formation in beds or members can be made.

For a detailed description of the lithology and structure of the Rove formation, the reader is referred to Bulletin 24 of the Minnesota Geological Survey by F. F. Grout and G. M. Schwartz.

KEWEENAWAN

The Puckwunge formation is the oldest rock of Keweenawan age in Cook County. It is composed of sandstone and conglomerate that lies over the Rove slates and directly beneath the Keweenawan lava flows. Its dip is so nearly the same as that of the Rove as to leave doubt regarding the presence of an unconformity between them. However, there is a marked break in the lithology and in the degree of metamorphism. Furthermore, a conglomerate at the base of the sandstone is evidence also of a break in the sequence of sediments.

There are a number of exposures of the Puckwunge formation in the region of Grand Portage Bay. It crops out also on Grand Portage Island and on Lucille Island. A typical section is exposed in the SW¼, Sec. 1, T. 63 N., R. 5 E., where approximately 50 feet of sandstone may be observed beneath lava flows that form a pronounced east-west ridge. The outcrop faces a low, swampy area of Rove slate. The section of sandstone from the base of the basalt downward is as follows.

Section of Puckwunge Formation in Sec. 1, T. 63 N., R. 5 E.*

	THICKNESS (feet)
Massive, fine-grained, gray sandstone with thin, shaly layers	15
Thinly bedded, fine-grained, gray sandstone, slightly shaly	13
Buff, fine-grained sandstone	10
Gray, shaly sandstone	12
Total	50

*Measured by Clemens Nelson, University of Minnesota.

The exposure on Grand Portage Island is found on the northeast corner of the island situated in Grand Portage Bay. Here the formation strikes N. 65° E. and dips 12° to the southeast. The section downward from the basalt is as follows.

Section of Puckwunge Formation on Grand Portage Island

	THICKNESS (feet)
Dark gray, dense sandstone	2
Coarse, pink, arkosic sandstone	5
Coarse, gray, pebbly sandstone	3
Pink and gray calcareous sandstone	4
Total	14

The Puckwunge formation is covered by such thick lava flows that few if any wells reach this water-bearing sandstone.

The Middle Keweenawan is represented by the lava flows, gabbro, redrock, and diabase sills and dikes. The flows occur along the shore of Lake Superior from the southwest corner of the county northeastward to a few miles beyond Hovland. They extend inland from the shore 5 to 15 miles and dip toward the lake at an angle of about 12°. North of the flows the predominant rock is gabbro. It extends northward to the zone of Rove slate that parallels the international boundary. In the gabbro area there are narrow strips of redrock that extend in a general east-west direction from Brule Lake eastward toward Greenwood Lake. A zone of redrock 1 to 3 miles wide crosses the county directly to the north of the lava flows.

The diabase sills and dikes are most abundant in the area of the Rove formation, where they are responsible for the development of the conspicuous ridges that characterize that region. They are especially numerous in T. 64 N., R. 5 E., and from there eastward to Pigeon Point.

WATER SUPPLIES

Grand Marais

The city of Grand Marais is located at a natural harbor that owes its development to the presence of massive and columnar diabase, which is more resistant to the erosive power of wave action than the softer flow rocks. The city is built on a terrace of low land developed at the head of the harbor or bay.

Water for the public supply system is taken from a group of springs on the hillside about one mile north of the city near the Gunflint Trail. There are a number of private shallow dug and drilled wells from 15 to 40 feet deep and several shops in the city pump water from Lake Superior. Several small springs at the outskirts of the city produce sufficient water for domestic purposes.

At Rustic Inn one mile east of Grand Marais the well penetrates 4 feet of gravel and enters the lava flows to a total depth of 20 feet. The yield of water is very small.

At a group of cottages 2 miles east of Grand Marais sufficient water is obtained from very shallow wells to supply the summer homes. The Dina Larson well is 9 feet deep and ends on the bedrock surface. The A. Larson well is 18 feet deep in lava rock. Its yield is good. Pete Rasmussen obtains water from a spring pit dug to a depth of 7 feet, whereas M. Rasmussen has a dug well that terminates on the bedrock surface at a depth of 12 feet. All these wells are supplied by underground seepage from the high land several miles back from shore.

A short distance west of the city the drift is from 25 to 50 feet thick. A well near the highway one mile west of the city penetrates 44 feet of bouldery clay and 121 feet of lava rock. It produces one gallon per minute with a drawdown of 75 feet.

At the Northern Light CCC Camp 15 miles north of Grand Marais on the Gunflint Trail, a well was drilled to a depth of 723 feet in the Duluth gabbro. The static level was 40 feet below the surface, but the well produced only 1 gallon per minute, which was not sufficient to supply the camp.

A shallow well at the Gunflint CCC Camp penetrates 33 feet of glacial drift and 15 feet of fractured, gray slate. The static level is 22 feet below the surface and the well produces 30 gallons per minute.

At Devil Track Lodge about 4 miles northeast of Grand Marais, drinking water is obtained from springs, and water for other household purposes is taken from the river.

Lutsen

Lutsen is a small settlement that centers around a resort at the mouth of the Poplar River. Between the resort and the highway, which is a short distance inland, the river flows through a gorge with many cascades, falls, and potholes. Drinking water for the resort buildings is taken from a spring a short distance up the hill from the resort. Water for other household purposes is taken from the Poplar River. Several small dams on this stream are used to generate power.

A well at the newly constructed plant of the Lutsen Power and Light Company penetrated 12 feet of drift and lake sediment and entered bedrock to a total depth of 256 feet. It produces about 7 gallons per minute with a drawdown to 100 feet below the surface.

The school well at Lutsen reaches bedrock 8 feet below the surface and terminates at a depth of 227 feet. It produces 6 gallons per minute from a casing 5 inches in diameter.

A well at the summer home of Dr. Curtiss, a short distance west of the resort, was drilled 235 feet into the lava rock. The static level is 4 feet below the surface, and the well produces 10 gallons per minute with a drawdown of 45 feet. The water is too hard to be used for domestic purposes.

A few hundred feet east of Dr. Curtiss' well, the water from a well 151 feet deep is far less hard. The static level in this well is 24 feet below the surface.

Schroeder

The village of Schroeder is located near the southwestern corner of the county at the mouth of the Cross River. There is no public water supply system. Stickney's Resort obtains water for its hotel and cabins from a well that is 5 inches in diameter and 280 feet deep. It entered bedrock at a depth of 70 feet. Water in this well develops a pressure of 22½ pounds.

A well drilled by Ellis Smith penetrated 8 feet of gravel and sand and 5 feet of decomposed lava rock. Water rose to the surface, but the yield was small.

Some water is brought to the village from springs on the hillside beyond the resort. One is located 1000 feet north of the highway and several others have been developed about 2000 feet up the slope beyond the highway. The yield from the springs is small.

The Star of the North Hotel gets water from two springs, one of which is located 400 feet and the other 600 feet up the hillside slope beyond the highway.

Cascade

Cascade is a resort village at the mouth of the Cascade River about 10 miles southwest of Grand Marais. The Cascade Lodge, which is operated during the winter months as well as during the summer, obtains water from several spring pits that are deepened to the bedrock surface.

Tofte

The village of Tofte is a resort and deep sea fishing center with a population of about 200. Water is obtained from springs, from shallow dug wells, and from deep wells drilled into the lava flows. John Tofte has an artesian well 100 feet deep that yields a few gallons per minute from fissures in the basaltic rocks. The Tofte Lodge has a well 9 feet deep that produces most of the water required for the resort, but this supply is augmented by water from a group of springs beyond the highway.

A well at the CCC Camp on the Sawbill Lake road about 16 miles north of Tofte penetrated 75 feet of glacial drift before encountering bedrock. It was drilled to a total depth of 157 feet. At a depth of 120 feet the well produced 2½ gallons per minute and at 146 feet it flowed with a small yield. It was deepened to 157 feet, where it yields 50 to 100 gallons per minute by pumping.

Hovland

The village of Hovland is located on the shore of Lake Superior about halfway between Grand Marais and Grand Portage. Some wells drilled into rock in this area have yielded up to 12 gallons per minute, whereas others produce so little that they have been abandoned.

A well at the Hovland Transient Camp flowed at the surface, but the water contained an abundance of dissolved sulphates and was not suitable for domestic purposes.

The accompanying log gives the subsurface rock formations.

Well at Hovland Transient Camp

		DEPTH (feet)	THICKNESS (feet)
Glacial drift	Clay and boulders	0–55	55
Keweenawan	Purplish basalt	55–115	60
	Gray and green sandstone	115–125	10
	Purplish basalt	125–160	35

A well approximately 500 feet up hill from the transient camp produces water with a very low sulphate content. This well was dug 35 feet to the bedrock surface. It was then drilled 125 feet into bedrock to a total depth of 160 feet. The static level is 18 feet below the surface.

In the region of Chicago Bay a thick mantle of old beach gravels deposited on the floor of glacial Lake Duluth covers the bedrock surface. In this area water may be obtained near the bottom of the sand and gravel deposits.

At Sunny Dale Cabins a layer of gravel about 10 feet thick covers the bedrock. Ample water may be obtained from the upper part of the rock.

A well at the Hovland school drilled to a depth of 400 feet produced less than a gallon per minute and was abandoned.

Two miles inland from the lakeshore the drift thickens considerably. A well in Sec. 34, T. 63 N., R. 4 E., penetrated the following formations.

Farm Well, Sec. 34, T. 63 N., R. 4 E.

		DEPTH (feet)	THICKNESS (feet)
Glacial drift	Red and blue clay	0–35	35
	Hardpan	35–72	37
	Soft clay	72–90	18
	Hardpan	90–111	21
Keweenawan	Basalt	111–158	47

The static level of this farm well is at the surface, where it flows about one gallon per minute. When pumped it yields 5 gallons per minute with about 60 feet of drawdown.

Grand Portage

A well drilled in 1938 at the Grand Portage School in Sec. 3, T. 63 N., R. 6 E., penetrates 22 feet of lake sediments and glacial drift and enters bedrock to a total depth of 178 feet. Water rises to the surface. The yield is small.

TABLE 22. — ANALYSES OF WATERS OF COOK COUNTY *

	1	2	3	4	5
Depth (feet)	...	...	134	90	shallow
Hardness	44	78	110	2000	53
Alkalinity	43	120	76	20	66
Iron	.1	.05	1.0	4	.4
Manganese	tr.	.05	.08	.01	.05
Chlorine	3	.75	...	1700	7.1
Fluorine	.3	.4	...	...	0.3
SO_4 radical	10	5	...	...	7.2
Turbidity	1	.5	13	32	...
Color	12	3	7	10	...
Odor	...	...	...	...	...
pH value	6.8	7.95	7.9	7.6	6.2

*Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Gunflint Springs, Grand Marais, 1934.
2. Grand Marais, 1943.
3. Grand Portage, Independent School District 2, Feb. 20, 1940.
4. Hovland Ranger Station, T. 62 N., R. 4.
5. Hovland, shallow dug well, August 28, 1938.

CROW WING COUNTY

SURFACE FEATURES

Crow Wing County is located near the center of the state. The Mississippi River traverses it nearly centrally from northeast to southwest. The river enters the county in Dean Lake Township in the northeast and flows diagonally across it to Fort Ripley Township southwest of Brainerd. Most of the county stands between 1200 and 1300 feet above sea level, there being only a few square miles above 1300 feet and only narrow strips along valleys below 1200 feet.

The Mille Lacs moraine of the Patrician ice sheet traverses the eastern townships. Much of the moraine is very rugged, especially in the region of Hanging Kettle Lake and from there northwestward to Rabbit Lake. North of the Mississippi River the moraine is also generally strong and locally high and rugged. Lakes and swampy depressions are very numerous. The northwestern part of Mille Lacs Lake projects into the moraine about 2 miles, thus reducing its width locally, but to the north the moraine broadens again.

North of the Mississippi River there is a nearly continuous outwash plain from the western or outer border of the Mille Lacs moraine westward to the inner edge of the St. Croix moraine of south-central Cass County. This zone of glacial outwash extends north as far as Whitefish Lake and Lake Emily.

South of the Mississippi River a large outwash area occurs between the two parts of the Mille Lacs moraine. It comes within a mile of the Mississippi and reaches from Little Rabbit and Portage lakes to Serpent, Reno, and Lookout lakes near Deerwood.

The outwash areas are typically pitted plains with numerous lakes and marshes. The lakes near the Mississippi River have been partially drained by underground flow to the river and some near the channel have been broached by horizontal planation. Several tributaries of the Mississippi River have cut down accordantly with the master stream, draining pit lakes and marshes in the process. Locally the fine outwash sands have been transported by wind action into dune topography. Areas of dunes occur both north and south of the river southwest of Brainerd. They are most extensively developed along the Mississippi Valley, where the regional water table has been lowered by discharge into the river.

The geologic history of the Mississippi River in the Brainerd area has been described in detail by Dr. W. S. Cooper in Bulletin 26 of the Minnesota Geological Survey.

UNCONSOLIDATED SURFACE MANTLE

Since all the county with the exception of the northeasternmost township is covered with glacial sediments deposited by the Patrician ice sheet, the surface mantle is mainly sandy and stony red drift. However, in the moraine of the eastern townships the deposits are generally clayey. West of Mille Lacs Lake and northward to the Mississippi the moraine is mostly of loose texture and contains many cobblestones and small boulders. East of Deerwood, however, there are places in which a heavy clay till is found.

A stony clay loam is found in the till plain that interrupts the outer part of the Mille Lacs morainic system in the northeast corner of the county. An eskerlike sand and gravel ridge, the surface of which is strewn with cobbles and boulders, starts near Birchdale Lake, in the northern part of Sec. 4, T. 137 N., R. 25 W., and extends westward with a somewhat winding course across Sec. 5 and into the northeastern part of Sec. 6.

Over the western half of the county the mantle rock is predominantly glacial outwash that is loose-textured and permeable. The local areas of dunes represent sands of eolian-grade size transported and deposited in characteristic fashion over areas of till and in drained outwash pits. Some of the dunes have lee slopes as much as 60 feet high.

The northern half of the county is dotted with hundreds of lakes that occupy irregular depressions in the drift mantle. Many of the depressions are partly or entirely filled with peat and marl. The region around Star Lake has one of the most extensive deposits of marl in the state. It is one of a group of seven lakes in irregular basins in an area of coarse, gravelly and sandy drift. The topography is sufficiently rugged to allow the active circulation of ground water toward the basins. Thus the general subsurface conditions are such that the leaching of calcium-bearing carbonates takes place readily. The resulting bicarbonate makes its way to the lake basins, where it is precipitated as marl.

Star Lake, which covers approximately 300 acres, is underlaid by a marl bed ranging from 15 to more than 25 feet in thickness.[1]

The thickness of the drift varies considerably, but not so greatly as in counties where the bedrock surface protrudes through the glacial deposits. It reaches a thickness of more than 350 feet in the Mille Lacs moraine of the eastern townships and averages about 150 feet in the outwash areas of the Cuyuna Range region. In the northwestern townships the bedrock surface is encountered at depths of 95 to 250 feet. Still farther northwestward in Cass County the drift is as much as 500 feet thick. Typical thicknesses are shown in Table 23.

ROCK FORMATIONS

There are no known outcrops of bedrock in Crow Wing County. However, extensive drilling for iron ore and mining operations on the Cuyuna Range have revealed the nature of the rock formations under the glacial drift (Figure 18).

[1] Stauffer, C. R., and Thiel, G. A., The limestones and marls of Minnesota: Minn. Geol. Survey Bull. 23, p. 135, 1933.

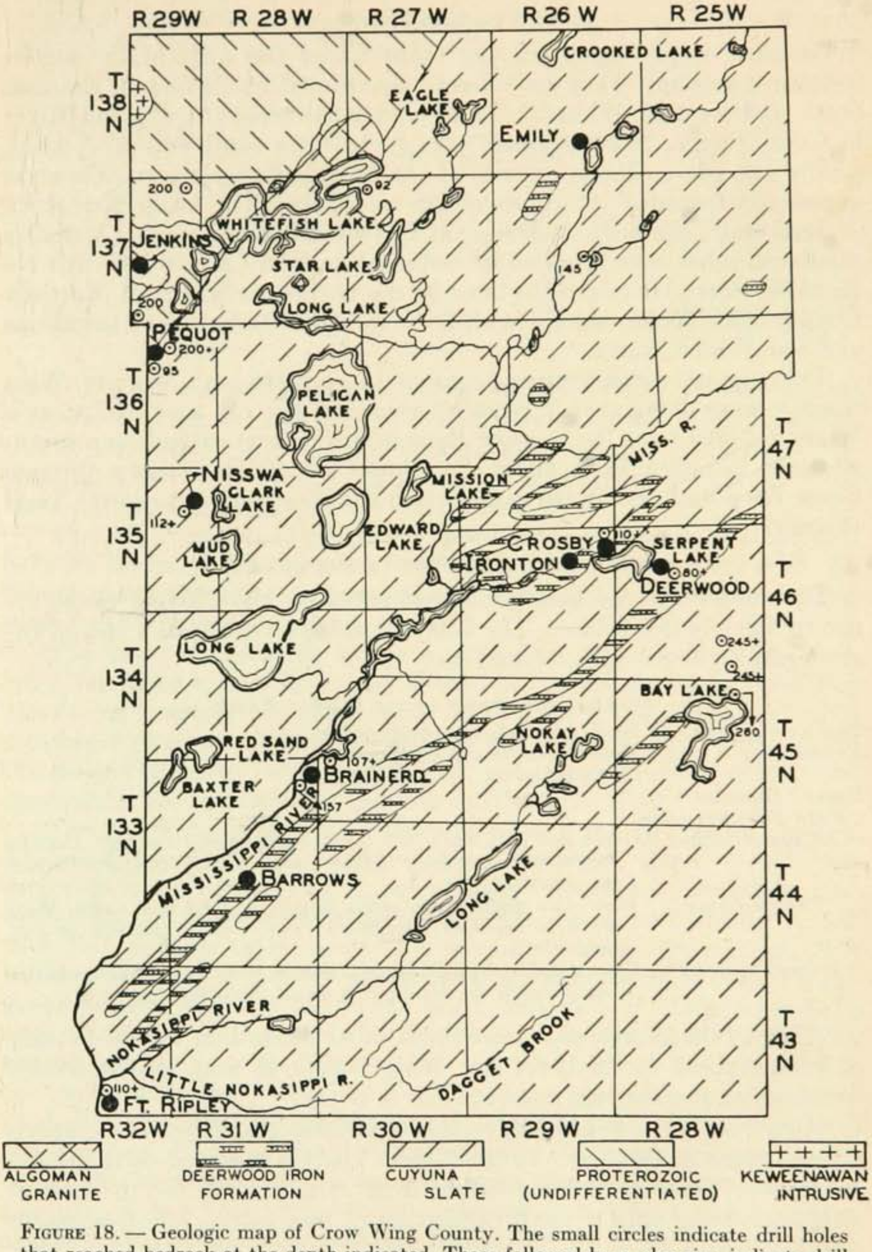

FIGURE 18. — Geologic map of Crow Wing County. The small circles indicate drill holes that reached bedrock at the depth indicated. Those followed by a plus sign indicate drill holes that did not reach the bedrock surface.

PRE-CAMBRIAN

Granites of pre-Cambrian age occur under the drift in the northwestern townships. They have been encountered by drilling in the area north and west of Whitefish Lake, and northwestward at Pine River in Cass County. These granites may represent a southwestward extension of the Giants Range granite of the Mesabi Range region. They are apparently intruded into mica schists and slates. The latter have been entered under the drift by drilling at Pequot and near Jenkins. A similar relationship has been reported in southeastern Cass County in T. 134 N., R. 31 W.[2] Granites related to those in the northeastern part of Morrison County may occur under the drift in the southeasternmost townships of Crow Wing County.

The magnetic iron-bearing rocks of the central part of Crow Wing County were discovered in 1895 by means of the dip needle. The area is now referred to as the Cuyuna Range. This district extends in a southwesterly direction from about the center of Aitkin County through Crow Wing and northwestern Morrison counties into east-central Todd County.

STRATIGRAPHY OF THE CUYUNA RANGE

The succession and geologic age of rocks on the Cuyuna range are not completely determined. The following table gives Zapffe's idea of the stratigraphy of the rock formations.[3]

GEOLOGIC SUCCESSION IN THE CUYUNA RANGE

Post-Keweenawan	Shaly sediments and conglomerates
Keweenawan	Basic intrusives and eruptives Acidic intrusives
Upper ? Huronian	
Crow Wing formation	
Cuyuna member	Green and gray slaty and cherty rocks, partly volcanic. Includes Deerwood iron-bearing members, some strongly magnetic. Schistose intrusives.
Emily member	Dark slaty rocks, some green. Few if any volcanic rocks. Many scattered lenses of ferruginous rocks, slightly magnetic or nonmagnetic.
Aitkin formation	Gray slates and phyllites; no volcanic rocks. Some iron carbonate but probably no iron-bearing lenses. Not magnetic.

"The Aitkin formation is so complex in structure that almost nothing is known about it. Of the Crow Wing formation only the Deerwood iron-bearing member has been studied in detail.

"*Deerwood Iron-Bearing Member.*—Limonitic and hematitic cherts are abundant in the North range. A little chert is reported on the South range also. There are all gradations from siliceous iron ore to chert or slate containing only a small percentage of iron oxide. The ferruginous

[2] Allison, I. S., The geology and water resources of northwestern Minnesota: Minn. Geol. Survey Bull. 22, p. 55, 1932.

[3] Zapffe, C., The Cuyuna iron-ore district: 16th Internat. Geol. Congr. Guidebook 27, pp. 72–88, 1933.

TABLE 23. — THICKNESS OF DRIFT AND NATURE OF BEDROCK IN CROW WING COUNTY

Location	Depth to Rock (feet)	Kind of Rock
Sec. 34, T. 137 N., R. 29 W.	200	Mica schist
Sec. 10, T. 136 N., R. 29 W.	95	Black slate
T. 134 N., R. 31 W.	115	Gray granite
Sec. 6, T. 137 N., R. 27 W.	92	Granite
Sec. 22, T. 137 N., R. 26 W.	145	Slate
Sec. 1, T. 137 N., R. 29 W.	200	Mica schist
Sec. 2, T. 45 N., R. 28 W.	260	Schist and slate
Sec. 1, T. 43 N., R. 30 W.	110	Graphite schist
Sec. 35, T. 46 N., R. 28 W.	245	Slate and schist
Sec. 25, T. 45 N., R. 31 W.	157	Slate and schist

chert consists almost entirely of silica and iron oxide. In the original rocks from which the iron ores of the Cuyuna range are largely derived, cherty and argillaceous beds alternate with beds rich in ferrous carbonates. Some have a banded or laminated appearance; others are thick bedded. Magnetite is a common constituent.

"The richer primary beds of the iron-bearing formation are enclosed between layers of schist or slate which may be similar on both sides. Although most of the slates and schists are of sedimentary origin, some schists appear to be of igneous origin.

"The iron-bearing rocks occur in seven or eight main belts, some being less than a mile long, and others, in the South range, extending almost continuously for many miles. All of these trend in the northeast-southwest direction. There are belts of iron-bearing rock north of the Mississippi River, as far as Lake Emily, but those of proved commercial importance are almost all in the area south of the river.

"The North range includes a series of belts of the Deerwood member. The most northerly belt, south of the Mississippi River, is not well explored. South of this belt is one of more importance, containing the manganiferous iron ore bodies of the Merritt, Ferro, and Algoma mines. This belt appears to be more or less manganiferous throughout. Still farther south are a number of scattered occurrences of iron and manganese-bearing rocks in the region north and west of Mahnomen Lake and southwest of Rabbit Lake. South of these scattered bodies and almost connecting with them on the eastern end near Rabbit Lake is the main productive belt of the Cuyuna range, extending for a distance of about eight miles. It contains many important iron and manganiferous iron ores. North of the central portion of this main belt and southeast of Mahnomen Lake is a manganiferous iron-bearing area. South of this area is the Croft-Armour No. 2-Pennington belt, which is rather narrow but contains important ore bodies, mostly of iron, though some manganiferous ores appear locally. South of these are local occurrences of manganiferous and nonmanganiferous iron-bearing formation and ore in the southernmost areas of the North range.

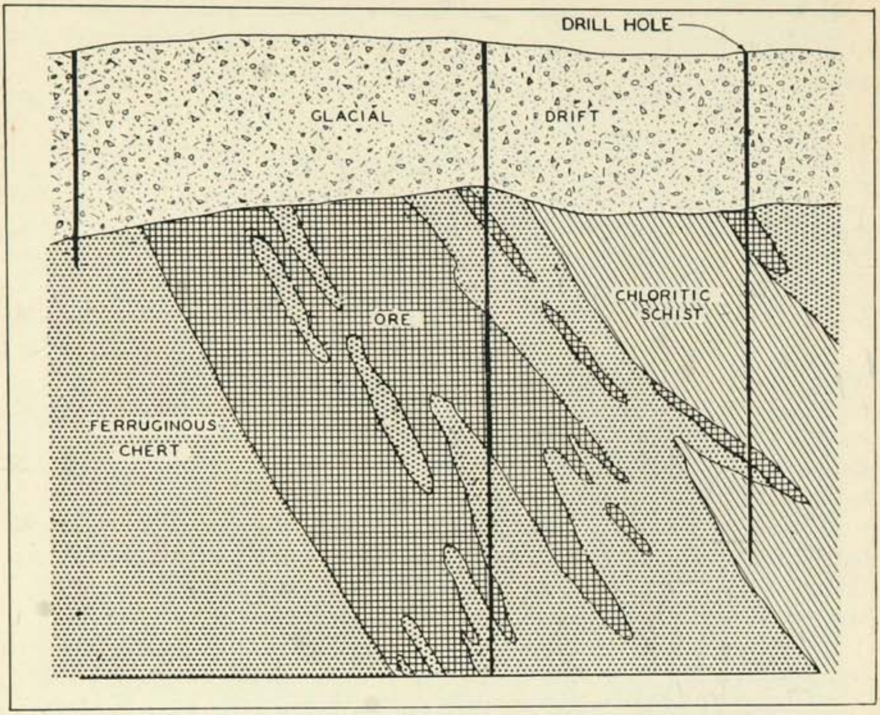

FIGURE 19. — Cross-section showing subsurface relations of rocks and iron ore on the Cuyuna range. The ore is more porous than the rock and is recharged with water from the glacial drift. After Harder and Johnston.

"The South range of the Cuyuna range, consisting of several long, narrow belts, lies south of the Northern Pacific Railway tracks. The northerly belt of the South range has been traced for 24 miles from Deerwood to a point a short distance southwest of Barrows. Mines have been developed along this belt, but they have been idle since World War I. South and southeast of Brainerd and south of Barrows, a second belt runs parallel to and about one and a half miles south of the long belt. There are ore bodies on it, but it has not been thoroughly explored. Other belts of the iron-bearing rock in Morrison County, which are continuations of the South range, are short and are scattered over an extensive area. Isolated belts occur also south of the South range in Crow Wing County.

"*Structure of the Deerwood Member.* — All the rocks of the Deerwood and older formations have been folded into a complex series of close folds with steep dips to the northwest and southeast, those to the southeast predominating [Figures 19 and 20]. The fact that the pitch of the folds is commonly almost horizontal causes the formation to

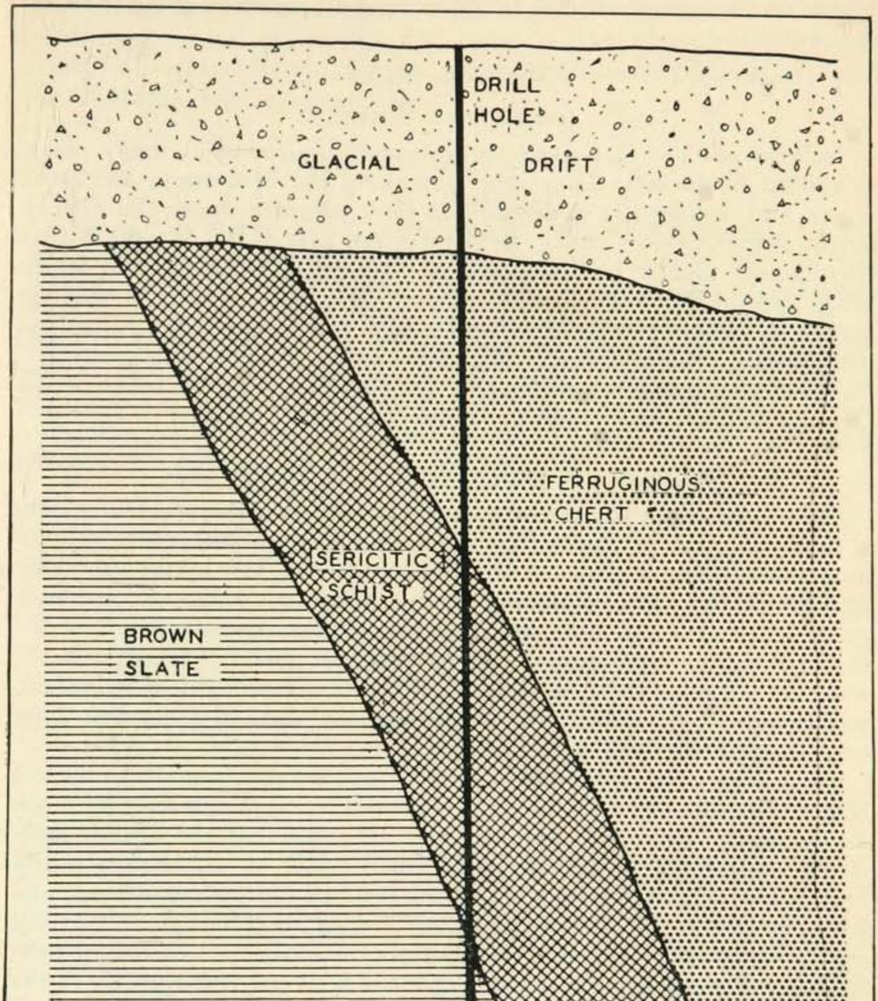

FIGURE 20. — Generalized cross-section showing the steeply dipping beds of slate and chert typical of the structure in central Crow Wing County. After Harder and Johnston.

appear on the erosion surface as approximately parallel northeast-southwest belts."[4]

Mesozoic Rocks

CRETACEOUS SYSTEM

Isolated patches of Cretaceous sediments are found at many places in central Minnesota. They crop out along the Mississippi and Sauk rivers, and drilling has demonstrated their presence under the drift in north-central Aitkin County. In the western part of the Mesabi district they consist mainly of basal beds of ferruginous conglomerates which grade upward into ferruginous clays and shales. No Cretaceous beds are known to crop out in Crow Wing County, but exploratory drilling has demonstrated the presence of horizontal strata of shales and sandy ferruginous glomerates unconformably over the iron-bearing rocks of the Cuyuna district. These beds are thought to be Cretaceous in age.

GENERAL UNDERGROUND WATER CONDITIONS

Over large areas the gravel and sandy drift are saturated to within a short distance of the surface, and they yield water generously to numerous shallow wells, most of which are driven. This is true especially throughout the areas of outwash and in the sandy moraines, although water is found in the moraines at greater depths. The clayey till of the red drift contains numerous veins of sand and gravel which supply the wells in that area. These veins are local and of different thickness, extent, and texture; consequently the depth and the yield of wells also differ even when the wells are close together.

In the outwash areas the water table is generally from 10 to 30 feet below the surface and in the hilly portions it is approximately as much deeper as the height of the hills. This indicates that the drift is sufficiently permeable to permit underground water to establish a nearly even water table approximately at the level of the surface streams and lakes. So free is the underground flow of water that raising or lowering the level of lakes by means of dams affects the water level in shallow wells for some distance from the lakes. This has been noted frequently in the region of Whitefish and Cross lakes in the northwestern part of the county.

The hydraulic gradient toward the Mississippi River is shown by the level of the surface of the water in the lakes of the Brainerd region. In Gilbert Lake the water stands 1174 feet above sea level, in Perch Lake 1188 feet, in Mud Lake 1204 feet, and in Bass Lake, which is still more distant from the river, the surface is about 1206 feet above sea level.

The bedrock formations under the drift are not a very satisfactory source of water. However, where the iron formation is oxidized and partially leached, the resulting concentration of iron oxide is rendered

[4] Emmons, W. H., and Grout, F. F., Mineral resources of Minnesota: Minn. Geol. Survey Bull. 30, pp. 23–26, 1943.

porous and more permeable than the fresher ferruginous cherts. Such zones yield water generously. The same is true of enriched iron ore bodies. These are saturated with water which must be pumped from the ore during mining operations.

MUNICIPAL WATER SUPPLIES

Brainerd

The city of Brainerd has a number of wells that terminate in the glacial drift. A well drilled in 1934 is 16 inches in diameter and 107 feet deep. It was tested at 1800 gallons per minute and showed a drawdown of 55 feet. Another well completed in 1938 with a gravel pack, is 120 feet deep. No bedrock was encountered. The static level of this well is 16 feet below the surface and when tested at 1860 gallons per minute it showed a drawdown of 30 feet.

An analysis of the water (Table 24) shows 1 part per million of iron and nearly a similar amount of manganese.

Table 24. — Analysis of Water from Brainerd City Wells, 1931*

	Parts per Million
O_2 consumed, 30 minutes	1.00
SiO_2, insoluble silica	14.40
Al_2O_3	.57
Fe	1.00
CaO	83.00
MgO	29.25
NaCl and KCl	29.80
Na and K equivalent as Na_2	11.71
Mn	.80
Cl	.70
S	7.13
pH	7.00
Alkalinity (methyl orange)	198.00
Ammonia nitrogen (N)	.006
Aluminoid ammonia nitrogen	trace
Nitrites — nitrogen	.003
Nitrates — nitrogen	.18
Temporary hardness	209.00
Permanent hardness	32.00
Total hardness	241.00
Total solids (dried 125°)	287.00

*Reported by Carl Zapffe, Econ. Geol., vol. 26, p. 812, 1931.

Owing to the action of bacteria, a black precipitate of iron and manganese formed in the pipes of the water supply system. The constituents of this precipitate are given in Table 25.

In order to eliminate the "black water" resulting from fine particles of oxides in suspension, the water is put through a demanganizing plant. The process in its essentials consists of discharging the water from the underground wells into a chamber containing pyrolusite of small size, then down a slide which exposes the water to the atmosphere, and into a bed of special-sized coke of large surface area from which it overflows into a regulation type of open sand filter. By this process the manganese content of the water is reduced from .80 to .02 parts per million.

TABLE 25. — ANALYSIS OF PRECIPITATE IN WATER PIPES OF BRAINERD WATER SUPPLY SYSTEM, 1931*

	Per Cent
Fe (dried at 212° F.)	14.46
Mn (dried at 212° F.)	29.93
SiO_2	7.08
Al_2O_3	.67
CaO	5.55
MgO	.56
Loss on ignition	23.52
Total	81.77

*Reported by Carl Zapffe, *op. cit.*

An old well at the shops of the Northern Pacific Railway Company is 8 inches in diameter and 647 feet deep. It penetrated 157 feet of glacial drift and 490 feet of slates and schists. It produced a small amount of water at a depth of 275 feet and was tested at 55 gallons per minute at that depth. Drilling was continued and at 647 feet it produced 90 gallons per minute. The pump line extended to 140 feet below the surface. The well is no longer in use.

The well at the Farmers Cooperative Creamery is 3 inches in diameter and 134 feet deep. No bedrock was encountered and the static level in the well is 30 feet below the surface.

The Northwestern Paper Company uses great quantities of water at its plant at the north edge of the city, but its water is pumped from the Mississippi River.

CROSBY

The city of Crosby is located at the west end of Serpent Lake. The city has two wells that supply the public water system. One well is 16 inches in diameter and 110 feet deep and the other is 12 inches in diameter and 90 feet deep. The first is pumped at 500 gallons per minute and the second at 225 gallons. Both terminate in porous glacial sands and gravel. The static level is 12 feet below the surface.

IRONTON

The city of Ironton adjoins Crosby on the west. For many years the water supply for Ironton was taken from a group of seven shallow wells at the south edge of the city. The water from the wells was pumped into a reservoir 16 feet in diameter and 28 feet deep.

A new city well was drilled in 1943. It penetrates sandy clay and fine sand to a depth of 33 feet, where 3 feet of gravel was encountered. The well is 52 inches in diameter and is finished with a screen 10 feet long surrounded by a gravel pack. The static level is 6 feet below the surface and when pumped at the rate of 230 gallons per minute it has a draw-down of 19 feet.

Deerwood

The village of Deerwood is located at the east end of Serpent Lake. In this area much of the glacial drift is clayey and impervious, and even where it has a thickness of more than 300 feet satisfactory supplies of ground water may not be obtained owing to the absence of sand or gravel layers in the glacial deposits.

The village well is 6 inches in diameter and 80 feet deep. Water is obtained from a vein of sand that occurs just under a thick layer of hardpan.

A well at the depot of the Northern Pacific Railway Company is 8 inches in diameter and 300 feet deep. It penetrated clayey till for nearly the entire depth. No satisfactory yield of water could be developed and the well was abandoned.

A similar condition was found 3 miles southeast of Deerwood in Sec. 26, T. 46 N., R. 28 W. Here a well penetrated 245 feet of clayey glacial till and 5 feet of slate and schist. Very little water seeped into the well even after a charge of dynamite was used to loosen the rock and clay at the bottom of the drilled hole.

Pequot

The village of Pequot has no public water supply system. The private wells are driven, dug, or drilled to depths of 35 to 100 feet and obtain water from the glacial sands. A well a short distance northwest of the village penetrated 200 feet of drift and entered a soft mica schist to a total depth of 210 feet. The static water level was found to be 26 feet below the surface.

Jenkins

The wells in this vicinity are mostly driven and bored into the glacial outwash sands that are saturated with water to within about 25 feet of the surface. There is no village well.

Nisswa

The village of Nisswa has no public water supply system, and most private wells are driven into the sandy glacial outwash. A drilled well owned by N. K. Schwartz penetrated more than 50 feet of white clay. The accompanying log shows the nature of the sediments that were encountered.

Well in Village of Nisswa*

		DEPTH (feet)	THICKNESS (feet)
Drift	Sand	0–36	36
	Hardpan	36–48	12
	White soft clay	48–110	62
	Gravel	110–112	2

*Data from Martin Norris, driller, Pequot.

Emily

In this region the glacial drift ranges from 200 to 300 feet in thickness and none of the wells enter the bedrock. Exploratory drilling a few miles southwest of the village has revealed the thickness of the drift and the lithology of the underlying rock formations. A body of iron ore has been outlined in Sec. 4, T. 137 N., R. 26 W.

About 5 miles south of the village in Sec. 22, T. 137 N., R. 26 W., a farm well penetrates 147 feet of drift and 2 feet of slate. A good supply of water was obtained at the contact of the drift and the bedrock.

Fort Ripley

In the vicinity of Fort Ripley the wells average about 100 feet in depth; none enter bedrock. A well at a grocery store at the south edge of the village is 110 feet deep. Most others are from 40 to 75 feet in depth and all yield generously.

Table 26. — Analyses of Waters of Crow Wing County *

	1	2	3	4	5	6
Depth (feet)	25	47	140	...	...	...
Hardness	220	150	170	140	150	210
Alkalinity	120	150	200	150	140	200
Iron	.1	4.5	.35	.9	1.5	1.2
Manganese	.05	.48	.1	.28	.6	.8
Chlorine	24	4.9	2.5	3	4	...
Fluorine	0	0	0	.15	5	...
SO_4 radical	120	4.9	24	0	.05	...
Turbidity	.1	40	4	20	6	...
Color	0	40	4	12	3	...
Odor	...	...	...	0	...	7.5
pH value	6.8	7.4	7.55	7.9	...	...

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Riverton, dug well, 1942.
2. Ironton, drilled well, 47 feet deep, 1943.
3. Deerwood, drilled well, 1942.
4. Breezy Point Lodge, Pelican Lake.
5. Crosby, drilled well No. 2, 1944.
6. Brainerd, drilled well, 1933.

ISANTI COUNTY

SURFACE FEATURES

All of Isanti County, with the exception of a few square miles in the northwest corner, lies within the area covered by the Grantsburg lobe of the Keewatin glacier. Thus the surface is characterized by moraines, till plains, and outwash areas. Ponded glacial water and marginal glacial streams along the north edge of the ice decreased the relief of the region by eroding morainic hills and by depositing lacustrine silts and clays in the depressions. The Anoka sand plain covers much of the southern part of the county and a narrow zone extends north as far as Braham.[1] Over some of this area dune topography is superimposed on the glacial features.

The general surface slope is toward the south. Along the north county line the surface elevation is from 1050 to 1100 feet above sea level, whereas the sandy plain in the south-central part of the county stands at about 950 feet. The greater part of the county is drained southward through the Rum River to the Mississippi, but the southeastern townships drain eastward to the St. Croix River.

The influence of the shape of the ice lobe on regional drainage is shown by the pattern of the Rum River in this county. It enters the county west of Spencer Brook and flows northeastward as far as the northwestern part of Cambridge Township (T. 36 N., R. 23 W.), where it makes an acute turn and flows back southwestward toward St. Francis. This channel was undoubtedly established by drainage near the margin of the ice. A similar lobate pattern has been developed by Stanchfield Creek.

UNCONSOLIDATED SURFACE MANTLE

The mantle rock is composed of glacial till and outwash, lacustrine silts and clays, dune sands, and recent alluvial sediments. The glacial tills are the thickest and most widespread. The other sediments occur as a thin veneer over the glacial deposits. The depth to the bedrock surface varies from less than 100 to more than 200 feet. Its average thickness is about 150 feet.

Table 27 illustrates the variations in thickness of the unconsolidated surface deposits.

ROCK FORMATIONS

Pre-Cambrian

No exposures of bedrock formations are known in Isanti County, and no drilling has reached the pre-Cambrian granites and related crystalline rocks. However, a deep well at St. Francis directly beyond the south county line is reported to have encountered granite at a depth of about

[1] Cooper, W. S., History of the upper Mississippi River in late Wisconsin and postglacial time: Minn. Geol. Survey Bull. 26.

TABLE 27. — VARIATIONS IN THE THICKNESS OF GLACIAL DRIFT

Location	Depth to Bedrock (feet)
SE¼, Sec. 2, T. 34 N., R. 25 W.	190
NE¼, Sec. 2, T. 34 N., R. 25 W.	180
NE¼, Sec. 2, T. 34 N., R. 23 W.	120
SW¼, Sec. 19, T. 35 N., R. 22 W.	70
NW¼, Sec. 23, T. 35 N., R. 24 W.	98
NW¼, Sec. 1, T. 35 N., R. 23 W.	98
Sec. 30, T. 35 N., R. 23 W.	130
NE¼, Sec. 32, T. 36 N., R. 23 W.	100
SE¼, Sec. 5, T. 37 N., R. 22 W.	150
SE¼, Sec. 2, T. 37 N., R. 23 W.	80

400 feet, and at Princeton, a few miles to the west in Mille Lacs County, granite occurs at a depth of 150 feet.

Pre-Cambrian sandstones may be directly beneath the drift in the northwesternmost township, where the Hinckley formation occurs between the red clastic Fond du Lac beds and the fossiliferous marine strata of the St. Croixian series. On the geologic map of Minnesota published by the Minnesota Geological Survey in 1932, the Hinckley sandstone is shown as occurring beneath the drift as far southeastward as the city of Cambridge. However, more recent drilling has demonstrated the presence of shell-bearing sandstone as far northwestward as Day in Sec. 7, T. 37 N., R. 24 N., and Braham in Sec. 2, T. 37 N., R. 23 W. Thus the southeastern margin of pre-Cambrian rocks may follow a general northeast-southwest direction from the region north of Day toward upper Rice Lake, which lies to the west of Braham, or the contact between the Paleozoic and the pre-Cambrian rocks may be still farther toward the north in Kanabec County.

PALEOZOIC ROCKS

CAMBRIAN SYSTEM

Upper Cambrian rocks of the St. Croixian series underlie the drift of most if not all of Isanti County (Figure 21). In the southern townships glauconitic silts and sandstones suggest the presence of the Franconia formations. However, since the Dresbach sandstones that crop out at Taylors Falls are very glauconitic, it is probable that all the Cambrian sandstones of Isanti County are members of the Dresbach formation.

The lowest member, the Mt. Simon, is exposed along the valley of the St. Croix River northward beyond the mouth of the Kettle River, which is more than 10 miles north of the county line. The Eau Claire member occurs directly above the Mt. Simon. It is composed of fine-grained sandstone, siltstone, and shale. East of Rush City in Pine County, where these strata are exposed, small brachiopod shells and shell fragments are very abundant. This same fossiliferous horizon is

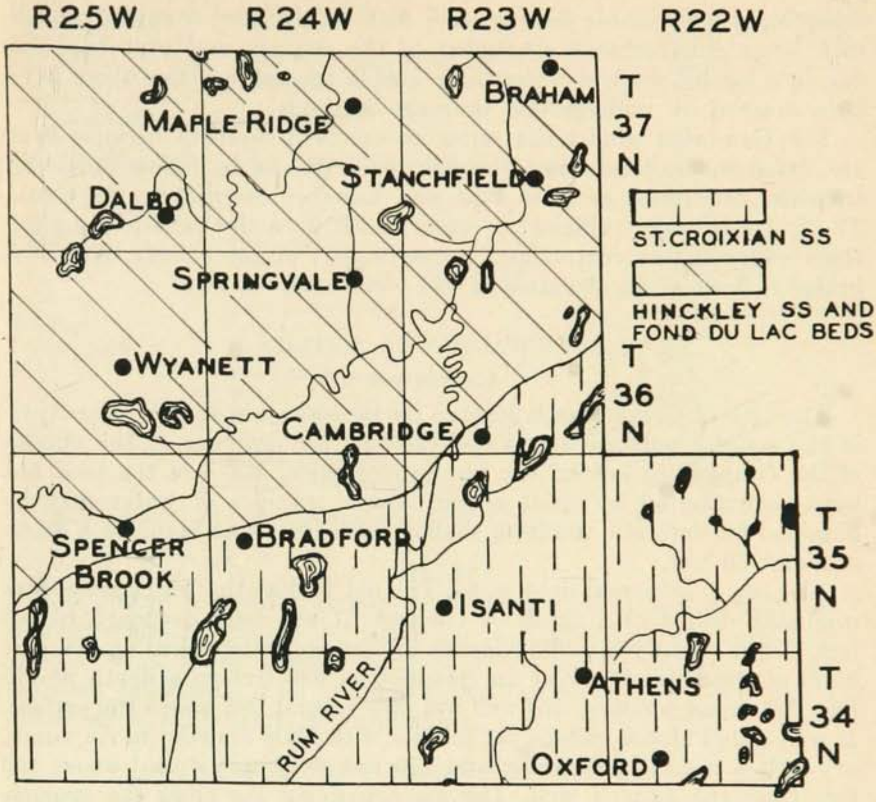

FIGURE 21. — Geologic map of Isanti County.

reported from drill cuttings in Isanti County as far north as Braham and the inland village of Day near the northwestern corner of the county. Similar shell-bearing beds occur as far south as the village of Isanti. Thus it appears that the Eau Claire member of the Dresbach lies directly beneath the drift over most of the county.

The bedrock surface slopes toward the south at a low angle. At Braham it stands at an elevation of 940 feet, at Cambridge at 875 feet, and at Isanti at 870 feet above sea level. Structurally the strata are a part of the southeastward-dipping monocline that characterizes the east-central part of the state.

GENERAL UNDERGROUND WATER CONDITIONS

Owing to the sandy character of the glacial drift the movement of underground water is relatively rapid, and consequently there are no marked differences in the static level of the water table. There is, however, some confined water in the drift and at a few places where the topography is favorable flowing wells may be obtained from the mantle rock layer. Furthermore, a number of the swamps and peat bogs are due to a locally perched water table and in several localities these have been drained by underground drainage methods.

The Cambrian sandstones serve as excellent aquifers because they are recharged by percolation through the drift and by inflow down dip from the catchment areas in Pine and Kanabec counties to the north. The water is under sufficient pressure to lift it to the surface along the Rum valley in the central and southern part of the county. At Cambridge it flows at an elevation of 925 feet above sea level.

MUNICIPAL WATER SUPPLIES

Cambridge

The city of Cambridge is located on the east side of the Rum River in the zone of outwash sands reworked by the drainage at the margin of the Grantsburg lobe of the Keewatin glacier. Much of the sand has been redistributed by wind action. Ample supplies of water may be obtained for domestic use from shallow wells driven or bored to a depth of about 30 feet.

The city has several deep wells. The old well at the water tower was originally drilled to a depth of 110 feet. It was later deepened to 223 feet. More recently a well 12 inches in diameter was drilled on the east bank of the Rum River at an elevation of 920 feet to a depth of 175 feet. When not pumped this well will flow several feet above the surface. It was tested at 250 gallons per minute with little drawdown. An auxiliary well 4 inches in diameter and 150 feet deep was drilled about 150 feet from the 12-inch well. The accompanying log gives the geologic succession.

Old City Well near Water Tower, Cambridge (elevation 965 feet)*

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–100	100
Dresbach			
Eau Claire	Soft white sandstone	100–155	55
	Light gray sandstone	155–205	50
	Green shale	205–223	18

*Data from J. Lufi, driller, Isanti

A well at the starch factory about a block south of the city well on the bank of the Rum River penetrated the following formation.

Well at Starch Factory, Cambridge (elevation 925 feet)*

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–60	60
Dresbach			
Eau Claire	Soft white sandstone	60–90	30

		DEPTH (feet)	THICKNESS (feet)
	Hard, clean, gray sandstone	90–150	60
	Sticky green shale	150–165	15

*Data from J. Lufi, driller, Isanti.

Well at State Colony for Epileptics, Cambridge (elevation 964 feet)*

		DEPTH (feet)	THICKNESS (feet)
Drift	Fine sand	0–31	31
	Clay	31–35	4
	Fine sand	35–51	16
	Sand and gravel	51–88	37
Dresbach			
Eau Claire	Soft sandstone	88–119	31
	Hard sandstone	119–162	43
	Sandy shale	162–235	73
	Bluish-green shale	235–240	5
	Hard, fine white sandstone	240–247	7
	White sandstone	247–287	40
	Soft yellow sandstone	287–290	3

*Based on drill cuttings from the McCarthy Well Company, St. Paul.

Isanti

The village of Isanti is located in the south-central part of the county, a short distance east of the Rum River. There are numerous shallow private wells in the village, many of which are driven into the sandy outwash sediments. The accompanying logs of deeper wells give the character of the subsurface formations.

Creamery Well at Isanti (elevation 960 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–90	90
Dresbach			
Eau Claire	Yellowish sandstone	90–100	10
	Fine greenish sandstone and shale	100–180	80

Farm Well ½ Mile North of Isanti

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–90	90
Dresbach			
Eau Claire	Greenish sandstone and shale	90–175	85
Mt. Simon ?	Gray, medium-grained sandstone	175–275	100

Braham

The village of Braham is located at the north boundary of the county in the marginal zone between young gray and young red drifts of the Keewatin and Patrician glaciers respectively. The glacial deposits are less sandy than farther southward in the county and consequently less permeable to the flow of underground water. However, the sandstones under the drift are excellent aquifers. The village well is 6 inches in diameter and 150 feet deep. It terminates in a white sandstone that contains numerous shell fragments. The accompanying log gives the geological succession.

Village Well at Braham (elevation 1020 feet)*

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–80	80
Dresbach			
Eau Claire	Soft white sandstone	80–100	20
	Hard white sandstone, very fossiliferous	100–150	50

*Data from Mr. Forsberg, driller, Braham.

Farm Well 3 Miles East of Braham, SE¼, Sec. 5, T. 37 N., R. 22 W.

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–150	150
Dresbach			
Eau Claire	Soft white sandstone	150–160	10
	Hard white sandstone, many shell fragments	160–198	38

Dalbo, Grandy, Stanchfield, and Stanley

These villages have no public water supply systems. However, in the inland village of Dalbo is an old private well nearly 600 feet in depth. It was drilled deep in an attempt to obtain a flowing well for a starch factory. No log of this deep well is available.

FARM WATER SUPPLIES

There are still many dug, bored, and driven farm wells in Isanti County. Such wells are quite satisfactory because much of the mantle rock is very sandy and therefore permeable to the flow of underground water. The capacity of these wells is not great, but the supply is ample in many localities. Where the yield from the drift is not sufficiently great, generous supplies can always be obtained by drilling through the glacial deposits and into the underlying sandstone in which the water is under sufficient pressure to rise to a reasonable pumping distance from the surface. The accompanying logs are typical of the deeper farm wells in the county.

Farm Well, NE¼, Sec. 2, T. 34 N., R. 23 W.

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–120	120
Dresbach	Glauconitic yellowish sandstone	120–180	60

Farm Well, NE¼, Sec. 2, T. 34 N., R. 25 W.

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–190	190
Dresbach	Glauconitic sandstone	190–220	30

Farm Well, NE¼, Sec. 2, T. 34 N., R. 25 W.

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–170	170
Dresbach	Glauconitic sandstone	170–180	10

Farm Well, SW¼, Sec. 19, T. 35 N., R. 22 W.

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–70	70
Dresbach	Soft white sandstone	70–100	30
	Hard glauconitic sandstone	100–120	20

Farm Well, NW¼, Sec. 23, T. 35 N., R. 24 W.

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–98	98
Dresbach	Glauconitic sandstone	98–140	42

TABLE 28. — ANALYSES OF WATERS OF ISANTI COUNTY*

	1	2	3	4
Depth (feet)	150	225	176	235
Hardness	280	193	210	223
Alkalinity	300	200	220	228
Iron	.35	0	.05	.6
Manganese	1.6	...	1	0
Chlorine	3.5	...	2	...
Fluorine	0	...	0	...
SO_4 radical	7.3	...	8.7	...
Turbidity	.3	0	.2	3
Color	4	5	2	10
Odor	...	0	...	...
pH value	7.85	...	8.2	...

*Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Braham, drilled well, 1942.
2. Cambridge, drilled well, 1919.
3. Cambridge, drilled well, 1942.
4. Cambridge, State Home for Epileptics.

ITASCA COUNTY

SURFACE FEATURES

The west end of the Mesabi Range crosses the southeastern part of Itasca County in a general northeast-southwest direction. The granite range that forms a conspicuous feature in the topography in St. Louis County to the east has a thick mantle of glacial drift superimposed on it throughout most of its zone across Itasca County. There are natural exposures north of Grand Rapids and north of Nashwauk, but their area is small and they stand approximately 150 feet lower than the crest of the range near Virginia and Mountain Iron. The highest point in the county is located west of Keewatin on the ridge in Secs. 11 and 12, T. 57 N., R. 22 W., where the surface is 1675 feet above sea level. A zone of rugged topography extends from Grand Rapids northward toward Marcell and thence northeastward toward the northeasternmost township of the county. The western half of the county has extensive tracts with level to gently undulating surface, most of which is poorly drained ground moraine.

The central and southern part of the county contains numerous lakes, the majority in the drainage basin of the Mississippi River. They are especially numerous in the region 10 to 30 miles north and west of Grand Rapids, where many of the smaller lakes have no surface outlets. The two largest lakes lying entirely within the county are Bowstring Lake, containing about 20 square miles, and Pokegama Lake, containing about 10 square miles. Lake Winnibigoshish, lying near the southwestern corner of the county and partly in Cass County, is a shallow body of water covering an area of more than 50 square miles.

The gradient of the Mississippi River across the county is shown in Table 29.

UNCONSOLIDATED SURFACE MANTLE

All of Itasca County is covered by the young gray (Mankato) drift deposited by the St. Louis lobe of the Keewatin glacier. Throughout much of the central part of the county, however, the gray drift is no more than a thin veneer over a rugged moraine of Patrician or young red drift. This zone of overridden moraine extends from Big Fork at the north to Marcell and southward through the region of Grand Rapids, and from there to the southern border of the county, south of Pokegama Lake. In the southeastern townships a similar zone extends from Swan Lake southward to beyond the village of Goodland. The less rugged parts of the Patrician moraine are so deeply covered by the Keewatin drift that they no longer express themselves in the topography.

The Keewatin drift seems to have little or no typical terminal moraine, but instead presents a smooth to gentle undulating type. Where it is deposited over the red drift, it tends to reduce rather than accen-

TABLE 29. — ELEVATIONS ALONG THE MISSISSIPPI RIVER, ACROSS ITASCA COUNTY

Location	Feet above Sea Level
Southwest corner of Itasca County	1299
Lake Winnibigoshish, also Little Winnibigoshish Lake, formerly	1290–1293
Lake Winnibigoshish, as raised by dam of reservoir system*	1298
Mississippi River at head and foot of small rapids 3 miles below little Winnibigoshish Lake	1288–1287
Mouth of Leech Lake River	1279
White Oak Point	1276
Outlet of Pokegama Lake, formerly	1270
Head of Pokegama Falls, formerly	1269
Head of Pokegama Falls, as raised by dam	1275
Foot of Pokegama Falls, 900 feet from head of Pokegama Falls	1254
Head of Grand Rapids, one-third mile from foot of Pokegama Falls	1248
Mouth of Split Hand River	1236
Southern edge of Itasca County	1230

*This dam is constructed with the capacity to raise the lake to 1304 feet, but it is not expected that it will be raised higher than 1300 feet.

tuate the roughness of the surface by filling the depressions among the knolls and ridges.

Besides the difference in color the Keewatin drift is generally of more clayey and less stony character than the underlying Patrician drift. Thus the two drifts are readily distinguished wherever exposed. In the walls of the mine excavations northeast of Grand Rapids a third layer of drift is exposed beneath the red Patrician drift. This is an old gray drift from the Keewatin center and is of Nebraskan or Kansan age.

The contrast in stoniness of the red and gray drifts is shown strikingly in the walls of the open-pit mines. The red drift is sandy and very stony, whereas the gray drift is clayey with numerous calcareous pebbles. The clayey character of the gray Keewatin drift is probably due to the incorporation of clayey shale from formations in southern Manitoba and northwestern Minnesota in the path of this ice sheet. South of the Mesabi Range, in the southeastern townships of the county, the clayey Keewatin drift is red in color, and thus distinctly different from the yellow and gray colors of the same drift to the north and west of the range. This red color is due in the main to the incorporation of red products of weathering from the iron-bearing formations on the range, rather than to deep oxidation since the drift was deposited.

The drift varies in thickness from 0 to more than 300 feet. Ledge rock crops out through the drift in Sec. 35, T. 150 N., R. 25 W., Sec. 11, T. 61 N., R. 24 W., and in the region to the north and to the south of the Bear River. A similar area of thin drift occurs west of Sturgeon Lake in T. 60 N. and Ranges 22 and 23. The drift is thin also along the axis of the Giants Range granite, which forms a ridge extending from the eastern side of the county in T. 57 N. southwestward to beyond the falls of the Prairie River near the south side of T. 56 N., R. 25 W.

TABLE 30. — THICKNESS OF GLACIAL DRIFT ON MESABI RANGE IN ITASCA COUNTY

Location	Thickness (feet)
Sec. 3, T. 55 N., R. 25 W.	15
Sec. 27, T. 56 N., R. 24 W.	220
Sec. 28, T. 56 N., R. 24 W.	200
Sec. 29, T. 56 N., R. 24 W.	100
Sec. 12, T. 56 N., R. 23 W.	50
Sec. 14, T. 56 N., R. 23 W.	120
Sec. 15, T. 56 N., R. 23 W.	130
Sec. 19, T. 56 N., R. 23 W.	140
Sec. 21, T. 56 N., R. 23 W.	165
Sec. 6, T. 56 N., R. 22 W.	100
Sec. 23, T. 57 N., R. 22 W.	35
Sec. 24, T. 57 N., R. 22 W.	125
Sec. 27, T. 57 N., R. 22 W.	135
Sec. 32, T. 57 N., R. 22 W.	135
Sec. 33, T. 57 N., R. 22 W.	183

On the Mesabi Range the drift varies in thickness from 70 to 250 feet. A well half a mile north of the dam at Grand Rapids encountered granite at a depth of 70 feet, and the village well at Taconite was drilled to a total depth of 258 feet without encountering any ledge rock. In the western townships, to the north of the Mississippi River, no wells are known to have reached bedrock, and consequently the thickness of the drift has not been determined.

ROCK FORMATIONS

PRE-CAMBRIAN

Archeozoic. — Fine-grained green schists that are thought to be of Archeozoic (Keewatin) age crop out at several places in the northeastern part of Itasca County. In T. 61 N., R. 26 W., at and near Rice Rapids, and at several localities between Rice Rapids and the mouth of the Deer River are various types of basic igneous rocks that are highly metamorphosed. They include recrystallized basalts of extrusive origin and intrusive diabases or diorites. A hard, green, somewhat schistose rock crops out in Sec. 23, T. 62 N., R. 25 W., at and near a dam on Deer River. The schistosity strikes N. 38° E. and stands nearly vertical. Other exposures of greenstone occur about 10 miles below the mouth of Deer River in the vicinity of Little Falls.

Keewatin greenstones are thought to underlie much, if not all, of Townships 60 and 61 in Ranges 22, 23, and 24. Both massive and agglomeratic facies crop out in Sec. 34, T. 61 N., R. 22 W. Much of the rock is now a hornblendic schist. Exposures of sericitic hornblende schist occur in Secs. 7 and 18, T. 60 N., R. 22 W., and in Secs. 11 and 12, T. 60 N., R. 23 W. These rocks strike toward the northeast.

Magnetic surveys followed by exploratory drilling have demonstrated the presence of narrow zones of banded, jaspilitic iron formation extending southwestward from the southern part of T. 61 N., R. 22 W., to the region of Marcell and Bowstring Lake. None of this rock is known to crop out at the surface.

Laurentian.—From present field observations one is not justified in correlating any of the granitic rocks in Itasca County with the Laurentian. This does not mean that there are no Laurentian rocks in the county, but no one is at present able to state with certainty where such rocks are located. The granites that crop out at the surface contain inclusions of the Knife Lake schists and slates and other petrographic characteristics which indicate that they are of Algoman Age.

Proterozoic.—The Knife Lake series of slates, graywackes, and conglomerates are known to occur over a large area in Koochiching County, directly north of Itasca County, but no exposures have been found within the limits of the county that can be correlated definitely with the slaty rocks north of the Mesabi Range in St. Louis County or with the schists and slates of the Rainy Lake region. It is quite probable that some of the schists along the Big Fork River northeast of the village of Big Fork belong to the Knife Lake series, but that stratigraphic position has not been established definitely.

It is likewise reasonable to suppose that rocks of early Proterozoic and pre-Algoman age occur to the north of the Giants Range granite, in the east-central part of the county, but no drill cuttings are available to verify such an interpretation.

Algoman Granites.—The Giants Range of Algoman granite extends from St. Louis County southwestward across most of the southeastern part of Itasca County. This belt of granite lies directly to the north of the rocks of the Mesabi Iron Range (Figure 22). It enters the county in T. 57 N., R. 22 W., and extends southwestward to beyond the Prairie River in T. 56 N., R. 25 W. Numerous exposures may be seen in T. 57 N., R. 22 W., but farther toward the southwest the granite is buried under the mantle of glacial drift. A well half a mile north of the dam on the Mississippi River at Grand Rapids entered granite under 70 feet of drift, and a short distance northwest of Cohasset granite was encountered under 140 feet of drift and 20 feet of quartzite.

Granites with inclusions of slate and schist crop out along the Bowstring and Big Fork rivers (Figure 23). In Sec. 25, T. 150 N., R. 25 W., the rock is a coarse-grained, hornblende granite which is greenish gray in color. The greenish color is due to the alteration of much of the hornblende to chlorite and epidote. Similar rock is exposed near the east side of Sec. 25, T. 61 N., R. 27 W., and at the southwest corner of Sec. 30, T. 61 N., R. 26 W.

Animikean.—The rocks of Animikean age were formed from sands and gravels, iron-bearing siliceous sediments, and muds. Named in stratigraphic order these have been altered by metamorphism to the Pokegama quartzite, the Biwabik iron-bearing formation, and the Virginia slate.

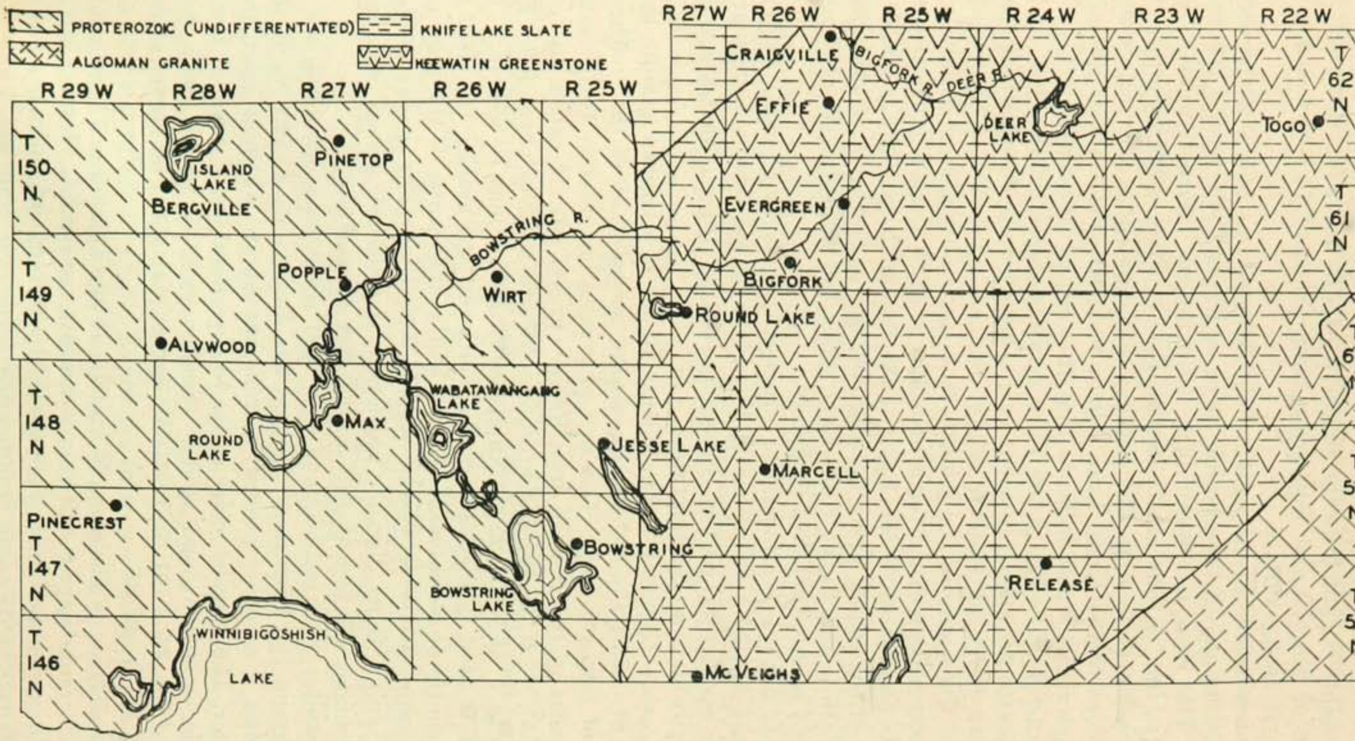

FIGURE 22. — Geologic map of northern Itasca County.

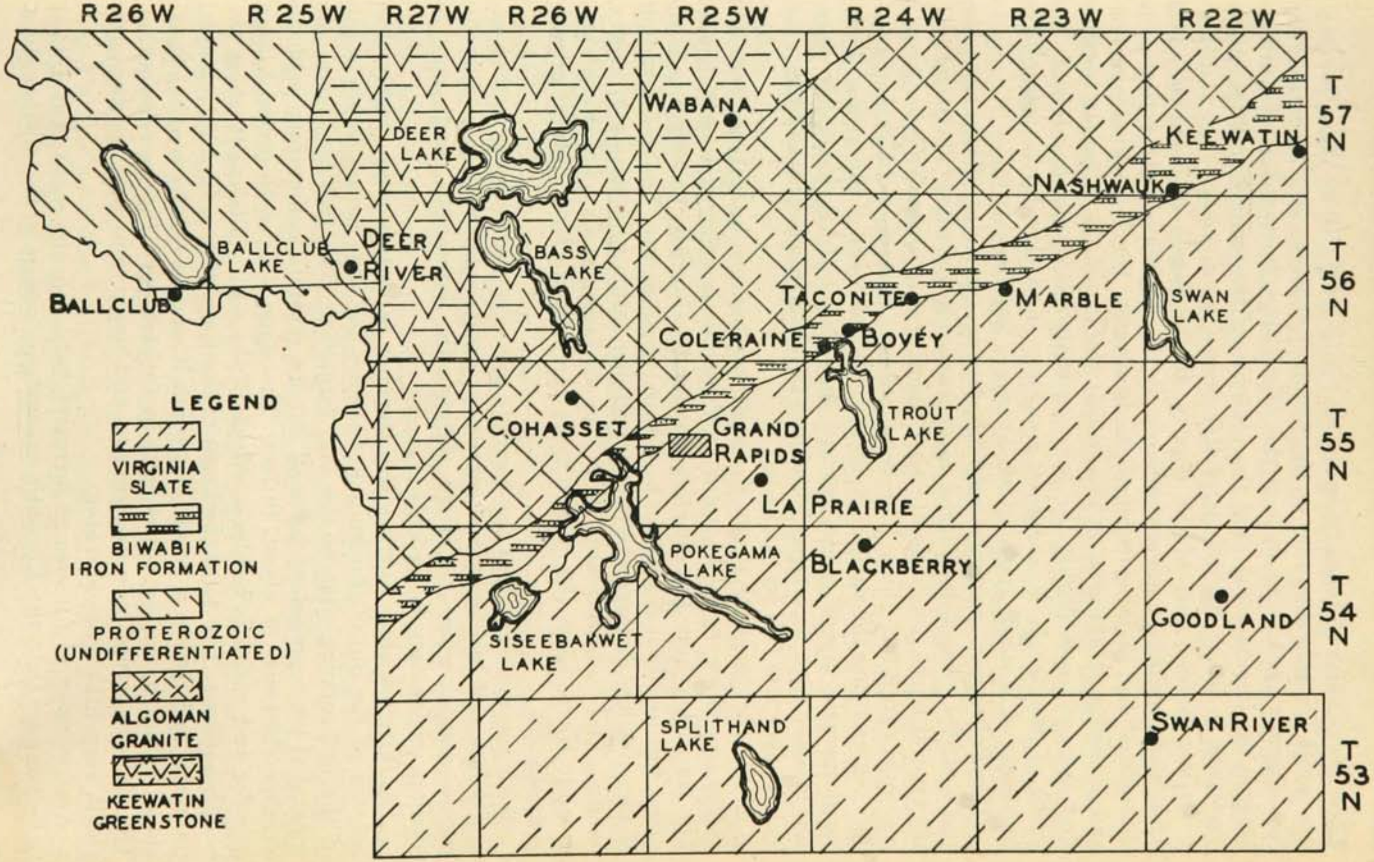

FIGURE 23. — Geologic map of southern Itasca County.

These rocks enter the county on the east in T. 57 N., R. 22 W., and extend in a southwesterly direction to the Mississippi River at Pokegama Falls. No outcrops are known west of the Mississippi, but exploratory drilling for iron ore has demonstrated the presence of the same formation southwestward as far as the village of Remer in Cass County.

In the eastern part of the county, in the region of Nashwauk, the Animikean rocks rest uncomformably on the Archeozoic greenstones, but throughout the major portion of the iron range the Pokegama quartzite and overlying strata rest on the eroded surface of the Algoman granites that were exposed during the long post-Algoman erosion interval. The strike of the strata is northeast-southwest and the dip is toward the southeast at a small angle which averages less than 10°.

The Pokegama quartzite includes vitreous quartzite of various colors and textures, micaceous quartz slates, and conglomerates. The basal beds are typical basal conglomerate that forms a very irregular layer from a few inches to 8 feet thick. The conglomerate contains pebbles and boulders representing the various facies of the older rocks of the region. These conglomeratic layers grade upward into thin-bedded quartzitic slates and massive pink quartzite. The formation as a whole ranges from a few feet to over 200 feet in thickness.

Above the quartzite is the Biwabik iron-bearing formation, from 400 to 700 feet thick, composed of a rock commonly referred to as taconite. The transition from the quartzite to the iron-bearing formation is fairly sharp, but locally it is marked by a thin conglomerate. The various kinds of taconite are distinguished by qualifying terms such as slaty, cherty, banded, and conglomeratic. Any type of taconite may be altered into iron ore where silica is removed from the taconite by a natural process of leaching.

Both the quartzite and the taconite are very brittle rocks and therefore joints and bedding-plane cracks are exceedingly numerous. For this reason ground water circulates through the formations, and small to medium yields may be expected.

The Virginia slate overlies the Biwabik formation conformably, but because of the dip of the Animikean series the slate occurs to the south of the outcropping edge of the iron formation. The two formations are separated by a persistent layer of impure crystalline limestone with an average thickness of about 10 feet. The slate is gray to greenish gray in color and varies in hardness. Much of the rock splits easily along the bedding planes. The total thickness of the formation is probably several thousand feet, but as a result of erosion it wedges out to zero thickness along its north margin where it is in contact with the iron formation. The slate is exceedingly fine-grained and impervious and consequently yields very little ground water.

Keweenawan.—An area of intrusive basic igneous rocks that appear to be younger than the Keewatin greenstones occurs in the northeasternmost township of Itasca County, north of Bear River. Drilling has demonstrated the presence of similar rock under the glacial drift to the south of Island Lake near the northwestern corner of the county. The stratigraphic position of these intrusive masses has not been established definitely, but they are correlated tentatively with the Duluth gabbro of the Middle Keweenawan.

Cretaceous System

Marine sedimentary rocks of Cretaceous age occur as a mantle on the uneven surface of the Huronian iron formation. They are exposed in the walls of the open-pit mines from Coleraine eastward across the county. A basal conglomerate composed of fragments of oxidized ferruginous chert, iron ore, paint rock, and porphyry pebbles indicates that the sediments were derived largely from the local underlying iron formations and other pre-Cambrian rocks. The coarse basal conglomerate grades vertically through a somewhat glauconitic fine-pebble conglomerate or grit which grades upward into ferruginous sandstone and shale. The grit and sandstone beds are very fossiliferous with an abundant molluscan assemblage. Many of the fossils are oyster-like pelecypods.

All the Cretaceous sediments are a part of the Coleraine formation which, from the evidence of the invertebrate fauna, is considered the age equivalent of the lower Benton in the Colorado series of the Great Plains.

The following description of the Cretaceous in the vicinity of Coleraine is given by Bergquist.

"The Cretaceous sediments have been exposed in several pits around Coleraine. Shale containing oyster beds once extended over nearly the entire Hill Walker pit and continued eastward into the western part of the Morrison pit. In the Canisteo pit, near the entrance to the Walker pit, the basal conglomerate bore pebbles of quartz, iron formation, and highly altered igneous and metamorphic rock, all firmly cemented. This graded through a few inches of a red-green, fine pebble conglomerate into a few feet of massive fine lean iron ore. The overlying material was removed prior to survey investigations. A few fish scales were found in the lean ore. In the north cut there were about 20 feet of Cretaceous conglomerates and soft shales.

"Abundant shark and reptile teeth and a few vertebrae have been collected by survey members from the dump of lean ore at the screening plant of the Canisteo pit, 1½ miles south of Bovey, Minnesota.

"The Cretaceous is no longer exposed in the Morrison mine north of Bovey, Minnesota, but formerly existed in the south end of the pit. About a foot of coarse conglomerate occurred at the base; the pebbles were composed of the underlying iron-ore formation, some being highly polished pieces of hematite and limonite in a greenish iron-clay matrix.

Over this conglomerate was about 8 feet of greenish iron-clay with concretions of the same material. No fossils were ever found in the concretions. Along the west side of the pit about 6 inches of fine pebble conglomerate in a green gritty matrix was overlain by 5 to 7 feet of green to red soft fine lean ore. The overlying Cretaceous shale of the Walker pit area has been removed by erosion of mining operations from the Morrison region. In the eastern part of the pit 3 to 4 feet of hard limy shale bearing poor fossils, were exposed at one time."[1]

Similar sections have been exposed by mining operations in the vicinity of Marble, Calumet, and Keewatin.

Cretaceous shales crop out along the Deer River in T. 62 N., R. 25 W., and other exposures may occur on the Bowstring River, but they have not been definitely separated from the horizontal clays and sands which were deposited in glacial Lake Agassiz.

MUNICIPAL WATER SUPPLIES

Grand Rapids

The city of Grand Rapids has used several types of wells, some shallow and one deep. The upper surface of bedrock is very irregular in the region of the city. At the old city well the glacial drift is 205 feet thick, at the cooperative creamery it is 190 feet, and half a mile north of the dam on the Mississippi River it is only 70 feet thick. The accompanying section is of the well drilled through the iron-bearing formation and into the underlying quartzite.

Grand Rapids, Old Deep Well*

		Depth (feet)	Thickness (feet)
Drift	Unclassified	0–205	205
Biwabik	Oxidized taconite	205–380	175
	Massive taconite	380–552	172
Pokegama	Dense quartzite	552–602	50

* Data from Jack Schultz, well driller.

At present most of the water for the city supply is taken from a new well 12 inches in diameter and 167 feet deep with a static level 8 feet below the surface. This well terminates in the glacial drift. When pumped at the rate of 500 gallons per minute it has a drawdown of 25 feet. During a pumping test the well produced 1200 gallons per minute.[2]

The well at the cooperative creamery obtains its water from the contact zone between the Biwabik formation and the Pokegama quartzite. (See the accompanying log.)

[1] Bergquist, Harlan R., Cretaceous of the Mesabi Iron Range, Minnesota: Jour. Paleontology, vol. 18, pp. 1–30, 1944.

[2] Data from Harold E. Hanson, Superintendent of the Water Department.

Cooperative Creamery Well, Grand Rapids*
(elevation approximately 1320 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift and alluvium	Unclassified	0–190	190
Biwabik	Iron ore	190–204	14
	Slaty taconite	204–380	176
Pokegama	(Entered)		

* Data from Jack Schultz, well driller.

A few miles south of the city, at low points in the topography, flowing wells may be obtained from the glacial drift at a depth of 80 to 130 feet.

Coleraine

The city of Coleraine is located at the north end of Trout Lake, in the region of the overridden Patrician glacial moraine. The water supply for the city is taken from a well that is located one city block from Trout Lake and that terminates in the glacial drift at a depth of 142 feet. The well has a casing 18 inches in diameter and a pumping pipe 10 inches in diameter. It yields about 450 gallons per minute.

Bovey

The village of Bovey is supplied with water by the city of Coleraine. A water main connects directly with the Coleraine supply system.

A well at the Holman-Cliffs Washing Plant penetrated 550 feet of the Virginia slate before reaching the iron-bearing formation. This well has a total depth of 775 feet, with 116 feet of 6-inch casing, 160 feet of 4½-inch, and 311 feet of 3-inch casing. The static water level in the well is about 60 feet below the surface. (See the accompanying log.)

Well at Holman-Cliffs Washing Plant

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–95	95
Virginia slate	Hard, gray slate	95–581	486
	Slate and sandstone	581–645	64
Biwabik	Taconite	645–778	133

Marble

The village of Marble is located at the south margin of the zone along which the Biwabik iron formation occurs under the glacial drift. The water for the village supply is taken from a well that penetrates 268 feet of the iron-bearing formation. The well is 20 inches in diameter and has a total depth of 400 feet. Its static level is 135 feet below the surface. When pumped at the rate of 250 gallons per minute it shows very little drawdown. (See the accompanying log.)

Marble, Village Well

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–132	132
Biwabik	Slaty and massive taconite	132–400	268

Nashwauk

The village of Nashwauk is located near the southwest corner of T. 57 N., R. 23 W., in the zone along which the Biwabik iron formation occurs directly beneath the glacial drift. The water for the village supply is taken from two wells, both of which terminate in the iron-bearing rocks. Some water for the village is taken from the Hawkins mine shaft. The wells are 18 inches in diameter with 8-inch casings. Each well is pumped at the rate of 120 gallons per minute. (See the accompanying logs.)

Nashwauk Village Wells

		DEPTH (feet)	THICKNESS (feet)
Well No. 1			
Drift	Unclassified	0–110	110
Biwabik	Oxides of iron formation	110–210	100
	Massive iron formation	210–414	204
Well No. 2			
Drift	Unclassified	0–115	115
Biwabik	Iron formation	115–360	245

Well at Galbraith Ore Washing Plant, Sec. 28, T. 57 N., R. 22 W.
(elevation 1488 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–35	35
Biwabik	Taconite and paint rock	35–165	130
	Iron ore	165–215	50

Calumet

The village of Calumet is located a short distance south of the north margin of the Virginia slate, in Sec. 21, T. 56 N., R. 23 W. In this area the drift is about 130 feet thick. The new well that furnishes water for the village supply is 8 inches in diameter and 495 feet deep. It is cased to a depth of 155 feet and its static water level is 200 feet below the surface. The accompanying log shows the stratigraphic succession.

Calumet Village Well, Drilled in 1940

		DEPTH (feet)	THICKNESS (feet)
Drift	Sandy clay and hardpan	0–135	135
Virginia slate	Green shale	135–150	15
	Brown shale	150–180	30
	Bluish shale	180–311	131
Biwabik	Red iron formation	311–450	139
	Hard taconite	450–490	40
	Paint rock	490–495	5

Taconite

The village of Taconite is located in the SW¼, SW¼, Sec. 22, T. 56 N., R. 24 W., about 3 miles northeast of Trout Lake. In this area the glacial drift is about 80 feet thick. The well for the village water supply is 4 inches in diameter and 280 feet deep. Its static level is 100 feet below the surface and when pumped at the rate of 50 gallons per minute it shows a drawdown of 30 feet. (See the accompanying log.)

Taconite Village Well

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–80	80
Virginia slate	Green slate	80–110	30
Biwabik	Iron formation	110–280	170

A well at the Danube Washing Plant, west of Taconite, is 12 inches in diameter and 132 feet deep. The static level is 78 feet below the surface. The well that supplies the shop at the mine is 8 inches in diameter and 208 feet deep. Its static level is 94 feet below the surface and when pumped at the rate of 200 gallons per minute it shows a drawdown of 30 feet. (See the accompanying log.)

Well at Shop of Danube Mine (elevation 1347 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–7	7
Biwabik	Iron ore and taconite	7–65	58
	Iron ore and paint rock	65–90	35
	Iron ore and taconite	90–201	111
	Paint rock	201–208	7

Keewatin

The village of Keewatin is located on the eastern border of the county in Sec. 25, T. 57 N., R. 22 W. It is at the south margin of the outcropping edge of the Biwabik iron formation where six open-pit mines are located less than 2 miles north of the village. The extensive pumping at the mines has developed a deep cone of depression in the regional water table, and consequently the static level in the village well is about 175 feet below the surface. Some of the water for the public supply system is pumped from the Bennett mine, where a pumping shaft has been dug to a depth of 140 feet below the floor of the pit.

The village well is a dug shaft 4 by 8 feet that penetrates 100 feet of glacial drift and 102 feet of the upper part of the Biwabik iron formation.

Deer River

The city of Deer River is located to the north of the chain of lakes that occur along the Mississippi River to the southeast of Lake Winnibigoshish. The city is situated a short distance west of the mouth of the

Deer River and southwest of Deer Lake. Owing to the high, rugged topography to the north of the city, the ground water under the area of the city has sufficient head to be lifted to the surface. The street elevation in the city is about 1280 feet above sea level, whereas the water level in Deer Lake is slightly more than 1300 feet above the sea.

The water supply for the city is taken from two wells 140 feet deep that terminate in the glacial drift. The static level is 15 feet below the surface and when they are pumped at the rate of 135 gallons per minute there is a drawdown of 30 feet.

Warba

The village of Warba is located in the southeastern part of the county, in the area of ground moraine deposited by the St. Louis lobe of the Keewatin glacier. The public water supply is taken from a well that terminates in the glacial drift at a depth of 127 feet. No further data are available.

Cooley

The village of Cooley is supplied with water from a well at the shop of the Harrison mine. The well is 12 inches in diameter and 537 feet deep. When the pump was installed the static level in the well was 72 feet below the surface, but heavy pumping at the mine and at the shop has lowered the static level to 480 feet. The capacity of the pump is 600 gallons per minute. In 1942 the pump operated about 8 hours per day. (See the accompanying log.)

Well at Shop of Harrison Mine (elevation 1438 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–149	149
Virginia slate	Green slate	149–310	161
Biwabik	Massive taconite	310–537	227

The well at the Patrick ore beneficiation plant in Sec. 12, T. 56 N., R. 23 W., is 10 inches in diameter and 237 feet deep. Its static level is 160 feet below the surface. (See the accompanying log.)

Well at Patrick Concentration Plant, Cooley (elevation 1422 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–86	86
Biwabik	Massive taconite	86–237	151

Wells and Pump Shafts at Iron Mines

Bennett Open-Pit Mine, Sec. 24, T. 57 N., R. 22 W. (elevation 1390 feet).—The two wells, 50 feet apart, used to depress the water table at the Bennett open-pit mine, were drilled 30 inches in diameter and 240 feet deep. They are equipped with casing 18 inches in diameter and with pumps that have a capacity of 850 gallons per minute. When the wells are in operation the static level is about 1250 feet above sea level.

Harrison Open-Pit Mine, Sec. 6, T. 56 N., R. 22 W.—The drainage well at the Harrison mine is 24 inches in diameter and 290 feet deep. It is equipped with a pump that has a capacity of 1000 gallons per minute. When pumped at the rate of 850 gallons per minute, the static water level is depressed to 275 feet below the surface. The water from the well flows into Pickerel Lake, which in turn drains out into Swan Lake. (See the accompanying log.)

Drainage Well at Harrison Mine (elevation 1425 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–75	75
Biwabik	Ore and taconite	75–290	215

Cannisteo Open-Pit Mine, Sec. 30, T. 56 N., R. 24 W.—The pump for draining the mine is mounted on a raft that floats on a drainage basin in the bottom of the pit. The pump has a capacity of 2000 gallons per minute and its discharge flows over the surface into Trout Lake. The total head is about 200 feet.

Sargent Mine, Secs. 23 and 26, T. 57 N., R. 22 W.—The drainage shaft at the Sargent Mine is 215 feet deep. It is equipped with two pumps over casings that are 6 inches in diameter. Each pump has a capacity of 500 gallons per minute. The discharged water is used at the Mesabi Chief washing plant.

FARM WATER SUPPLIES

Nearly all farm wells draw water from the glacial drift. Since much of Itasca County is flat and poorly drained, there are many shallow wells with almost inexhaustible supplies of water. However, in some localities the drift is so clayey and impervious that the yield from shal-

TABLE 31.—SEASONAL FLUCTUATION OF GROUND-WATER LEVEL NEAR DEER RIVER *
(Water level, in feet below land-surface datum, 1943)

Date	Feet	Date	Feet	Date	Feet	Date	Feet
July 26	18.38	Sept. 6	18.04	Oct. 18	18.65	Nov. 29	19.32
Aug. 2	18.27	Sept. 13	18.14	Oct. 25	18.80	Dec. 6	19.41
Aug. 9	18.16	Sept. 20	18.22	Nov. 1	18.92	Dec. 13	19.55
Aug. 16	18.10	Sept. 27	18.35	Nov. 8	18.99	Dec. 20	19.66
Aug. 23	18.04	Oct. 4	18.49	Nov. 15	19.10	Dec. 27	19.75
Aug. 30	18.06	Oct. 11	18.54	Nov. 22	19.24		

* Well observed by Corps of Engineers, U.S. Army, SE¼, NW¼, Sec. 26, T. 146 N., R. 27 N., near the town of Deer River. Driven well, 1¼ inches, depth 30 feet, used for observation only. Measuring point, top of casing, 4 feet above land surface. Well shows influence of impounded Lake Winnibigoshish.

Source: United States Department of the Interior, Water Levels and Artesian Pressure in Observation Wells in the United States in 1943, Part 3, North-Central States: U.S. Geol. Survey Water-Supply Paper 988, p. 163.

low wells is inadequate. In such areas deeper wells with more abundant and more regular supplies are drilled to the sand and gravel beds near the base of the red Patrician drift. In the lowland along the Mississippi River and around many of the lakes, ample supplies of water for farm use may be obtained from shallow driven wells.

TABLE 32. — ANALYSES OF WATERS OF ITASCA COUNTY *

	1	2	3	4	5	6	7	8	9
Depth (feet)	...	...	...	...	...	...	140	327	230
Hardness	0	76	209	200	110	368	290	117	183
Alkalinity	205	240	172	160	120	392	320	132	196
Iron	.03	1.1	.6	.4	.25	1.4	.2	.2	.4
Manganese	.07	.1	...	.1	0	...	.07	...	...
Chlorine	0	5.4	3	6.5	6.6	3	3.9	0	0
Fluorine	.2	0	...	.2	.1	...	.2	...	...
SO_4 radical	0	2.5	...	50	7.5	...	8	...	...
Turbidity	0	10	8	3	8	10	4	0	3
Color	7	20	25	6	0	20	6	0	20
Odor	...	...	0	...	0	e–1	...	0	0
pH value	7.8	7.6	...	7.5	7.7	...	7.7	...	...

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Grand Rapids, new well, April 1939.
2. Grand Rapids, August 1944.
3. Coleraine, 2 drilled wells, 1921.
4. Bovey, 1944.
5. Nashwauk, 1944.
6. Deer River, drilled well, 1918.
7. Deer River, flowing well No. 1, 1939.
8. Nashwauk, dug and drilled well, 1919.
9. Keewatin, dug well, 1917.

KANABEC COUNTY

SURFACE FEATURES

Much of the surface of Kanabec County is a glacial till plain. Three moraines deposited by the Patrician ice sheet cross the county from east to west, but of these only the Mille Lacs moraine, which covers parts of the northernmost townships, has typical rugged morainic topography. Elsewhere morainic features are weak and locally they have been made gently undulating by the action of temporary glacial lakes. Several conspicuous esker ridges extend in a north-south direction a short distance west of Mora. The surface of the county as a whole slopes from north to south; it is 1200 to 1300 feet above sea level in the northern part and about 950 feet in the southernmost townships.

Almost the entire county is drained by the Snake River and its tributaries. Only a few square miles in Pomroy and Kroschel townships drain eastward through the Grindstone River. Owing to the fact that the area near the southern county line was at the north margin of the Grantsburg lobe of the Keewatin glacier, a marginal glacial lake covered much of the southern townships. This lake, referred to as glacial Lake Grantsburg,[1] resulted from the ponding of melt-waters which normally would have flowed to the south to the St. Croix or Mississippi rivers.

Interglacial valleys cut in the old gray drift which lies under the red drift over much of the county have been only partly filled by deposits left by the Patrician ice sheet. Many swamps and bogs occur along the lines of such partially filled valleys.

UNCONSOLIDATED SURFACE MANTLE

All of Kanabec County with the exception of a few square miles along the southern county line is covered with a mantle of young red drift of Patrician age. In many places this drift is resting on an old weathered gray drift of Kansan or Nebraskan age.

The drift varies in thickness from 25 to 200 feet. It is thickest along the morainic zone in the northernmost townships and thinnest in the areas near the rock ledges along the Ann River and the Snake River. Small areas of outwash occur immediately north of Mora and a thin veneer of lacustrine silts covers much of the glacial till in Grass Lake and Brunswick townships (T. 38 N., R. 23 W., and T. 38 N., R. 24 W.). Recent alluvial sediments are found in the valley of the Snake River.

ROCK FORMATIONS

Pre-Cambrian Igneous Rocks

Granitic rocks of pre-Cambrian age occur in widely separated regions. (Figure 24). One area is found along the Snake River near the northern

[1] Cooper, W. S., History of the upper Mississippi River in late Wisconsin and postglacial time: Minn. Geol. Survey Bull. 26, p. 33, 1935.

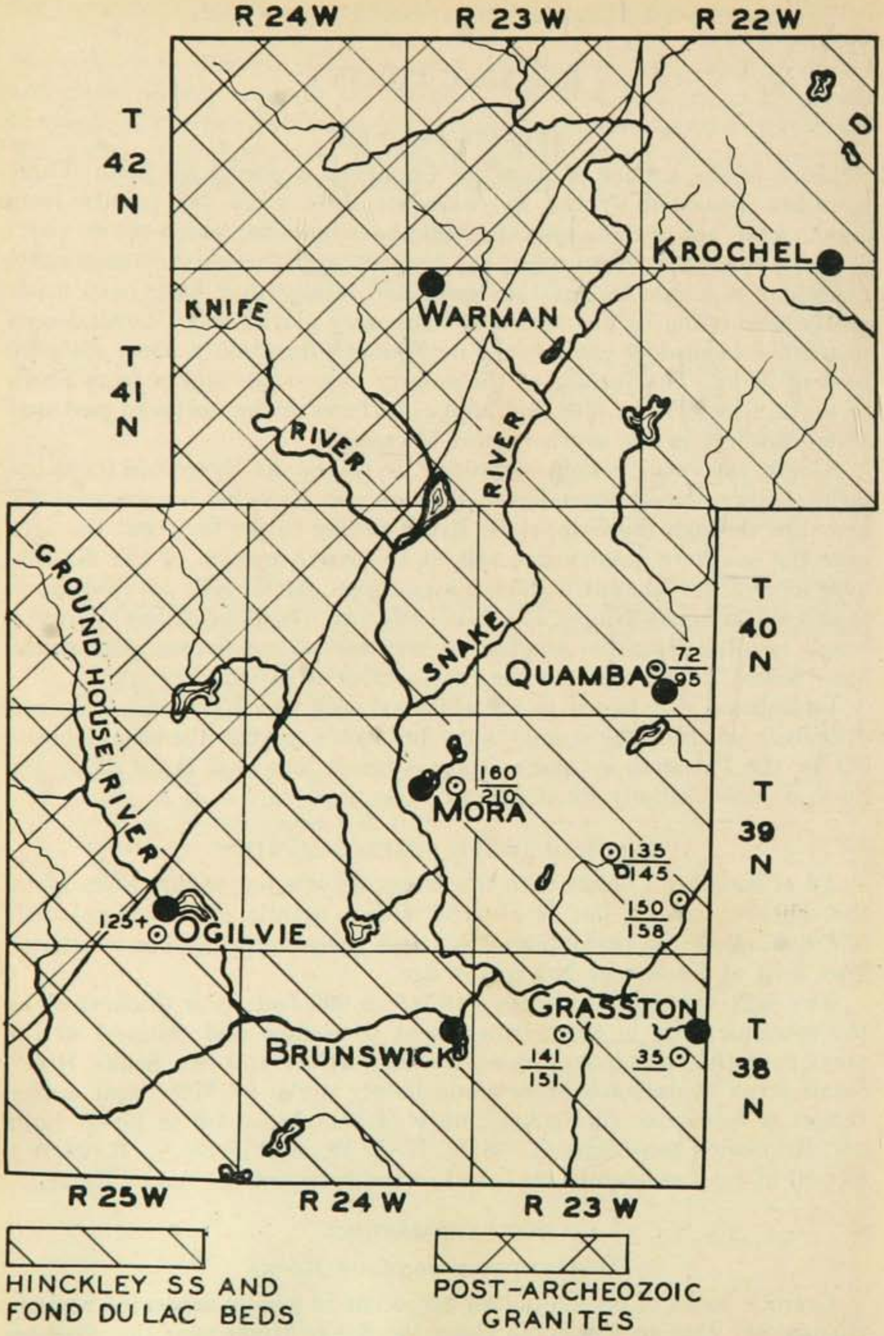

FIGURE 24. — Geologic map of Kanabec County. The small circles indicate drill holes that reached bedrock at the depth shown by the upper figures. The lower figures show the total depth of the wells.

county line, another near Warman Creek in the north-central part of the county, and a third northwest of Mora in the western part of Knife Lake Township (T. 40 N., R. 24 W.) and the eastern part of Ann Lake Township (T. 40 N., R. 25 W.). In this last area the rocks crop out along the valley of the Ann River.

The exposures along the Snake River are found upstream beyond the big bend in the river in Secs. 15 and 16, T. 42 N., R. 23 W. In this locality the river flows eastward and the outcrops occur at Lower Falls, a short distance west of the bridge over the river. The exposures occur along the river for a distance of about 3000 feet. The rocks are pink and gray biotite granites with large inclusions of quartzose biotite schist.

Farther upstream a number of scattered outcrops may be seen as far north as Sec. 4, T. 42 N., R. 23 W., and westward up the valley of Hay Creek into Sec. 9, T. 42 N., R. 23 W. About one-third of a mile north of the mouth of Hay Creek the rocks form a reef across the Snake River, producing a rapids known as Upper Falls.

In the Warman Creek area granite is quarried in the southeast corner of Sec. 6 and the southwest corner of Sec. 5, T. 41 N., R. 23 W. The granite is of medium-grained texture and light gray in color, with considerable amounts of biotite in a matrix of quartz and white feldspar.[2]

The Ann Lake region lies from 4 to 7 miles northwest of Mora. The granite outcrops occur near the boundary between Secs. 19 and 20, T. 40 N., R. 24 W., just north of the east-west road along the south line of these sections. The largest exposure forms a small hummock overlooking a marsh a short distance north of the road. The rock is a light pink biotite granite with abundant quartz and white and pink feldspar.

Other granitic ledges along the Ann River are reported by Upham in Secs. 29, 30, and 32, T. 40 N., R. 24 W., and along the Little Ann River north of Ann Lake in Secs. 26 and 14, T. 40 N., R. 25 W.[3]

Several low outcrops of an intermediate or basic rock occur about one mile northwest of Mora. These ledges are not mentioned by either Upham or Harder and Johnson. One area of exposures occurs in the SE¼, Sec. 3, T. 39 N., R. 24 W., and another in the NW¼, Sec. 10 and the NE¼, Sec. 9, T. 39 N., R. 24 W., where a road along the section line passes over a low glaciated outcrop.

Pre-Cambrian Sedimentary Rocks

Outcrops of pink and red sandstone may be seen at various points along the valley of the Snake River to the north of Mora. The most southwesterly exposures occur in the NE¼, Sec. 10, and NW¼, Sec. 3, T. 39 N., R. 24 W. In Sec. 3 the rock occurs along the west side of the

[2] For a detailed description of the physical properties and composition of this rock, see Thiel, G. A., and Dutton, C., The architectural, structural, and monumental stones of Minnesota: Minn. Geol. Survey Bull. 25, p. 102, 1935.

[3] Winchell, N. H., The geology of Minnesota: Final Rept., Minn. Geol. and Nat. Hist. Survey, vol. 2, pp. 617–618, 1888.

river, where it forms a ledge 300 feet long and 75 feet wide. It rises from 5 to 10 feet above the river and is composed of a coarse-grained to conglomeratic sandstone of gray to reddish-brown color. Some of the quartz pebbles are from 2 to 3 inches in diameter. The strata dip toward the southeast at an angle of about 15°.

The next sandstone outcrops to the north occur in Sec. 33, T. 41 N., R. 23 W. These outcrops also are exposed along the Snake River and consist of interbedded red sandstone and ash-colored shale. Still farther northward similar strata are exposed just south of the big bend in the river in Sec. 23, T. 42 N., R. 23 W. Here the largest exposure is found on the west bank of the river, where it forms a small cliff for a distance of about 300 feet along the stream. It consists of interbedded coarse-grained sandstones of varying color and texture. Most of the rock is light pinkish-gray to pink with layers of red shale. The strata dip 10° to 15° toward the southeast.

All the sandstones that crop out along the Snake River are correlated with the red Fond du Lac beds that are typically exposed along the St. Louis River southwest of Duluth. These strata represent part of the Lake Superior sandstone series of Upper Keweenawan age.

The Hinckley sandstone is not known to crop out in Kanabec County. However, many of the wells that reach bedrock in the area southeast of Mora and east of the Snake River, in the east-central part of the county, enter a white to pinkish-yellow sandstone under the drift. This sandstone is undoubtedly the Hinckley formation, which crops out along the Whetstone River at Hinckley and along the Kettle River at Sandstone. The accompanying logs of farm wells are typical of the geological succession in the southeastern part of the county.

Farm Well, SE¼, Sec. 9, T. 38 N., R. 23 W., Owner, P. Lodin (elevation 970 feet) *

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–141	141
Hinckley	White sandstone	141–151	10

* Data from Berg Brothers, drillers, Mora.

Farm Well, SW¼, Sec. 9, T. 38 N., R. 23 W., Owner, Dan Davidson (elevation 1030 feet) *

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–135	135
Hinckley	White sandstone	141–151	10

* Data from Berg Brothers, drillers, Mora.

Farm Well, Sec. 25, T. 39 N., R. 23 W. (elevation 990 feet) *

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–150	150
Hinckley	White sandstone	150–158	8

* Data from Berg Brothers, drillers, Mora.

GENERAL UNDERGROUND WATER CONDITIONS

In the eastern part of the county, where Keweenawan sandstones are present under the glacial drift, ample supplies of ground water may be obtained from the bedrock formations. This area includes all the region east of the Snake River and Grass Lake Township (T. 38 N., R. 23 W.) to the south of the river. The sandstones dip toward the east, and in areas where the overlying drift is clayey and impervious the water in the sandstone is confined under sufficient head to lift it well above the regional water table. A few wells flow at the surface.

In the western and south-central townships the drift is underlaid by granites and related crystalline rock. Where such conditions prevail, ground water supplies must be developed in the glacial sediments. Since much of the drift is sandy clay, its permeability allows the flow of water in sufficient amounts to supply the needs of farms and small industries. In the sandy moraines the water under the hills does not rise much above the level of the lakes and swamps in the hollows near by. The permeability of the sands is so great that the water establishes a nearly uniform level. Where clayey layers are incorporated in the drift, they serve to hold up the water level somewhat by restricting the movement of water downward.

The slope of the water table conforms with the general southward slope of the surface of the county. At Mora the static level in water-table wells is about 940 feet above sea level, whereas in the northeastern part of Pomroy Township (T. 41 N., R. 22 W.) it is at an elevation of 1075 feet. Table 33 illustrates this relationship.

TABLE 33.—STATIC UNDERGROUND WATER LEVELS IN KANABEC COUNTY

Location	Surface Elevation (feet)	Static Level (feet)
Sec. 9, T. 38 N., R. 23 W.	975	950
Sec. 24, T. 39 N., R. 23 W.	960	955
Sec. 16, T. 39 N., R. 23 W.	1040	1020
Sec. 26, T. 40 N., R. 23 W.	1070	1045
Sec. 23, T. 40 N. R. 23 W.	1045	1040
Sec. 22, T. 41 N., R. 22 W.	1085	1075

MUNICIPAL WATER SUPPLIES

MORA

The city of Mora is near the west margin of the white and pink sandstones that underlie the eastern part of the county. Granitic rocks crop out about one mile northwest of the city and drilling indicates that they are continuous westward under the drift. Water for the public supply system is taken from a well 8 inches in diameter and 210 feet deep. It penetrates about 160 feet of glacial drift and terminates in sandstone. No detailed log is available. The well was tested at 150 gallons per minute and when not pumped the static level is 50 feet below the surface.

A well at the cooperative creamery has a total depth of 157 feet. Its static level is 30 feet below the surface and when pumped at 180 gallons per minute it has a drawdown of 6 feet.

OGILVIE

The village of Ogilvie is located on the undulating till plain in the southwestern part of the county. All the wells in this vicinity obtain water from the glacial drift, the total thickness of which is not known. However, a few miles north of the village granite is encountered at a depth of 50 feet.

The village well at Ogilvie, drilled in 1917, is 8 inches in diameter and 125 feet deep. It penetrates 25 feet of impervious glacial clays and 100 feet of sandy outwash sediments. Its static level is about 20 feet below the surface and when the well is pumped at the rate of 50 gallons per minute there is little drawdown.

QUAMBA

The village of Quamba has no public water supply system. A farm well less than a mile to the northeast in SE¼, Sec. 26, T. 40 N., R. 23 W., entered sandstone at a depth of 72 feet. The water in this well has a static level 30 feet below the surface.[4]

GRASSTON

There is no public water supply system in the village of Grasston, and most private supplies are obtained from wells driven into the sandy outwash sediments. The deeper drilled wells a few miles west of the village enter white sandstone at a depth of about 135 feet. The water from the sandstone is under sufficient pressure to lift it to within 20 feet of the surface, or to an elevation of about 950 feet above sea level.

FARM WATER SUPPLIES

Along the valley of the Snake River many supplies of water for farms are obtained from driven or bored wells. East of the river most drilled wells continue down through the drift and into the underlying Keweenawan sandstones. In South Fork Township south of Ogilvie the drift is very stony and boulders interfere with drilling. However, satisfactory supplies of water for farm use may generally be obtained from wells less than 100 feet deep. To the north of Ogilvie in Ann Lake Township the granitic rocks are so near the surface that it is often difficult to find sand or gravel layers in the drift before encountering the impervious bedrock. A similar condition exists north of Knife Lake in the region of Warman.

The logs of a number of farm wells are given in the section on pre-Cambrian sedimentary rocks, page 139.

[4] Data from Berg Brothers, drillers, Mora.

TABLE 34. — ANALYSES OF WATERS OF KANABEC COUNTY *

	1	2	3	4
Depth (feet)	209	209	110	300
Hardness	106	130	160	150
Alkalinity	124	132	170	160
Iron	.4	.15	.1	.38
Manganese	...	...	.14	.24
Chlorine	2.5	2	1	5
Fluorine	...	...	0	.1
SO_4 radical	...	...	7.3	12
Turbidity	0	3	.1	1.7
Color	15	8	6	7
Odor	e–1	0	...	...
pH value	...	...	7.55	8.1

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Mora, drilled well, 1916.
2. Mora, drilled well, 1926.
3. Mora, two drilled wells, 1942.
4. Ogilvie, drilled well, 1942.

KOOCHICHING COUNTY

SURFACE FEATURES

Koochiching County includes an area of 3141 square miles which was cut off from the northern townships of Itasca County in 1906. Approximately 90 per cent of the county falls within the limits of glacial Lake Agassiz and a high proportion of this former lake bed is still swampy land. Most of the naturally drained areas occur on the immediate borders of streams, but in the southeastern townships several large interstream areas are fairly well drained.

The northeastern townships of the county border on Rainy Lake, and in this region low rounded bosses of rock alternate with areas of water and swampy land.

All of Koochiching County drains eventually into Hudson Bay. Most of the streams discharge into the Rainy River, which runs westward along the northern side of the county. The largest streams are the Big Fork and Little Fork rivers. The former flows northward through the central part of the county and the latter flows northwest through the east-central part of the county. These streams flow in sinuous channels 5 to 20 feet below the general level of the surface, which is from 1200 to 1300 feet above sea level. A small area in the southwestern townships drains westward into Red Lake, whose waters eventually find their way to Hudson Bay. In addition to the natural drainage lines, there are many miles of artificial drainage ditches.

UNCONSOLIDATED SURFACE SEDIMENTS

Nearly a million acres in Koochiching County are covered with from 2 to 20 feet of peat. About 700,000 acres of the peat is in muskeg swamps, where it has accumulated to an average thickness of 7 feet. Most of this peat is of the built-up or high-moor type. Only a comparatively small percentage of the bog land represents filled lakes, and in these areas the peat is unusually deep and of a different character. In such deposits the area of deepest peat is surrounded by successive zones of shallower peat which grades out into the sphagnum growth that is typical of the flat interstream areas.[1]

The glacial drift in the better drained areas is chiefly a calcareous boulder clay deposited by the Keewatin glacier. These glacial sediments are covered by a thin veneer of lake silt deposited on the floor of glacial Lake Agassiz. The highest shore of Lake Agassiz is marked by a well-defined gravel and sand ridge or beach. This extends from the southeast corner of the county westward through the southern tier of townships as far as T. 63 N., R. 27 W. From there it extends northwestward and crosses the western border of the county in the northern part of T. 151

[1] Soper, E. K., The peat deposits of Minnesota: Minn. Geol. Survey Bull. 16, pp. 172–185, 1919.

N., R. 29 W. A group of isolated beach ridges occurs in the area from 6 to 10 miles south of Big Falls, and several are crossed by the railroad grade south of Little Fork.

Leverett and Sardeson describe the relation of the Patrician and Keewatin drifts as follows.

"In the northeastern part of the county on the borders of Rainy Lake and southward to Lake Kabetogama there are rock hills with very thin deposits of drift on their slopes. South of these rock hills there are ridges of drift which seem to be composed mainly of Patrician drift but which are coated with the calcareous Keewatin drift. They appear, therefore, to be overridden moraines of the former drift. There are other ridges in the vicinity of the Minnesota and International Railroad from Little Fork southwestward for several miles which have a nucleus of Patrician drift and a veneer of Keewatin drift. A few miles farther southwest there is a morainic strip running from northwest to southeast which is crossed by the Big Fork River just below the mouth of Sturgeon River and which runs southeastward on the north side of Big Fork River past Big Falls and thence with slight interruptions to Little Fork River in the east part of T. 65, R. 25W. The same belt reappears between Little Fork and Net Lake rivers and continues southeastward into St. Louis County, passing just south of Net Lake and leading past the south side of Pelican Lake to the west end of Vermilion Lake. This morainic strip seems to have been formed in the main by the Patrician ice field but it carries a somewhat heavy deposit of Keewatin drift. For several miles in the vicinity of Big Falls and in much of its course gravel and sand deposits are abundant, thus distinguishing it from the ridges farther north which are composed chiefly of bowlder clay."[2]

ROCK FORMATIONS

Archeozoic

Keewatin greenstone and greenstone schists crop out along a narrow zone from the south shore of Rainy Lake east of Ranier, southwestward into T. 70 N., R. 23 W. In this area glaciated knobs of greenstone protrude through the thin mantle of glacial drift. Similar rocks are encountered on a group of islands in Rainy Lake in Ranges 22 and 23 west.

Several outcrops of green schists along the Little Fork River in T. 63 N., R. 22 W., have been interpreted as part of the Keewatin series (Figure 25). The schists strike N. 79° E. and dip 90°. Drilling has demonstrated the presence of a grayish-green crystalline rock under the glacial drift as far west as T. 63 N., R. 25 W.

Laurentian rocks have not been found outcropping in Koochiching County. From present field observations one is not justified in correlating any of the granite rocks in this county with the Laurentian. This

[2] Leverett, Frank, and Sardeson, Frederick, The surface formations and agricultural conditions of northeastern Minnesota: Minn. Geol. Survey Bull. 13, pp. 59–60, 1917.

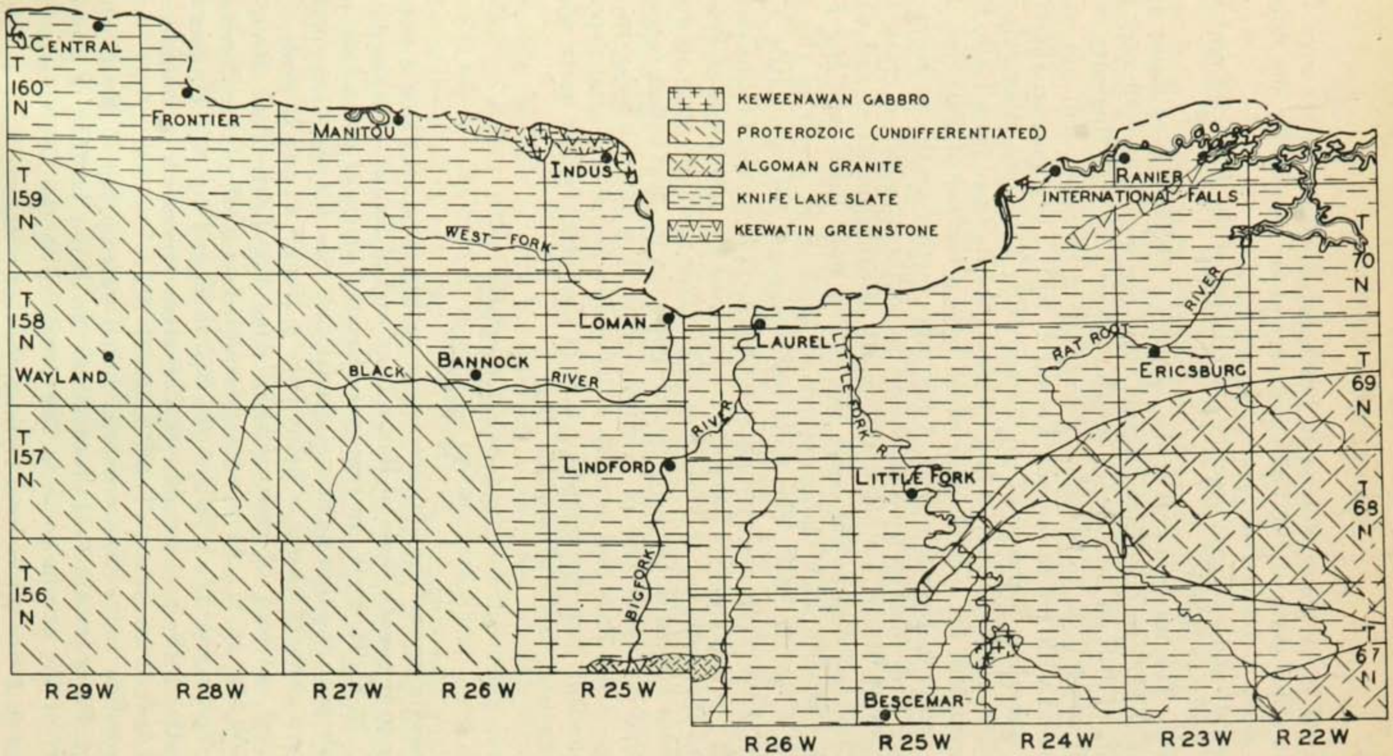

FIGURE 25. — Geologic map of northern Koochiching County.

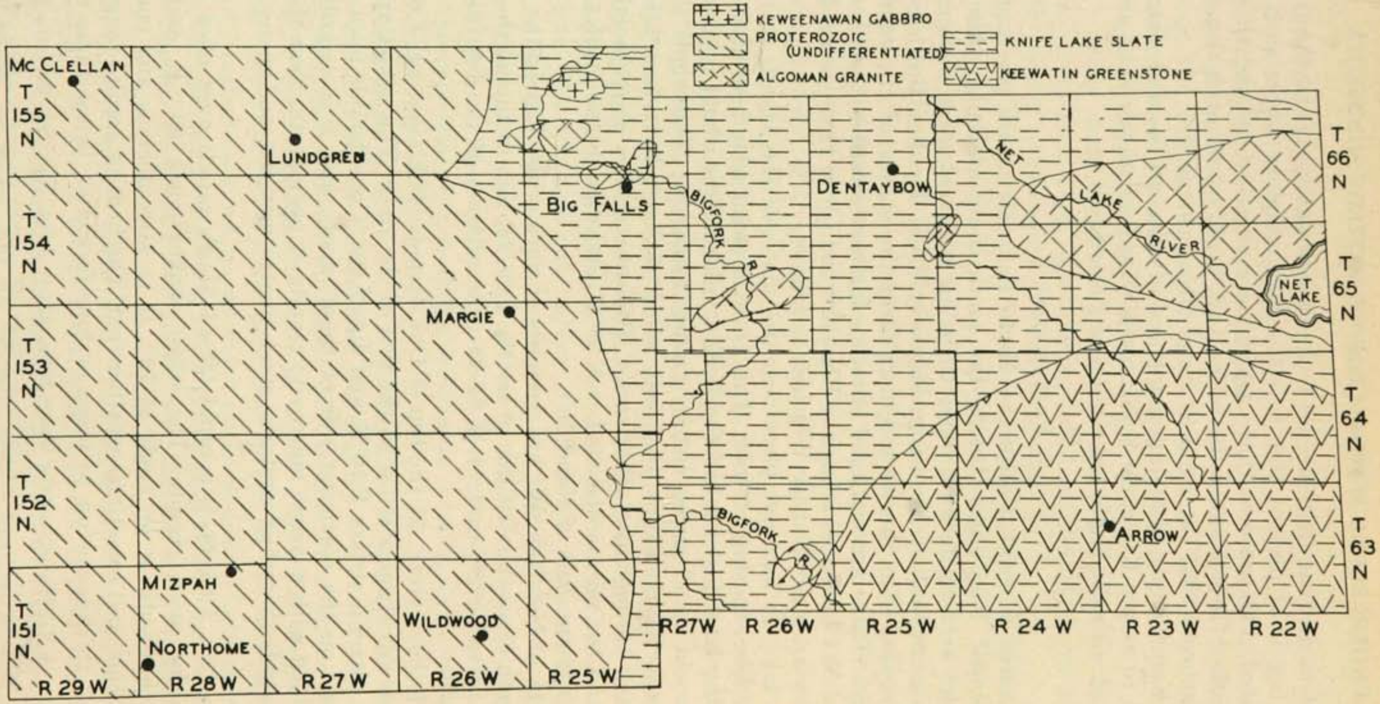

FIGURE 26. — Geologic map of southern Koochiching County.

does not mean that there are no rocks of Laurentian age in the county, but no one is at present able to state with certainty where such rocks are located. The granites that crop out are observed cutting the slates and schists of the Knife Lake series and, furthermore, inclusion of the schists indicate that the granites are of Algoman age.

The Koochiching formation composed of mica schists and slates was referred to as pre-Keewatin by Lawson.[3] However, these rocks are now correlated with the Knife Lake series of Proterozoic age.[4]

PROTEROZOIC

The rocks correlated with the Knife Lake series are pre-eminently mica schists. They extend along the south shore of Rainy Lake from the outlet area to Jackfish Bay; there for a considerable distance the shore is composed of Keewatin. However, from Jackfish Bay eastward to the county line the mica schists form the shores of the numerous deep bays. There are scattered outcrops farther toward the south in the region of Net Lake and along the Big Fork and Little Fork rivers (Figure 26). They are described by Winchell as follows.

"Net lake. In only one place near the shores of this lake is there any considerable exposure of rock. This is on a small island, near the east side of the lake, just west of the Indian village. This island is composed of mica schist and gneiss cut by granite intrusions. The whole is then cut by a large greenstone dike from which stringers have been sent out across and through the other rocks. The dike strikes about north and south, and the mica schist strikes N.58°E. and dips to the south of this direction at an angle of about 70°.

"North of Net lake. We have reports of mica schist just to the north of the granite on the east line of sec.13, T.66–22; also to the north of the granite in sec. 22,23 and 24, T.66–23. The relation of the two rocks is not known.

"Little Fork river. At the top of Oak Rapids (N.E.¼sec.22, T.65–24) is an outcrop of mica schist in the bed of the river. This schist appears to be in place; it strikes E.10°S. and dips S.20°. Considerable mica schist is exposed on the northeast side of these rapids, and it is described as interbedded with a coarse muscovite granite or pegmatyte. Near the foot of the rapids the schist contains much quartz in veins, and many small garnets.

"In sec.31, T.66–24, is a rapid (Dead Man's rapid) over mica schist 'interbedded' with granite. The schist strikes north 80° E. and dips toward the south at an angle of 72°. It is very silicious and contains quartz veins, and sometimes weathers red. The beds of granite (or gneiss) are of all thicknesses up to three or four feet. Just below these rapids

[3] Lawson, A. C., Geology of the Rainy Lake region: Amer. Jour. Sci., 3rd ser., vol. 33, pp. 473–480, 1887.

[4] Grout, F. F., Koochiching problem: Geol. Soc. Am. Bull., vol. 36, pp. 351–364, 1925.

is an exposure of massive dioryte, and a short distance below this mica schist occurs again cut by granite.

"Following down the river a number of other outcrops of mica schist are found. Frequently these are cut by, or 'interbedded' with, granite or gneiss. The last[5] exposure is in the S.W.¼ sec.14, T.68–25, where there is a low exposure of mica schist and granite in thin beds dipping north at a high angle and striking east and west.

"A ridge of mica schist and granite is reported by Mr. L. A. Ogaard on the county road from Koochiching to Grand Rapids. This ridge lies near the centre of the south edge of T.67–24.

"Big Fork River. The first exposure on this stream is about fifteen miles above its mouth. Here is an outcrop, about 200 feet long, of granitic rock on the west bank. Patches of mica schist occur in the granite and at the lower end of the exposure is mica schist banded with thin belts or sheets of granite. Phases of the rock occur in which garnets are abundant. About seven miles above this exposure is another one of mica schist. About thirty miles above the mouth of the river mica schist, veined and striped with granite, crosses the river. The strike is east and west.

"A mile and a half below the mouth of Sturgeon river (This river comes from the west and enters the Big Fork river in the southeastern part of T.155–25) a low moutoneed surface of gray mica schist protrudes from the water. Half a mile below the mouth of Sturgeon river a low outcrop of mica schist crosses the river from southeast to northwest. This outcrop would be invisible at any time except when the river was very low. The schist is cut by two veins or dikes of granite. One of these is narrow, fine grained and gray in color, being composed very largely of quartz and feldspar and very little biotite and muscovite. The other is at least twelve feet wide; the specimens collected show a coarse mass of feldspar penetrated by quartz, forming an excellent example of coarse graphic granite.

"At Big Falls (sec.36 or 35, T.155–25) the rock is granite and mica schist which is cut at the head of the falls by a diabase dike at least twenty feet wide, running north 10° east. A quarter of a mile below the falls mica schist and granite outcrop in the river. The strike is north 68° east, and the dip is south at a high angle. At the falls the rock is much disturbed and has no constant strike and dip. Less than a mile above the falls is an outcrop in the river of granite and mica schist. The strike appears to be east 50° south, and the dip southwest at a high angle.

"No other outcrops occur until reaching a rapid about seventy-two miles from the mouth of the river; this is probably near the centre of

[5] Prof. G. E. Culver reports that an outcrop of hard, garnetiferous mica schist crosses the river four miles above its mouth. The strike is northeast and southwest, and the dip is nearly vertical.

T.63–26. Here fine mica schist occurs projecting only a few inches above the water. This outcrop would be hidden by high water. One or two small veins of granite cut the schist. A short distance above this is more mica schist, striking north 68° east and dipping northwest, at a high angle. The schist is quite hard in places and contains hornblende, chlorite and garnets. A little above this and on the east side of the stream the strike changes to north 40° east. Here is a dike, about ten feet wide, which runs nearly north and south. The schist is hard, fine, siliceous and brittle next the dike. On the west side of the river is some gray granitic rock which appears like a fine-grained syenyte. Only a few feet of this is visible, but it seems to cut the mica schist."[6]

The Algoman is represented by granite rocks that crop out in widely separated areas. At and near Rainy Lake they appear at the surface in five different regions. The first of these is at Koochiching Falls; the second, at the lake shore and on islands in Sec. 27, T. 71 N., R. 23 W.; the third, on Grassy Island in Sec. 25, T. 71 N., R. 23 W.; the fourth, in Secs. 3 and 4, T. 70 N., R. 22 W.; and the fifth, along the south shore of Kabetogama Lake.

North of Net Lake granite outcrops are reported from the east line of Sec. 13, T. 66 N., R. 22 W., and in the northeastern part of Sec. 36 in the same township. In T. 66 N., R. 23 W., granite crops out in Secs. 22, 23, and 24. To the south of Net Lake in T. 63 N., R. 22 W., outcrops of syenite and diorite with inclusions of mica schist occur along the Little Fork River. These rocks have the texture of a primary gneiss with oriented feldspar grains. Farther west along the Big Fork River, a short distance south into Itasca County, granite appears also in Sec. 35, T. 150 N., R. 25 W. The rock is a coarse-grained, hornblende granite, greenish red in color.

The intrusive relations of some of the above granites which are referred to as Algoman are not evident owing to lack of exposures. However, at most of the locations there are inclusions of schist in the granite or there are stringers and dikes of granite in nearby outcrops of schist, indicating that the granite rocks are younger than the schists. However, some of the granites may be of Laurentian age.

Rocks of Animikean age do not occur in Koochiching County so far as is known.

Cretaceous

The youngest marine sedimentary rocks known to occur in Koochiching County are of Cretaceous age. The base of these strata is not exposed in this county, but in Itasca County to the south, the basal conglomerate of the Cretaceous rest directly over pre-Cambrian rocks. Fossiliferous strata with typical Cretaceous fossils crop out at several points in the banks of the Little Rock River. However, the unconsoli-

[6] Winchell, N. H., The geology of Minnesota: Final Rept., Minn. Geol. and Nat. Hist. Survey, vol. 4, pp. 177–178, 1899.

dated nature of these strata, when lacking in fossils, renders them difficult to distinguish from glacial or postglacial lake sediments.

Fossiliferous beds occur in the bank of a creek which enters the Little Fork River in Sec. 9, T. 64 N., R. 23 W. They are composed of fine, sticky, horizontally stratified clay, which becomes shaly when dried. The clay is bluish gray in color and is in strata from 1 to 3 inches thick. A total thickness of about 40 feet is exposed. Fossils of fish scales and of characteristic Cretaceous Foraminifera have been reported.

Other exposures of Cretaceous rocks undoubtedly occur along the Little Fork and Big Fork rivers, but some of the thinly bedded shales and sands are not readily distinguished from the laminated clays and sands which were deposited on the floor of glacial Lake Agassiz.

GENERAL UNDERGROUND WATER CONDITIONS

Because of the large areas of poorly drained swamps in Koochiching County, the water table is near the surface. In the area of glacial Lake Agassiz dug wells and drainage ditches are generally filled with water almost to the surface. The high water level of this area is doubtless maintained in part at least by artesian pressure from the higher land south of the basin. This tendency is augmented because the bedrock surface stands high in the southwestern part of the county in the region of Northome and Mizpah and slopes toward the northeast. The lowest known elevations of the bedrock are within the Lake Agassiz basin.

In the morainic topography south of the upper beach of Lake Agassiz, the water level is between 10 and 30 feet below the surface. In that area the static level is at or a little above the level of the streams and lakes.

All supplies of water should be developed in the glacial drift. The amount obtained from the joints and fractures in fresh, solid bedrock is usually so small that drilling into the rock is inadvisable. Where the upper part of the rock is somewhat decomposed, it may yield small supplies of water. However, deep drilling into the rock is unwarranted, because the water generally is sealed off from the deeper portion of the residuary material and the unweathered rock beneath is rarely fractured sufficiently to form an adequate reservoir.

MUNICIPAL WATER SUPPLIES

International Falls

The city of International Falls is the county seat of Koochiching County. It is located at the west end of Rainy Lake and has a population of about 5500. Water for the public supply system is obtained from the lake. In the region of the city the glacial drift is too thin to furnish the volume of water required for the present population. There are a number of private wells, and most of them are dug to the base of the glacial drift.

Ranier

The city of Ranier uses water from Rainy Lake.

Big Falls

The village of Big Falls has several wells. One of the older wells entered the bedrock formations to a total depth of 300 feet. The rock surface was encountered 50 feet below the surface. A new well drilled to a depth of 60 feet did not reach the solid rock. The static level is 20 feet below the surface.

Little Fork

The village of Little Fork has a well 125 feet deep. The static level is about 18 feet below the surface.

Big Fork

The village of Big Fork does not have a public water supply system. The private wells are from 75 to 150 feet deep. Five miles east of the village the glacial drift is less than 100 feet thick.

Griegville

This village has no public water supply. Here a thin mantle of glacial drift rests on red granite. At a number of places near the village granite was encountered at a depth of no more than 30 feet. However, shallow dug wells produce ample water.

Mizpah

In the village of Mizpah the static level of the ground water is less than 10 feet below the surface. Many wells are dug about 15 feet deep and others are drilled to a depth of 50 to 75 feet. The yield of the water is ample.

Northome

In the region of Northome the glacial drift is about 80 feet thick. The static level of the water in the drift is 60 feet below surface. Wells drilled to bedrock produce sufficient water for small industries.

Some diamond drilling of an exploratory nature has been done in the bedrock of this region, but no ore deposits of economic value were discovered.

Rainy River Region

None of the villages in the northwestern part of the county have public water supply systems.

Some natural gas occurs in the glacial drift. About 15 miles east of Northome gas is trapped under 100 feet of blue glacial clay, and in the region between Northome and Effie gas has been encountered at a depth of 72 feet. The gas is not under sufficient pressure to be of commercial value.

TABLE 35. — ANALYSES OF WATERS OF KOOCHICHING COUNTY *

	1	2	3	4	5	6	7
Depth (feet)	...	...	124	...	...	...	...
Hardness	21	21	540	280	350	72.5	84
Alkalinity	36	14	520	330	330	74	350
Iron	.05	.26	1.6	4.8	.5	.8	5.2
Manganese	0	0	.18	.2	.06	...	.08
Chlorine	...	5.2	4.6	10	1	2.5	.6
Fluorine	...	...	0	.2	.4	...	.2
SO_4 radical	...	...	110	5	58	...	7.6
Turbidity	.8	4	25	33	5	2	12
Color	28	35	7	10	12	30	21
Odor	...	7.75	...	...	...	...	...
pH value	7.1	...	7.45	7.7	7.6	8.4	7.2

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. International Falls, Rainy River, 1933.
2. International Falls, Rainy River, 1943.
3. Little Fork, drilled well, 1944.
4. Big Falls, drilled well No. 2, 1943.
5. Big Falls, drilled well No. 1, 1939.
6. Northome, Barrett Lake, 1929.
7. Northome, drilled well, 1938.

LAKE COUNTY

SURFACE FEATURES

The northern part of Lake County, as far south as T. 61 N., is characterized by numerous bedrock hills and knobs among which are lakes and swamps. This area is covered by only a very thin mantle of glacial drift. The southern part of the county along the shore of Lake Superior also has numerous areas of bedrock exposures. This region was within the limits of glacial Lake Duluth and the barren rocks are due in part to the work of the lake waves which removed the drift covering. These rock outcrops extend back several miles from the present shore and reach an altitude of 0 to 1000 feet above the level of Lake Superior.

The waters of Lake Duluth extended back to a distance of 4 or 5 miles from the present shore of Lake Superior in the region from Knife River as far northeast as Beaver Bay. However, for several miles southwest from Beaver Bay a rock ridge, lying back only about 2 miles from the shore, stood slightly above the lake level. From Beaver Bay northeastward the waters of Lake Duluth extended only 1½ to 2 miles back from the present lake except in narrow inlets in the valleys of the Baptism and Manitou rivers. Rocky ridges bordering Lake Superior have greater breadth from Beaver Bay northeastward than they have to the southwest. The beaches of Lake Duluth are ill defined in these rocky areas but are distinctly seen in the form of definite gravel ridges where the shore was composed of glacial sediments. These ridges occur at various levels marking the successive lake stages down to the present shore. The highest beach is about 550 feet above the present level of Lake Superior. It shows a slight rise from southwest to northeast in its course across the county.[1]

The central part of the county lying between the rock ranges is less rugged and has a thick covering of glacial drift. A rugged terminal moraine enters the county in T. 60 N., R. 11 W., and extends eastward into R. 7 W. There it is overridden by the outer moraine of the Lake Superior lobe, which extends in a northeast-southwest direction from T. 54 N., R. 11 W., to T. 60 N., R. 6 W. Large swampy areas occur in the re-entrant between these two moraines.

The water of Lake Superior stands 602 feet above sea level and the highest points in Lake County rise about 1250 feet higher. The greatest elevations are found across the central part of the county, where the broad swells of the glaciated outcrops rise to more than 1850 feet above the sea. The elevation of some of the lake levels is given in Table 36.

The southern part of the county drains into Lake Superior through high gradient streams, such as the Encampment, Split Rock, Beaver

[1] Leverett, Frank, and Sardeson, Frederick, Surface formations and agricultural conditions of northeastern Minnesota: Minn. Geol. Survey Bull. 13, p. 54, 1917.

TABLE 36. — ALTITUDE OF LAKE LEVELS IN LAKE COUNTY *

	Elevation (feet)
Ogishkemuncie	1488
Kekequabic	1497
Knife Lake	1381
Sucker	1330
Basswood	1300
Fall	1313
White Iron	1395
Birch	1410
Kawishiwi River, T. 63 N., R. 9 W.	1491
Moose	1339
Snowbank	1424
Ensign	1342

* Winchell, N. H., The geology of Minnesota: Final Rept., Minn. Geol. and Nat. Hist. Survey, vol. 4, p. 267, 1899.

Bay, Baptism, and Manitou rivers. These streams are characterized by numerous waterfalls and rapids, which are due to variations in the hardness of the rocks. In most cases the water plunges over a massive basalt flow which is underlain by the softer amygdaloidal bed of the flow beneath. This softer material is undercut or worn out more rapidly than the hard bed above, thus causing the massive bed to break off in large blocks and leave vertical faces.

The broad, undulating plateau in the central part of the county is the area from which nearly all the streams of the county take their source. The headwaters of the St. Louis and Cloquet rivers reach the southwestern part of this area and the northern portion is drained by the headwaters of the Stony River.

To the north of the drift-covered plateau, lakes are very numerous. In the northern one-third of the county they are so closely spaced and the rivers are so large and lake-like that most of the travel is done by canoe. Here are located such well-known lakes as Fall, Snowbank, Moose, Kekequabic, Ogishkemuncie, Knife, and Ensign. Along the international boundary there is a continuous and deep watercourse, mostly formed by lakes such as Ottertrack, Basswood, and Crooked. All these northern lakes lie in rock-bound basins and their outlets are over low points in their rocky rims. Along the northern boundary the water descends westward toward Rainy Lake and thence through the Rainy River to Lake of the Woods and eventually to Hudson Bay.

UNCONSOLIDATED SURFACE MANTLE

Leverett and Sardeson describe the glacial deposits as follows:

"The greater part of Lake County was covered by Patrician ice which came in from the north, there being only a strip fifteen to twenty miles wide next to Lake Superior which was covered by the Superior ice field.

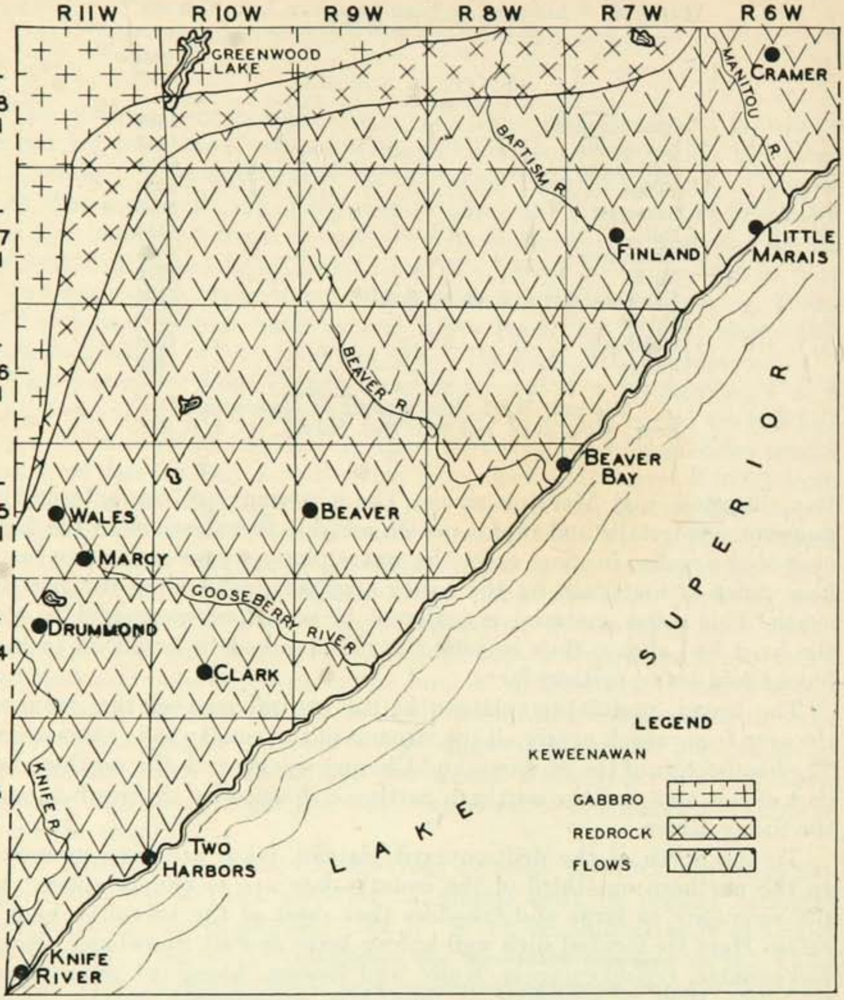

FIGURE 27. — Geologic map of southern Lake County.

Each of these ice fields produced a great system of moraines which became interlocked in the eastern part of Lake County. The system formed by the Patrician ice field leads westward from Tps. 59 and 60 R. 7W. across this county into St. Louis County, covering much of Tp. 59 R. 8W. and Tp. 60 Rs. 9, 10, and 11W. The several headwater branches of Isabella River start in this morainic system and Stoney River has most of its course among its ridges. Between the constituent morainic ridges there are narrow strips of gravel plain formed as outwash from the ice border in the course of the development of the mo-

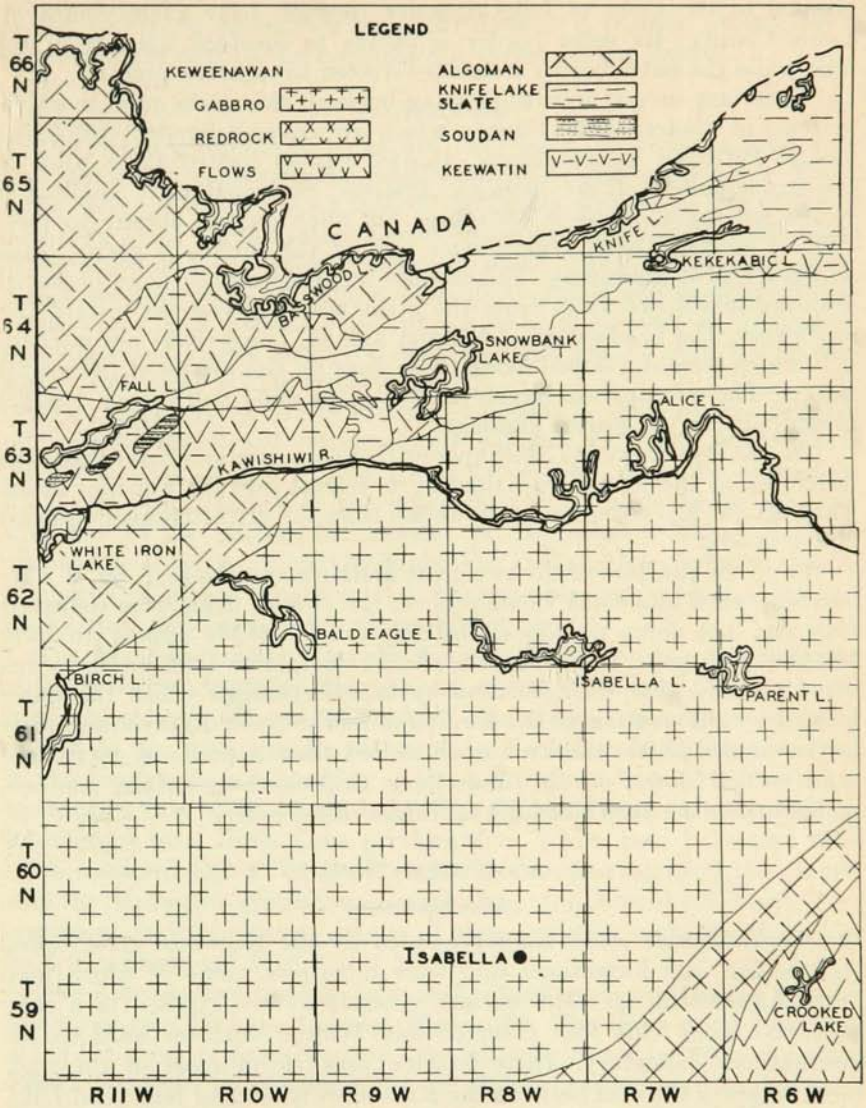

FIGURE 28. — Geologic map of northern Lake County.

rainic system. The amount of drift in this morainic system is several times as great, square mile for square mile, as in the district to the north of it, in the northern half of Lake County.

"A morainic system of the Superior lobe, which joins as a correlative of that of the Patrician ice field just described, leads from their place of junction, which is in Tp. 59, Rs. 7 and 8W, southwestward parallel to the shore of Lake Superior through Lake County into St. Louis County. Its inner border is twelve to fourteen miles from the lake while the outer border is usually sixteen to eighteen miles. . . .

"There are several townships lying between these two great morainic systems in western Lake County which are covered by drift belonging to the Patrician ice movement, the ice having melted there prior to the development of the morainic systems. Scattered drift knolls and ridges are found in these townships but they do not appear to form definite morainic belts. The greater part of the surface is nearly plane and much of it is swampy. This district was traversed by lines of glacial drainage which ran away from the great morainic systems toward the southwest. The headwaters of Cloquet and St. Louis rivers are in channels which were developed along those lines by the escape of the glacial waters. The swamps are largely underlaid by sand and gravel deposits brought in by the glacial drainage.

"On the slope toward Lake Superior there are narrow strips of moraine developed as the ice border halted in its retreat into the Superior basin. They are far less conspicuous, however, than the great morainic systems above noted.

"From the junction of the two great morainic systems in T. 59, R. 7W. northeastward into Cook County where the two ice fields were coalesced they did not form moraines. Instead, the ice fields appear to have blocked each other's movements almost completely and to have become ramified near their junction by tunnels through which the water formed by the melting of the ice flowed and deposited gravel and sand in the tunnels. After the ice was all melted these deposits of gravel and sand settled down on the underlying drift-covered surface, and remained there as steep sided gravel ridges called eskers." [2]

ROCK FORMATIONS

Archeozoic

The Archeozoic rocks are represented by the Keewatin greenstones, the Soudan iron formations, and later intrusives, some of which may be of Laurentian age. The ancient greenstones are exposed in a zone 10 to 20 miles wide that extends from Winton northeastward to the international boundary. These basaltic rocks form most of the high rocks ridges in the area between the Kawishiwi River and Basswood Lake (Figures 27 and 28). Associated with the igneous rocks are lenses of the Soudan iron formation that have been folded into the flows. The iron-bearing cherts are most abundant in T. 64 N., R. 11 W.[3] No large areas of Laurentian granites are known to occur within the boundaries

[2] Leverett, Frank, and Sardeson, Frederick, Surface formations and agricultural conditions of northeastern Minnesota: Minn. Geol. Survey Bull. 13, pp. 52–53, 1917.

[3] For a more detailed description of the lithology of the Soudan formation, see the report on St. Louis County, page 211.

of the county. However, the Saganawa granite is exposed extensively a short distance east of the northeastern corner of the county.

PROTEROZOIC

The oldest Proterozoic rocks are the slates, graywackes, and conglomerates that constitute the Knife Lake or Temiskaming series. These rocks crop out along a zone from 1 to 8 miles wide from Fall Lake to Saganaga Lake on the international boundary. The Knife Lake series is composed of many different kinds of rocks. Those found most abundantly are gray slates and graywackes, flinty slates, arkosic slates, tuffaceous slates, and various types of conglomerates, such as greenstone conglomerates, quartz porphyry conglomerates, granite pebble conglomerates, and white pebble conglomerates.

The complexity of the subsurface structure in this area is indicated by the generalized cross section shown in Figure 29. Major faults divide the Knife Lake district in long segments or belts, each one distinct in itself, but very difficult, if not impossible, to connect stratigraphically with any of the others. The amount of displacement along the fault planes cannot be measured definitely, but the relations indicate that in a number of places the horizontal displacement was several miles and the vertical movement many thousands of feet.[4]

The Algoman granites of Lake County represent the eastern margin of the Vermilion batholith and the east end of the Giants Range granite. An isolated area of granite south of Snowbank Lake is undoubtedly related to the other granite masses. The Vermilion batholith crops out in the northwestern townships of the county and from there eastward to Range 9 east of Basswood Lake. The Giants Range granites are seen in outcrops from Birch Lake northward to White Iron Lake and from there eastward into T. 63 N., R. 9 W. The contact between the granite and the Keewatin greenstone occurs along the Kawishiwi River. The structural and lithological details of these granitic rocks are described by I. S. Allison and F. F. Grout.[5]

The Keweenawan basaltic flows and related gabbro intrusives underlie the major part of Lake County (Figure 27). The flows occupy an area along the shore of Lake Superior that extends inland for 10 to 20 miles. This is bordered on the north by the Duluth gabbro and the red rock that is a differentiate from the same magmatic mass. The north margin of the gabbro enters the county from the west at Birch Lake in T. 61 N.

[4] For a detailed description of the lithology and structure of the Knife Lake region the reader is referred to Gruner, J. W., Structural geology of the Knife Lake area of northeastern Minnesota: Geol. Soc. Am. Bull., vol. 52, pp. 1577–1642, 1941.

[5] Allison, I. S., The Giants Range batholith: Jour. Geol., vol. 33, p. 488, 1925; Grout, F. F., The Vermilion batholith: Jour. Geol., vol. 33, p. 467, 1925; Grout, F. F., and Bolk, R., Structural study of the Snowbank stock: Geol. Soc. Am. Bull., vol. 45, p. 621, 1934; Tyler, S. A., Marsden, R. W., Grout, F. F., and Thiel, G. A., Studies of the Lake Superior pre-Cambrian by accessory-mineral methods: Geol. Soc. Am. Bull., vol. 51, p. 1429, 1940.

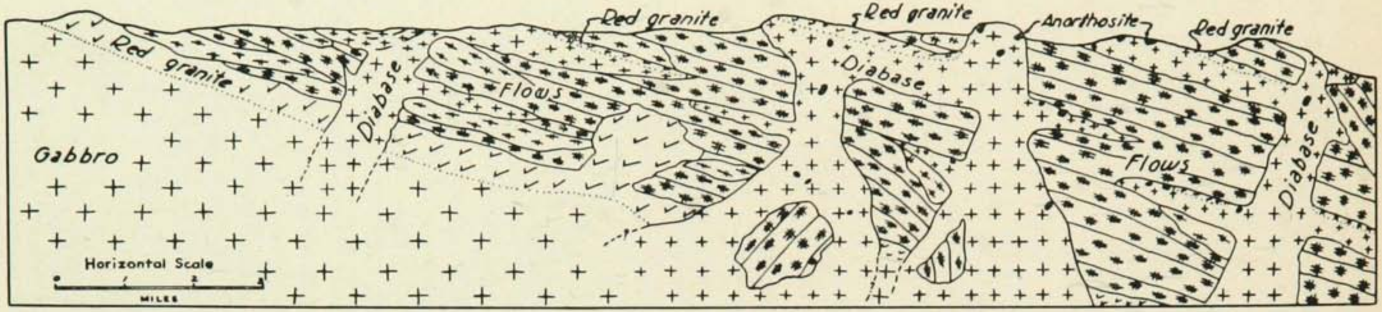

FIGURE 29. — Generalized cross-section showing the complex subsurface relationships between the Keweenawan rocks in northern Lake County. After Grout and Schwartz.

and extends northeastward toward Kekekabic Lake, east of which it crosses the east border of the county in T. 64 N., R. 6 W.

The basaltic flows are of several kinds and of varying thickness. Where well exposed, nearly all grade up to fine-grained tops full of amygdules. The central parts of flows are commonly brown from alteration, black when fresh, and green if more chloritic than average. Locally the ropy top surface and other parts are bright red because of oxidation. The flows dip toward Lake Superior at an angle of from 5° to 15°. Since the upper parts of the flows are somewhat porous and vesicular, the contacts between flows allow ground water to migrate down dip. Thus wells drilled through a series of such lava flows intercept the water that is trapped under the impervious lower part of the individual flows.

The amygdaloidal tops of lava flows are well exposed along the shore of Lake Superior. Typical examples may be seen on the shore of Burlington Bay at Two Harbors. From the sandy beach of the bay to the power house, the shore trends diagonally across the strike of the rocks and five distinct flows are exposed, forming sharp points of rock projecting into the bay. The divide between Burlington and Agate bays is formed by the fifth flow. One of the amygdaloidal beds directly below the tourist camp is unusually thick and contains much pink zeolite and white calcite. Such units in the flows allow small amounts of water to circulate through them.

Similar well-developed amygdaloidal tops of flows are exposed on the east bank of the Knife River and northward along the road. They are well exposed also several miles north of the Stewart River and a short distance north of the Encampment River. A porous and vesicular bed 20 to 25 feet thick lies beneath a massive basalt just east of the Lind farm near the mouth of the Gooseberry River. Such soft and porous units below the massive lower parts of flows are responsible for the water falls along many of the rivers that discharge into Lake Superior. Locally thin lenses of sandstone occur interbedded with the flows, and these act as channels for the migration of ground water.

Both the gabbro and the red rock are such thick, massive rocks that very little if any water percolates through them. However, the diabase sills and dikes that intrude the flows are of such dimensions that it is possible to drill through them. Where vertical dikes cut the flows at right angles to the dip, they tend to act like a dam and pond the underground water on the up-dip side of the dike. For this reason the lava flows contain very little water on the down-dip side of such intrusives.

Locally, in the areas where the diabase rocks are abundant, white knobs and peaks are conspicuous in the topography. These rocks, which weather white where exposed, are a variety of gabbro with a very high percentage of plagioclase feldspar. They are known as anorthosites. In the area near Lake Superior there are numerous concentrations of such anorthositic gabbro. They are conspicuous near Split Rock lighthouse, at

Beaver Bay and a few miles north, northeast of Lax Lake, at Nicado Lake, east of Finland and north of the road to Little Marais, and north of Cramer. There is a variety of sizes and shapes and compositions in each of these exposures, but in all there is a notable tendency for the larger bodies to resist erosion longer than the diabases and basalts. Nearly all masses of anorthosite are surrounded by diabase, only a few having been observed in basalt flows and in the red rock. None has been shown to be an independent intrusive, and not one shows any gradations from anorthosite to diabase.[6]

WATER SUPPLIES

Two Harbors

The city of Two Harbors received its name from the two small bays or natural harbors along the coast of Lake Superior. These bays were formed by the differential erosion of the lava flows which crop out over large areas along the shore. The rocks dip southward under the lake and strike about 45° east of north.

The yield of underground water from the lava flows is very small and consequently the city is obliged to pump water for its public supply system from Lake Superior. Chemical analyses and temperature variations of the water from the lake are tabulated in the report on the city of Duluth. (See page 232.)

There are many private wells in and near Two Harbors. The following are typical and reveal a variety of subsurface conditions and a great variation in the yield and character of the ground water.

Duluth and Iron Range Railroad.—The railroad company has a well at Two Harbors that is 5 inches in diameter and 214 feet deep. The depth to bedrock is 54 feet. The static level is at the surface and when pumped at the rate of 10 gallons per minute it has a drawdown of 100 feet.

Jessie Cleveland Dairy.—The dairy is located 2 miles southwest of Two Harbors and 3 miles west of Lake Superior. Water is obtained from fractures in the lava rock. The water has a peculiar taste. It is bottled and sold for its medicinal qualities. Analyses are not available.

Dairy Well

		DEPTH (feet)	THICKNESS (feet)
Glacial drift	Red clay	0–40	40
	Hardpan	40–53	13
	Gravel	53–58	5
Keweenawan	Lava flows	58–85	27

A well about 1 mile northeast of the dairy well penetrates 32 feet of glacial drift and 88 feet of rock. Water stands at a static level 20 feet below the surface. The well yield is from 5 to 7 gallons per minute, and

[6] For a detailed discussion of the origin of the anorthosites and a description of them the reader is referred to Grout, F. F., and Schwartz, G. M., The geology of the anorthosites of the Minnesota coast of Lake Superior: Minn. Geol. Survey Bull. 28, 1939.

the water does not have the peculiar taste that characterizes the well at the dairy.

Lundberg Farm.—This farm is located one mile north of the cemetery at Two Harbors. The well is 5 inches in diameter and 105 feet deep. The depth to bedrock is 35 feet. The static level is 37 feet below the surface and when pumped at the rate of 4 gallons per minute it has a drawdown of 53 feet.

Purtile Farm.—This farm is located 3 miles north of the cemetery at Two Harbors. The well is 6 inches in diameter and 78 feet deep. It terminates in the glacial drift and is cased to the bottom without a screen. The static level is 28 feet below the surface and when pumped at the rate of 10 gallons per minute it has a drawdown of 33 feet.

Anderson Farm.—This farm is located 5 miles north of Two Harbors. The well is 6 inches in diameter and 180 feet deep. The thickness of the drift is 120 feet. The static level is 35 feet below the surface and when pumped at the rate of 10 gallons per minute it has a drawdown of 25 feet.

Knife River

Knife River, located at the mouth of the stream that bears the same name, is the largest village between Two Harbors and Duluth. It has a population of about 250. The village does not have a public water supply system. On the northeast bank of the stream and northward along the highway are numerous outcrops of lava flows with well-developed amygdaloidal tops. The presence of the amygdaloidal rocks indicates the possibility of the penetration of ground water, and therefore a small yield may be expected from the bedrock formations. The following wells in and near the village are typical.

Hans Peterson Well.—The well is 5 inches in diameter and 119 feet deep. It penetrates 5 feet of glacial drift and 114 feet of lava flows. The static level is 30 feet below the surface and when pumped 7 gallons per minute it shows a drawdown to 75 feet below the surface.

Carl Erickson Well.—This well is 5 inches in diameter and has a total depth of 225 feet. All except the upper one foot is in bedrock. The well produces 5 gallons per minute.

Cliff Nelson Well.—The well is 6 inches in diameter and 157 feet deep. It penetrates 70 feet of glacial drift before entering the lava rocks. The static level is 40 feet below the surface and the yield is only 2 gallons per minute.

Frank Nelson Well.—The well is 6 inches in diameter and 102 feet deep. Bedrock was entered at a depth of 70 feet. It is cased but not cemented to bedrock. Some water enters at the bedrock surface and the well produces from 1 to 2 gallons per minute.

Paul Gilmore Well.—The well is 5 inches in diameter and 192 feet deep. It penetrates 40 feet of drift before entering the lava flows. The static level is 35 feet below the surface and when pumped at the rate of 20 gallons per minute it has a drawdown of 30 feet.

Carl Anderson Well.—This well would flow at the surface if not pumped. It is 5 inches in diameter and 121 feet deep. It enters bedrock lava flows at a depth of 11 feet. When pumped at the rate of 10 gallons per minute is has a drawdown of 70 feet.

There are several other flowing wells in and near Knife River, where an impervious diabase sill acts as the cap rock for the artesian system.

Larsmont

The village of Larsmont is located 3½ miles southwest of Two Harbors. The village has a population of about 100 and is mainly a resort center for lake trout fishing. In this area the lava rocks are tight and impervious and consequently most wells produce no more than 1 or 2 gallons per minute. The following wells are typical.

Clande's Well.—The well on this property is 5 inches in diameter and 162 feet deep. It enters the bedrock at a depth of 3 feet. The static level is 60 feet below the surface and it produces only one gallon per minute.

Skomar's Well.—At this well the drift is only 5 feet thick and bedrock was penetrated to a total depth of 100 feet. The static level is at the surface and when it is not pumped the well flows in a very small stream. If pumped more than one-half gallon per minute, the water level is lowered to the bottom of the well.

Gooseberry River State Park

The basaltic flows are well exposed along the gorge of the Gooseberry River. Just upstream from the bridge along the highway is a waterfall with a drop of 25 feet, and less than 300 feet downstream are two falls with a total drop of fully 75 feet. Upstream from the bridge at a distance of about a mile is still another waterfall. In the gorge below the falls the amygdaloidal upper parts of the lava flows may be seen grading downward into massive basalt.

The following wells illustrate the subsurface relations and yield of water that may be expected.

CCC Camp Well.—The well at the camp penetrated 2 feet of glacial drift and entered the igneous flow rocks to a total depth of 202 feet. The static level is 20 feet below the surface and when pumped at the rate of 9 gallons per minute it has a drawdown of 150 feet.

Nelson Farm.—This property is located one mile east of the Gooseberry River. The well is 189 feet deep and it enters bedrock at a depth of 4 feet. The static level is 5 feet below the surface and when pumped at the rate of 7 gallons per minute it has a drawdown of 100 feet.

Lake Shore Home.—A well at a summer home on the Gooseberry River between the highway and the lake shore is drilled to a total depth of 350 feet, all but 2 feet of which is in bedrock formations. The static level is unusually deep, standing 100 feet below the surface. The well produces only 2 gallons per minute.

Split Rock River and Lighthouse

The Split Rock River flows through a broad valley in the basaltic flows, but at its mouth it empties into Lake Superior through a narrow gorge in solid rock, whence its name. The rocky, bold cliffs along the coast at and near the lighthouse are due to the erosion of diabase along well-developed systems of joints and fractures. The same diabasic rocks form the numerous outcrops that may be seen along the highway between the Split Rock River and Beaver Bay. The prominent white hills of rock about three-fourths of a mile northeast of the river and west of the lighthouse are composed of anorthosite.

All the rocks referred to above are exceedingly dense and impervious. The only possible source of water from them is from the joints and fractures. Where these are closely spaced small yields may be expected. The following wells are typical of the area.

Ragnold Sve's Split Rock Cabins.—The well at the cabins is 5 inches in diameter and 78 feet deep. It enters bedrock at a depth of 17 feet. When pumped at the rate of 9 gallons per minute the water level is drawn down to 60 feet below the surface.

John Lind Well.—The well on this property is 5 inches in diameter and 135 feet deep. The glacial drift is 52 feet thick. When not pumped the static level is only a few inches below the surface, but when pumped at the rate of 10 gallons per minute it shows a drawdown of 78 feet.

Beaver Bay

At Beaver Bay the Beaver River empties into the lake through a gorge in diabase. Southwest of the mouth of the river are outcrops of anorthosite masses in diabase; beyond are cliffs of red porphyry, which forms a large part of the southwest headland. Most of the rock in this area is diabase and anorthosite, both of which are very poor sources of ground water. Fortunately the static level of the water is near the surface and consequently shallow wells dug in the drift and alluvium provide ample water for domestic purposes. Several fairly large springs issue from the hillside a short distance up the hill beyond the resort hotel. The dug wells vary in depth from 10 to 35 feet. The one at the garage is 12 feet deep.

Little Marais

In the region of Little Marais there are three well-developed beach zones of glacial Lake Duluth. One is a short distance above the present lake level, a second is just below the road, and the third or upper terrace is occupied by the road. Underground water from the high land to the west moves through the beach sediments toward Lake Superior. Shallow dug wells intercept this flow and yield sufficient water for domestic purposes.

Waldo

Waldo is a station on the Duluth, Mesabi, and Northern Railroad a short distance north of Two Harbors. In this area the drift is from 20 to 60 feet thick and most of the private wells terminate in the glacial drift. However, the well for the railroad is drilled to a total depth of 206 feet. It penetrates 40 feet of glacial drift below which it encounters red, oxidized lava flows. The well produces 5 to 10 gallons per minute. The water contains two to four parts per million of iron.

Other Inland Villages

Such villages as Silver Creek, Lax Lake, Sewart, Wales, Finland, and Isabella are in areas where the mantle of glacial drift is sufficiently thick to produce ample water for domestic purposes. These villages do not have public water supply systems.

Table 37. — Analyses of Waters of Lake County *

	1	2	3	4	5	6
Depth (feet)	...	...	...	...	...	156
Hardness	30	34	32	18	52.5	27.50
Alkalinity	32	36	42	50	42.5	200
Iron	tr.	tr.	.1	tr.	tr.	.4
Manganese	...	...	...	...	...	...
Chlorine	2	1	2	...	...	14
Fluorine	...	...	...	...	...	...
SO_4 radical	...	...	...	...	...	...
Turbidity	1	3	3	5	0	10
Color	7	8	2	none	9.0	55
Odor	m–1	0	0	0	0	0
pH value	...	...	...	...	...	...

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Lake Superior, Two Harbors, 1924.
2. Lake Superior, Two Harbors, 1925.
3. Lake Superior, Two Harbors, 1926.
4. Lake Superior, Two Harbors, April 1927.
5. Lake Superior, Two Harbors, June 1927.
6. Knife River, drilled well, 1917.

MILLE LACS COUNTY

SURFACE FEATURES

Mille Lacs County includes the southern half of Mille Lacs Lake and extends southward about 40 miles beyond the lake in a narrow strip, most of which is no more than 12 miles wide. The portion of the county bordering on Mille Lacs Lake is rugged and morainic. Another moraine crosses the county from the northeastern part of Benton County and extends northeastward into Kanabec County north of Mora. This morainic belt is about 4 miles wide. The remainder of the county is largely a till plain. The amount of relief is not great. Even in the moraines the differences in elevation are less than 100 feet. A large part of the county stands between 1200 and 1300 feet above sea level. The southern townships in the region of Princeton are at an elevation of about 1050 feet.

All the county lies within the Mississippi River drainage basin. Mille Lacs Lake has its outlet through the Rum River, which flows almost due southward through the entire length of the county. Its tributaries drain all but the eastern margin of the county, which is drained by the headwaters of the Snake River. An early enlarged Mille Lacs Lake of glacial origin may have had an outlet through Crow Wing County by way of the Nokasippi River into the Mississippi.

UNCONSOLIDATED SURFACE MANTLE

Nearly all the county is covered with the red drift deposited by the Patrician ice sheet that moved across this region from the northeast. Only the southeasternmost township has a mantle of young gray Keewatin drift over that of Partician age. The gray drift was deposited at the northwest margin of the Grantsburg lobe. Some of these gray sediments are lacustrine silts deposited in a temporary glacial lake formed by the

TABLE 38. — DEPTH AND CHARACTER OF BEDROCK IN MILLE LACS COUNTY

Location	Thickness of Drift (feet)	Character of Bedrock
Princeton	50	Sandstone
Princeton, 1 mile east	120	Sandstone
Sec. 9, T. 37 N., R. 27 W.	170	Red granite
Sec. 20, T. 37 N., R. 27 W.	56	Red granite
Sec. 21, T. 37 N., R. 27 W.	85	Mica schist
Sec. 26, T. 37 N., R. 27 W.	110	Granite
Sec. 18, T. 39 N., R. 27 W.	90	Granite
Sec. 26, T. 41 N., R. 25 W.	151	Granite
Sec. 5, T. 43 N., R. 25 W.	190	Granite
Estes Brook Store	40	Hornblende schist
Milaca	95	Mica schist
Isle Creamery	180	Granite
Wahkon	90	Granite
Wahkon, ½ mile south	24	Granite
Bayview, south shore Mille Lacs Lake	75	Granite

ponding of melt-waters at the margin of the ice. This lake, referred to as glacial Lake Grantsburg, extended as far north as Milaca. South of the lake sediments, outwash sands of the Anoka sand plain cover the red glacial till.

The drift varies in thickness from a few feet to more than 200 feet. Several wells east of Mille Lacs Lake terminate in the drift at a depth of 225 feet. Table 38 shows typical variations as reported by well drillers.

ROCK FORMATIONS

Pre-Cambrian

Granite rocks of pre-Cambrian age appear in outcrops at numerous places along the valley of the Rum River (Figure 30). They are most numerous in Onamia and Bradbury townships along Bradbury Brook and its tributaries. The most northerly outcrop on the Rum River is located a few miles south of Onamia in Sec. 18, T. 41 N., R. 27 W. From there southward low outcrops in the valley and on the floor of the channel may be found as far as Sec. 12, T. 40 N., R. 27 W. The rocks are granites, syenites, and biotite granite gneisses. The exposures along Bradbury Brook consist mainly of light-colored gray or brownish granite that is locally very gneissic.

West of Milaca along the West Branch Rum River a very coarse-grained, reddish granite, without much lithological variation, crops out in a number of low, glaciated ledges. This rock is very similar to that seen in outcrops in the eastern part of Benton and Morrison counties and is apparently a part of the same intrusive mass.

An isolated area of granite outcrops occurs about 4 miles south of Isle in Sec. 3, T. 41 N., R. 25 W. A quarry has been opened in the rock, which is light gray in color and of medium coarse-grained texture. Dikes and irregular masses of fine-grained aplite cut the gray granite. The fabricated rock is sold under the trade name of Cold Spring Pearl Gray Granite.

All the granitic rocks referred to above are described in greater detail by Harder and Johnson in Bulletin 15 of the Minnesota Geological Survey.

Low ledges of a basic, metamorphic rock crop out along a tributary of Estes Brook in Secs. 31 and 32, T. 37 N., R. 27 W., and in Sec. 6, T. 36 N., R. 27 W. The outcrops are scattered over an area of approximately one square mile. The rock is dense, massive hornblende and biotite schist. Its intense metamorphism suggests that it is of pre-Keweenawan age. Wells drilled to the northeast of this area have encountered the same type of rock at depths of from 50 to 125 feet.

Keweenawan sedimentary rocks are not known to crop out in Mille Lacs County, but red clastic sediments of the Fond du Lac beds are exposed along the Snake River in Kanabec County to the east and red paint rock is reported over granite and under white sandstone in a well in Princeton. The white sandstone is undoubtedly a southwestward ex-

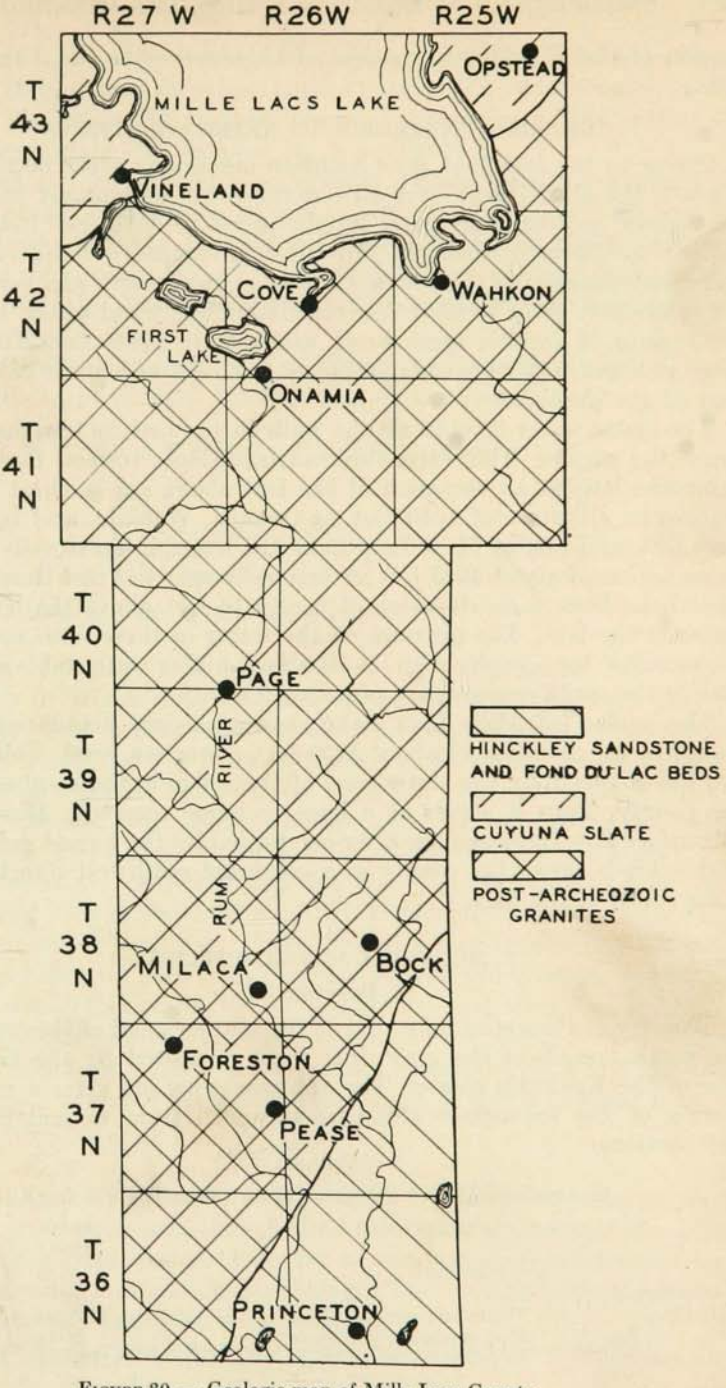

FIGURE 30. — Geologic map of Mille Lacs County.

tension of the Hinckley formation which overlies the red Fond du Lac beds.

GENERAL UNDERGROUND WATER CONDITIONS

Owing to the fact that pre-Cambrian crystalline rocks occur directly beneath the glacial drift over all but the southeasternmost township of the county, underground water supplies must be developed in the glacial sediments. However, since the drift sheet is composed of the red, sandy, and stony deposits of the Patrician glacier, its porosity and permeability are sufficiently great to allow free circulation of ground water. In some of the regions of granitic rocks south and east of Mille Lacs Lake, fairly large yields of water are obtained from fractures and joints in the upper part of the granite.

The static water level in all the wells in the drift is less than 50 feet below the surface. The water table surface slopes toward the south. At Princeton it is at an elevation of 945 feet above sea level, at Milaca it reaches an elevation of 1040 feet, at Onamia, Wahkon, and Isle it is at 1200 feet, and east of Mille Lacs Lake the water in open wells stands at an elevation of about 1225 feet. A few wells near the east shore of Mille Lacs Lake flow to an elevation of nearly 10 feet above the level of the water in the lake. The pressure on the water in these wells comes from the morainic topography with its attendant higher water table east of the lake in the southwestern part of Aitkin County.

The surface of Mille Lacs Lake shows seasonal fluctuations, but it stands at an elevation of about 1250 feet above sea level. This is about 300 feet higher than the static level of the water in the southern part of the county. Thus it serves as a huge recharge reservoir. However, the subsurface flow from this reservoir is retarded by the buried granite ridge that extends across the county in a northeast-southwest direction a few miles south of the lake.

MUNICIPAL WATER SUPPLIES

Princeton

The city of Princeton is located at the southern end of the county near the north margin of the gray drift sheet deposited by the Grantsburg lobe of the Keewatin glacier. The accompanying log gives a generalized section of the subsurface structure compiled from several incomplete well sections.

Generalized Log of Princeton Area (elevation 975 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–50	50
Pre-Cambrian			
Hinckley	White and pink sandstone	50–75	25
Fond du Lac	Red sandstone and shale	75–130	55
Algoman ?	Granite	130–275	145

The well that furnishes the public supply system is 10 inches in diameter and 273 feet deep. It terminates in granite. The static water level is about 30 feet below the surface. The well is pumped at the rate of 450 gallons per minute. No detailed log is available.

The well at the creamery is 4 inches in diameter and less than 50 feet deep. Its static level is also 30 feet below the surface. A well near the highway, owned by Mr. Leather, penetrated 50 feet of glacial drift over white and pink sandstone. At a depth of 75 feet the sandstone became very red and was interbedded with red shale (paint rock). Granite was encountered at a depth of 135 feet.

A farm well half a mile east of Princeton, between Silver Lake and the city limits, penetrated the following formations.

Farm Well Half a Mile East of Princeton*

		DEPTH (feet)	THICKNESS (feet)
Drift	Sand and gravel	0–25	25
	Blue clay	25–95	70
Pre-Cambrian	White and brown sandstone	95–130	45

* Data from George Smith, driller, Zimmerman.

Milaca

The city of Milaca uses shallow wells sunk into the alluvium near the Rum River. Test drilling indicates that the glacial drift is about 100 feet thick and is underlaid by gray crystalline rocks similar to the schists in the region of Onamia. The two city wells are 12 inches in diameter and from 25 to 30 feet deep. Each has been tested at 100 gallons per minute for 94 hours. The surface at the wells is 1045 feet above sea level.

The well at the creamery was dug 6 feet in diameter to a depth of 100 feet and then drilled at the bottom of the dug hole to a total depth of 125 feet, where hard gray, crystalline rock was encountered. A sandy gravel layer directly above the bedrock surface yields ample water. The static level is 30 feet below the surface or 1015 feet above sea level.

The Great Northern Railway Company uses water from the Rum River. A dam 5 feet high was constructed across the river and the channel above the dam was deepened by dredging. Water is pumped from the resulting reservoir.

Onamia

The village of Onamia is located in the Mille Lacs moraine of the Patrician ice sheet. Even though the topography is morainic the drift is not thick, for granitic rocks crop out at the surface about 2 miles south and also 2 miles northeast of the village. Test drilling indicates that the drift is about 115 feet thick in the village.

During the past ten years the village has drilled three wells, the deepest of which has been abandoned because of insufficient yield. The accompanying logs show the character of the drift and underlying rock formation.

Onamia Municipal Well No. 1, Drilled in 1935 (elevation 1250 feet)*

		DEPTH (feet)	THICKNESS (feet)
Drift	Sandy clay	0–2	2
	Stony gravel	2–19	17
	Sand and gravel	19–35	16
	Sticky brown clay	35–53	18
	Gray hardpan	53–84	31
	Quicksand	84–97	13
	Sand and gravel	97–103	6
	Hardpan	103–108	5
	Granite boulders	108–112	4
Pre-Cambrian	Decomposed granite	112–155	43

* Data from Druar and Milinowski, consulting engineers, St. Paul.

Onamia Municipal Well No. 2, Drilled in 1936 (elevation 1250 feet)*

		DEPTH (feet)	THICKNESS (feet)
Drift	Sandy clay	0–5	5
	Coarse gravel and sand	5–16	11
	Fine sand	16–19	3
	Gravel	19–22	3
	Brown clay	22–65	43

* Data from Druar and Milinowski, consulting engineers, St. Paul.

Well No. 2 is developed with a screen 10 inches in diameter and 11 feet in length. When not pumped the water stands 10 feet below the surface. When pumped at 78 gallons per minute it showed a drawdown of 28 feet, at 110 gallons per minute the drawdown was 35 feet, and at 120 gallons per minute the water was lowered 40 feet.

A third city well was drilled in 1942. It is 10 inches in diameter and 54 feet deep. Its static level is 11 feet below the surface and when pumped at the rate of 50 gallons per minute it has a drawdown of 12 feet.[1]

Isle

The village of Isle is located on one of the southeastern bays of Mille Lacs Lake. This area also is underlaid by granite which crops out and is quarried a few miles south of the village. Thus all underground water supplies must be obtained from the drift or from the thin zone of decomposed or fractured granite directly beneath the drift.

The public water supply is taken from a well 10 inches in diameter and 165 feet deep. Its static level is 18 feet below the surface and when pumped at the rate of 75 gallons per minute it showed a drawdown of 120 feet. The following log shows the character of the glacial drift.

[1] Data from the Layne-Western Well Company, Minneapolis.

Village Well at Isle, Drilled in 1936 (elevation 1240 feet)*

		DEPTH (feet)	THICKNESS (feet)
Drift	Clay	0–8	8
	Sand	8–18	10
	Clay	18–40	22
	Stony clay	40–50	10
	Sandy clay	50–138	88
	Sand	138–145	7
	Blue clay	145–155	10
	Sand (water-bearing)	155–159	4
Pre-Cambrian	Decomposed granite	159–161	2
	Hard granite	161–165	4

* Compiled by Druar and Milinowski, consulting engineers, St. Paul.

The creamery well at Isle is 8 inches in diameter and 198 feet deep. It penetrates 180 feet of drift and 18 feet of granite. The static level is 20 feet below the surface. Water enters the well from fractures in the granite.

Wahkon

The village well in Wahkon is 8 inches in diameter and 98 feet deep. It encountered granite at a depth of 92 feet. The static water level is 32 feet below the surface, and when pumped at the rate of 50 gallons per minute it showed a drawdown of 3 feet.

A dug well at the public school is 4 feet in diameter and 70 feet deep. The water in a sand and gravel bed at a depth of 70 feet rose to a static level of 30 feet below the surface.

A private well at the stone fabricating plant is 98 feet deep. It penetrated 90 feet of glacial drift and 8 feet of granite. Water enters the well from fractures in the upper part of the granite. A farm well half a mile south of the village entered granite at a depth of 21 feet. Ample water for farm purposes seeps from fractures in the granite.

FARM WATER SUPPLIES

The farm wells are of four types — driven, dug, bored, and drilled. Where the drift is thin and contains few pockets or lenses of sand and gravel, many of the wells are dug to a depth of 20 or 30 feet below the water table. This insures a large underground storage reservoir. Such wells have a rapid drawdown, but if the volume of water required is not great, satisfactory supplies may be obtained.

In the sand and gravel outwash areas many driven wells are still in use. Such wells are of small diameter, and where the water is hard the screened points soon become clogged with calcium carbonate and other encrustants.

The presence of a thick deposit of drift does not insure a large yield of underground water. In some localities where the glacial deposits are more than 100 feet thick, they are composed of such impervious boulder clay that their specific yield is very low. A typical example is seen in the

TABLE 39. — ANALYSES OF WATERS OF MILLE LACS COUNTY *

	1	2	3	4	5	6	7	8	9	10
Depth (feet)	...	20	...	...	...	180	300	69	55	166
Hardness	114	433	200	250	250	190	250	190	160	180
Alkalinity	128	246	138	228	220	188	180	150	140	210
Iron	.6	.4	.3	.5	.22	.8	0	.65	.3	.8
Manganese	...	...	.15	1.6	.24	...	0	.3	.15	.2
Chlorine	0	103.8	42	7.5	28	0	46	1.3	15	1.1
Fluorine	...	...	.15	0	.1	...	.2	...	.1	...
SO_4 radical	...	...	4.8	4.8	15	...	48	...	46	15
Turbidity	10	25	7	1	...	20	.2	.8	4	4
Color	85	11	17	20	...	140	2	20	68	20
Odor	e–1	e–1	...	...	...	0	...	...	...	...
pH value	...	...	7.9	7.3	7.2	...	8.0	8.1	7.4	...

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Rum River, Milaca, 1923.
2. Milaca, dug well, 1926.
3. Milaca, No. 1, 1938.
4. Milaca, No. 3, 1938.
5. Milaca, No. 4, drilled well, 1943.
6. Princeton, drilled well, 1918.
7. Princeton, drilled well, 1942.
8. Onamia, drilled well, 1936.
9. Onamia, new well, 1942.
10. Isle, village well, 1942.

well drilled by Berg Brothers on the farm of Mr. Bergstrom in the NE¼, Sec. 26, T. 41 N., R. 25 W. The well penetrated 151 feet of boulder clay which rested on massive granite. Even though the drill hole was blasted with 15 charges of dynamite, it could not be developed into a satisfactory well.

The opposite condition prevails in East Side Township (T. 43 N., R. 25 W.). There the confined water in a number of farm wells is under sufficient pressure to bring the water to and above the surface. This condition is illustrated by a well north of Port Royal in Sec. 5, T. 43 N., R. 25 W. The well penetrates 190 feet of drift and terminates on the top of the bedrock. Its static level is 7 feet below the surface.

The accompanying logs of farm wells are typical of underground conditions in various parts of the county.

Farm Well, Sec. 9, T. 37 N., R. 27 W., Owner, J. C. Roehl*

		DEPTH (feet)	THICKNESS (feet)
Drift	Yellow clay	0–58	58
	Gray, sticky clay	58–123	65
	Blue clay	123–138	15
	Red clay	138–146	8
	Hard white sand	146–172	26
Pre-Cambrian	Red granite	172–173	1

* Data from Mr. Jamison, driller, Bock.

Farm Well, Sec. 22, T. 38 N., R. 26 W. (elevation 1080 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Yellowish clay	0–40	40
	Bouldery gravel	40–60	20
	Blue clay	60–90	30
	Sand (water-bearing)	90–94	4

Farm Well, Sec. 18, T. 39 N., R. 27 W.

		DEPTH (feet)	THICKNESS (feet)
Drift	Bouldery clay	0–90	90
	Sand	90–100	10
Pre-Cambrian	Granite	entered	

EASTERN MORRISON COUNTY

SURFACE FEATURES

Morrison County is near the central part of Minnesota. The Mississippi River crosses the county from north to south a little west of the center. This report deals with only the part of the county that lies east of the river.[1] These eastern townships are for the most part a red drift till plain with a wide zone of outwash sediments over the till in the townships along the Mississippi River. A narrow strip of morainic topography crosses the county from north to south near the eastern boundary, and a less rugged moraine extends from a few miles east of Little Falls in a northeasterly direction and joins the Mille Lacs moraine in the northeasternmost township (T. 42 N., R. 28 W.) of the county.

Most of the drainage is southwestward through the Platte River and its tributaries and thence into the Mississippi south of Royalton. The headwaters of the Little Rock River drain the southeasternmost townships, and short tributaries of the Mississippi River drain the area south of Fort Ripley.

The outwash area along the Mississippi is about 1100 feet above sea level and the till plain to the east stands about 100 feet higher. In the morainic zones east of the Platte River many of the ridges are 1300 feet above sea level. The highest points are found in Hillman Township (T. 40 N., R. 29 W.), where some of the moraine reaches an elevation of 1350 feet.

UNCONSOLIDATED SURFACE MANTLE

All of Morrison County has a mantle of red drift that was deposited at the western margin of the Patrician glacier of middle Wisconsin age. The red color is due principally to iron minerals derived from ferruginous sandstones and iron formations over which the glacier passed. Over most of the county an older gray glacial till occurs beneath the red drift. This old gray drift was brought in from the northwest by a glacier from the Keewatin center of glaciation located west of Hudson Bay.

In the morainic zones the drift is prevailingly sandy, although some portions of it contain much clay. The till plains are mainly clayey drift, whereas the outwash areas are predominantly sand and gravel.

The drift varies in thickness from 0 to 250 feet. In the areas of exposures of bedrock in the central part of the county, the drift is locally very thin, but owing to the irregularity of the top of the granite it may thicken as much as 100 feet in a short distance horizontally. Such variations indicate that the surface of the rock is characterized by knobs and hollows with a relief of nearly 100 feet. The data on depth to bedrock given in Table 40 are typical of the south-central part of the county.

[1] The geology and underground water conditions of that portion of Morrison County west of the Mississippi River are reported by I. S. Allison in Bulletin 22 of the Minnesota Geological Survey, pages 128–135.

TABLE 40. — THICKNESS OF THE GLACIAL DRIFT IN SOUTH-CENTRAL MORRISON COUNTY

Location	Depth to Bedrock (feet)
Sec. 36, T. 40 N., R. 32 W.	158
Sec. 8, T. 40 N., R. 29 W.	35
Sec. 8, T. 39 N., R. 32 W.	178
Sec. 21, T. 39 N., R. 31 W.	145
Sec. 8, T. 39 N., R. 31 W.	200

ROCK FORMATIONS

PRE-CAMBRIAN

There are many exposures of pre-Cambrian formations in Morrison County, where they are represented by a great variety of rocks (Figure 31). Slates, schist, and other metamorphic rocks are intruded by both acidic and basic igneous masses. These rocks have been mapped by Harder and Johnston and their descriptions of the outcrops follows. Petrographic detail has been omitted.

"In Morrison County outcrops of silicic igneous rocks are abundant, especially in the central and eastern part, east of Mississippi River. The principal exposures occur in an area approximately 18 miles long, east and west, and 12 miles wide north and south, but small isolated outcrops are found outside of this area.

"Several small exposures of medium to coarse-grained syenite are found on the east bank of Mississippi River in Little Falls, about a quarter of a mile below the dam and approximately opposite the lower part of the island which occurs in the river at this place. The rock consists of hornblende and feldspar. . . . The occurrence of this igneous rock within a short distance of the slate and phyllite outcrops at the dam and on the island would seem to indicate that it is intrusive into the sedimentary rocks. No actual contacts, however, have been found.

"An important group of granite and gneiss outcrops is that occurring in the eastern part of Morrison County on Platte River, Skunk River, and Hillman Creek. In general these are of gray and pink biotite and hornblende granites, locally somewhat gneissoid in texture. A few outcrops of banded gneiss are found.

"The northernmost of these outcrops is a group of exposures occurring on both sides of the east-west township road between section 34, T. 42N., R. 31W., and section 3, T. 41N., R. 31W. Two types of granite occur in these exposures, a medium fine-grained grayish brown or brown decomposed biotite granite, considerably epidotized, and a grayish pink or pink hornblende granite. The former has a fairly uniform grain, but the latter varies in texture from fine-grained to very coarse-grained, almost pegmatitic, and also shows porphyritic phases. The hornblende granite appears to be intrusive in the biotite granite.

"In the northwest corner of section 1, T. 41N., R. 31W., and the

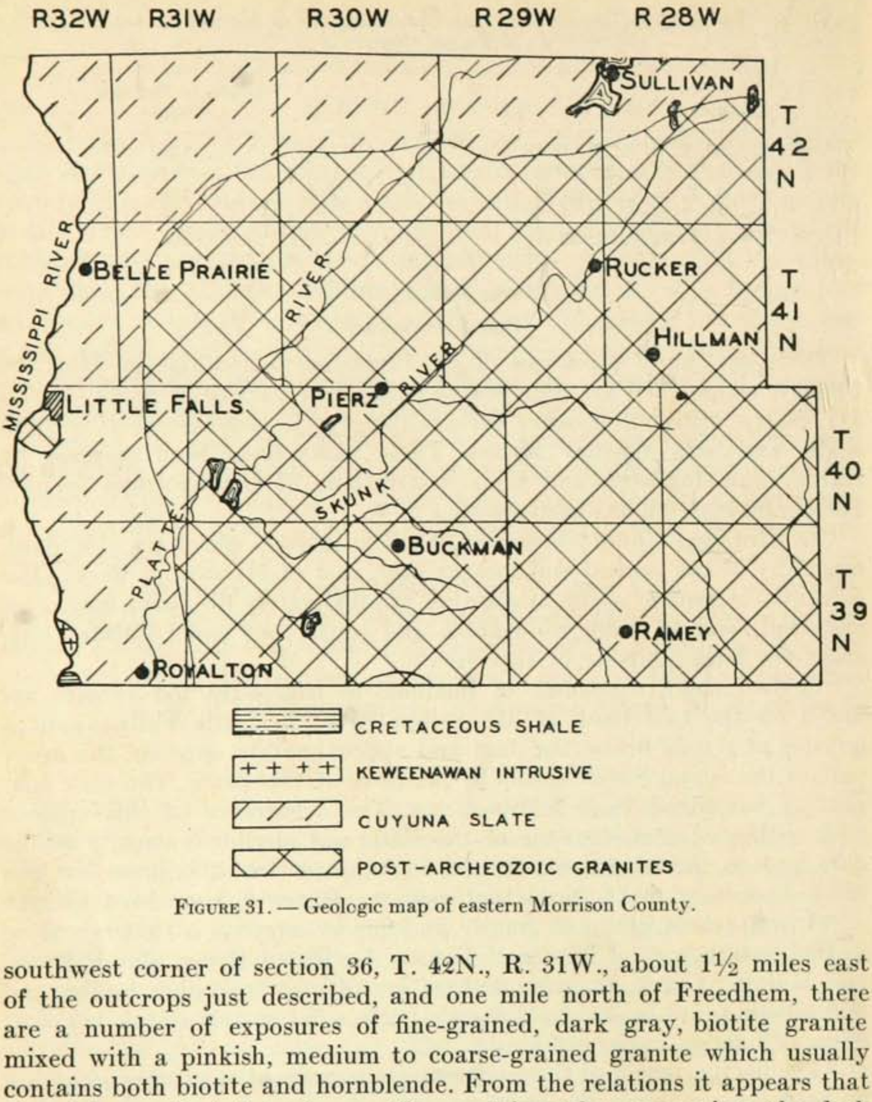

FIGURE 31. — Geologic map of eastern Morrison County.

southwest corner of section 36, T. 42N., R. 31W., about 1½ miles east of the outcrops just described, and one mile north of Freedhem, there are a number of exposures of fine-grained, dark gray, biotite granite mixed with a pinkish, medium to coarse-grained granite which usually contains both biotite and hornblende. From the relations it appears that the pink granite is intrusive as dikes and irregular masses into the dark gray granite which is by far the more abundant. The pink granite contains much pink feldspar while the dark gray granite is rich in quartz and biotite. The rocks crop out in a swamp both north and south of the township road.

"Near the center of section 6, T. 41N., R. 30W, about 1½ miles south of east from the outcrops just described, are a few scattered outcrops consisting principally of fine to medium-grained, dark gray biotite granite, rich in quartz, which is intruded by dikes of coarse-grained, pink biotite granite. In general the rocks resemble those occurring one mile north of Freedhem. . . .

"A group of exposures of considerable extent occurs north and south of the section line between sections 7 and 18, T. 41N., R. 30W., some distance east of the quarter post. It is located about 1½ miles south of the outcrops in section 6. Two kinds of rock are present, (1) a dark gray, fine to medium-grained biotite granite, and (2) a medium to coarse-grained pink biotite granite. There is a sharp line of division between these two types marked approximately by a diagonal road which cuts across the two sections in a northeast-southwest direction. To the southeast of the road the outcrops are of pink granite, while to the northwest they are of dark gray granite. The pink granite is found also as small irregular intrusions in the gray granite. A small quarry occurs in the area of the gray granite. . . .

"In sections 23 and 24, T. 41N., R. 31W., about 1½ miles north of the locality known as Gravelville, and about 2 miles southwest of the outcrops just described, a large number of granite exposures occur in an area of about one square mile. The principal exposures form a prominent ridge surrounded on three sides by low marshy areas. Some smaller exposures occur within the marshy areas. Several types of granite are present, the principal one being a dark gray, medium-grained granite with abundant hornblende and considerable biotite. Next to this in abundance is a coarse pink biotite granite which seems to be intrusive into the hornblende granite, but which since intrusion has suffered deformation. Besides these types a fine-grained black granite occurs which contains both hornblende and biotite, the former epidotized, while a fourth type consists of fine-grained pink biotite granite, in places porphyritic. These various types are irregularly intermixed and grade into each other. The medium-grained, dark gray hornblende granite is much more abundant than the other phases. At one point a small quarry occurs in it and here the rock is quite fresh, showing only a slight alteration of the ferromagnesian minerals to epidote and chlorite. The pink granites appear to be intrusive into it, although the occurrence is very irregular. The coarse and fine-grained varieties of pink granite have a similar mineral composition and are probably phases of the same rock. . . .

"A considerable number of outcrops of silicic igneous rocks occur on Skunk River and Hillman Creek, east of Little Falls. The area through which the outcrops are scattered is about 15 miles long in a northeast-southwest direction, and about 6 miles wide. The town of Pierz is in the southwestern part of the area. Most of the outcrops occur on the streams or within a short distance from them. As a rule the rocks do not rise far above the surface of the soil and in a few localities they have been exposed only by quarrying.

"The westernmost of these outcrops is at Meyer's quarry south of Fish Lake and about a mile west of the station of New Pierz. A very uniform, fine-grained, light gray, biotite granite occurs here and some of it has been quarried. There are no outcrops other than those in the quarry.

"Several other granite outcrops are found not far from the village of Pierz, one occurring on Skunk River near the station of New Pierz, another one near the junction of Hillman Creek with Skunk River east of Pierz, and a third one along the Minneapolis, St. Paul, and Sault Ste. Marie railroad, about 2½ miles east-northeast of the station of New Pierz.

"The first of these is an outcrop of medium-coarse, light gray, biotite granite, about 50 feet long, and 60 feet wide. It is situated about a fifth of a mile southeast of the railroad station on the east bank of Skunk River.

"The second outcrop is located on the south side of Skunk River about a fourth of a mile above the mouth of Hillman Creek. Several exposures of gray, banded biotite gneiss are found here. Most of the rock is fine-grained and dark, but layers of coarse-grained, light-colored rock occur interbanded with the fine-grained rock. Disseminated crystals of garnet similar to those occurring in the gneiss at Granite City, farther up Skunk River, are abundant. At one point a dike of medium coarse-grained pink syenite cuts the gneiss.

"The third one of the outcrops near Pierz occurs in a railroad cut near the west side of section 10, T. 40N., R. 30W. The rock is mainly light to dark gray, medium coarse-grained biotite granite. Locally it shows a marked gneissoid texture due to the parallel arrangement of biotite flakes and their segregation along certain bands. Small dikes of light-colored aplite cut the granite. . . .

"About 8 miles up Skunk River, northeast of Pierz, is a locality known as Granite City. . . . Outcrops of coarse-grained gray granite and of gray and white banded gneiss occur at this place on both sides of the river. The granite contains quartz, biotite, and white feldspar in approximately equal amounts. Locally the feldspar predominates, however, and occurs in somewhat larger grains, so that it gives the rock a porphyritic appearance. . . .

"In the NE¼ of the SW¼ of section 11, T. 41N., R. 29W., about 3 miles northeast of the Granite City locality just described, a small outcrop of granite occurs in the road. The rock consists of fine to coarse-grained gray biotite granite similar to that at Granite City, and contains a few small lenses of pegmatitic material. No gneiss occurs in this outcrop.

"In the SW¼ of section 12, T. 41N., R. 29W., at a locality known as Rucker, several small outcrops of rock are found along the west side of

Skunk River. Most of the exposures consist of a dark lavender or greenish gray hornblende rock. . . .

"A small knoll consisting of gray and pink granite occurs on the north side of Little Skunk River near the east side of section 6, T. 41N., R. 28W., about 2 miles above Rucker. The gray granite is a coarse-grained biotite granite, similar in appearance to that at Granite City. It contains frequent scattered crystals of hornblende, some of them more than half an inch long. The pink granite varies in texture and composition. Some phases of it are coarse-grained and almost free from ferromagnesian minerals, while other phases are medium-grained and contain abundant scattered biotite. . . .

"Several other rock outcrops occur on Little Skunk River and on the upper portion of Skunk River, both in section 6, T. 41N., R. 28W., and in section 1, T. 41N., R. 29W. One of the larger ones of these is found near the center of section 1 and consists of granite. Another one is mapped by Upham[2] as occurring along the northern boundary of section 6. The latter, however, could not be found and has probably been confused with the outcrop at Rucker as is indicated by the description.

"An interesting group of exposures of various kinds of granite is found along Hillman Creek and Little Hillman Creek in an area about 3 miles long east and west, and about 1 mile wide. The westernmost of these outcrops occur about 4½ miles east of Pierz in the eastern part of section 7 and western part of section 8, T. 40N., R. 29W. They form an elevation along the north side of Hillman Creek and consist of coarse gray biotite granite which is intruded by medium-grained pink biotite granite. The gray granite locally is porphyritic and contains conspicuous crystals of white feldspar, but for the most part it is even-grained. The pink granite shows pegmatitic facies locally, while elsewhere it is intruded as narrow dikes and is fine-grained.

"In the northeastern part of section 8, fine-grained pink and dark gray granites are intruded into coarse pinkish gray granite. The Minneapolis, St. Paul, and Sault Ste. Marie railroad cuts through two of the outcrops and two small quarries occur in them, one to the north and one to the south of the railroad. The fine-grained pink granite consists mainly of pink feldspar and quartz, but biotite and hornblende occur scattered through it. . . .

"Farther up Hillman Creek, in section 35, T. 41N., R. 29W., about a mile above the locality just described, are the remains of an old logging dam. At this place a large number of outcrops occur on both sides of the Creek and extend for some distance to the north. The Minneapolis, St. Paul, and Sault Ste. Marie railroad has cut through one of the larger outcrops. Most of the exposures south of the creek consist

[2] Upham, Warren, The geology of Crow Wing and Morrison counties: Geol. and Nat. Hist. Survey of Minn., Geol. of Minn., vol. 2, 1882–5, Pl. 53 and p. 592.

of coarse-grained gray granite with some gneissic phases, while those to the north are mainly fine-grained pink granite. . . .

"On Little Hillman Creek in section 9, T. 40N., R. 29W., about a mile east of the outcrops in sections 7 and 8, there is another group of exposures of gray and pink granite. The principal rock is a coarse-grained biotite granite, in general having a gray appearance, but in places containing pink feldspar in abundance. This rock is intruded by dikes of fine-grained light gray and dark gray granite and fine-grained white to pink aplite. . . .

"A few small outcrops consisting mainly of very coarse-grained pink biotite granite are found near the west side of section 18, T. 39N., R. 30W., about three miles southwest of Buckman. They occur in a barnyard a short distance from the north-south township road. The rock is considerably weathered and friable. It contains inclusions of a fine-grained dark gray rock. One of the outcrops consists of fresh pink granite with texture varying from fine-grained to coarse-grained in different parts. . . .

"Several exposures of subsilicic and intermediate igneous rock are found in the vicinity of Little Falls, Morrison County. One of these is at Williams' quarry in the northeast quarter of section 13, T. 129N., R. 30W., about a mile northeast of Little Falls. The rock varies greatly in texture at different points in the quarry. Some of it is dense and fine-grained and has a uniform dark gray color, while other phases are coarser grained and have a speckled appearance due to intermixed light and dark-colored minerals. The latter vary considerably in size of grain, as well as in color. In some, feldspars predominate; in others, ferromagnesian minerals. The various rocks have a fairly uniform mineral composition, except that the coarser grained varieties have suffered greater alteration.

"The diorite at Williams' quarry and the syenite occurring on the east bank of Mississippi River at Little Falls, are within a region in which slate and schist of sedimentary origin predominate. As the metamorphosed sediments have a fairly definite and regular structure throughout, it would seem that the igneous rocks are probably intrusive into them, although contacts between them have not been found.

"An outcrop of hard, dark rock occurs on the west bank of Mississippi River about three-quarters of a mile below the bridge of the Minneapolis, St. Paul, and Sault Ste. Marie Railroad, in section 32, T. 128N., R. 29W. It forms rapids in the river, known as Blanchard's Rapids, and outcrops of it are found on the east bank also. The rock is medium coarse grained and contains abundant pyroxene and calcic feldspar with locally phlogopite. It resembles gabbro in composition. Only a short distance above these outcrops, along the river bank, are exposures of staurolitic and garnetiferous biotite schist which are apparently the southernmost outcrops of these rocks on Mississippi River.

The relation of the schist to the igneous rock could not be definitely determined. Judging from the fact, however, that the cleavage of the schist strikes in the direction of the gabbro it would seem that the latter is intrusive, as is the case with the other subsilicic or dark igneous rocks in the vicinity of Little Falls." [3]

The surface of the pre-Cambrian rock slopes toward the south. Where the Mississippi River leaves the county they stand about 1030 feet above sea level. The southernmost outcrops are at an elevation of about 1050 feet. At Little Falls the outcrops rise to nearly 1100 feet and still farther north, in Sec. 34, T. 42 N., R. 31 W., the exposures of granite reach an elevation of 1250 feet. The highest outcrop of the surface occurs near Hillman, where the rocks stand more than 1300 feet above sea level.

TABLE 41. — ELEVATION OF BEDROCK SURFACE, EASTERN MORRISON COUNTY

Location	Elevation (feet)
Sec. 34, T. 42 N., R. 31 W.	1245
Sec. 28, T. 41 N., R. 28 W.	1300
Sec. 21, T. 41 N., R. 29 W.	1225
Sec. 23, T. 41 N., R. 31 W.	1215
Sec. 8, T. 41 N., R. 30 W.	1250
Sec. 13, T. 40 N., R. 31 W.	1160
Sec. 9, T. 40 N., R. 30 W.	1155
Sec. 8, T. 40 N., R. 29 W.	1270
Sec. 29, T. 39 N., R. 32 W.	1050

CRETACEOUS SYSTEM

No sediments of known Cretaceous age have been penetrated by wells in eastern Morrison County, but fossil-bearing, marine sediments are exposed along the west side of the Mississippi River just above the mouth of Two Rivers in T. 127 N., R. 29 W. Upham reported the presence of Mosasaur teeth and other fossils which indicate that the rocks are of Cretaceous age.[4]

Much of the material at this locality consists of unconsolidated or slightly consolidated gray clay which is locally stained yellow and brown with iron oxide. In some places it has many small concretions or pisolites that are so abundant as to make up most of the rock. Where the rock is iron-stained the concretions are dark brown. Elsewhere they are green or gray. Black shales and thin seams of lignite occur near the base of the exposures.

The total thickness exposed is only a few feet and the data available are not sufficient to indicate the horizontal extent of the sediments.

[3] Harder, E. C., and Johnston, A. W., The geology of east-central Minnesota: Minn. Geol. Survey Bull. 15, pp. 32–38, 50–52, 1918.

[4] Winchell, N. H., The geology of Minnesota: Final Rept., Minn. Geol. and Nat. Hist. Survey, vol. 2, pp. 601–603, 1888.

Since no wells are known to penetrate them, it is probable that they represent a remnant or outlier. The absence of sandstone strata in the clays suggests that no water is to be expected from them.

GENERAL UNDERGROUND WATER CONDITIONS

The yield of water is adequate where the drift is thick, but where the granites and related crystalline rocks are encountered at less than 50 feet below the surface there is less possibility of finding sand and gravel layers. In some localities several wells have had to be drilled before the desired amount of water could be obtained. However, owing to the youthful topography of the till plain, large areas are poorly drained; consequently the regional water table is near the surface and shallow wells often yield adequate supplies.

In the zone of outwash sediments along the Mississippi River the shallow dug, drilled, and driven wells produce freely, but if a large volume of water is required, a group of wells may be necessary to yield the quantity needed. These wells should not be placed too close together, in order to avoid interference. The dams at Little Falls and at Blanchard hold the level of the Mississippi River at 1107 and 1082 feet above sea level, respectively. These pools prevent the seasonal fluctuation of the water level in shallow wells near the valley.

MUNICIPAL WATER SUPPLIES

Little Falls

The city of Little Falls is situated on the Mississippi River in the west-central part of Morrison County. In this region the crystalline bedrock is covered with less than 50 feet of drift and alluvium. Consequently an underground water supply must be obtained from very shallow wells. The city has eleven wells: five are located between the pumphouse and the highway, and six are east of the pumphouse, which is located between Seventh and Eighth avenues northeast near the bank of the Mississippi River. The two groups are about 200 feet apart and the wells in each group are spaced at intervals of about 150 feet. All the wells are 12 inches in diameter. Those of the west group are from 76 to 108 feet deep, whereas the six wells of the east group are all less than 50 feet in depth. In this area bedrock is encountered at a depth of about 47 feet and is overlaid by sand and gravel. Neither of the wells in the western group reached the bedrock surface. Here also the glacial sediments are predominantly outwash sands and gravel. The wells are connected with one pump for each group. Those of the east group produce 650 gallons per minute, and the west group is pumped at the rate of 500 gallons per minute. The static level of all the wells is about 16 feet below the surface.

The water is high in iron and manganese and precautions must be taken to prevent the accumulation of the brown and black oxides of the metals in the storage tank and the water mains.

At numerous places in the southern part of the city the slates, schists, and other crystalline rocks occur at depths of 12 to 20 feet below the surface, and no satisfactory supplies of water can be obtained. Along the east edge of the city the drift is about 50 feet thick and satisfactory supplies of water for domestic use may be secured from dug wells. Drilled wells of small diameter produce only enough for the most restricted requirements.

Some water may be obtained from the fractures in the upper part of the slate. The accompanying log is typical.

Northern Pacific Railway Company Well, Little Falls (elevation 1111 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–12	12
Pre-Cambrian	Slate	12–51	39

The static level is 8 feet below the surface.

Royalton

The village of Royalton is located at the southern boundary of the county about 2 miles east of the Mississippi River. In this vicinity the upper surface of slates and schists is capped by a layer of clayey residues produced by the weathering of the rocks. These products of decomposition lie about 150 feet below the surface.

The water for the public supply system of the village is taken from a well 110 feet deep that penetrated 50 feet of alluvial sands and gravel and terminated in glacial till. No bedrock was encountered. The static level is 30 feet below the surface or at an elevation of 1055 feet above sea level.

The well at the depot is 35 feet deep and ends in alluvial sands. The static level is 25 feet below the surface.

A farm well 3 miles northeast of the village in Sec. 21, T. 39 N., R. 31 W., penetrated 145 feet of impervious glacial till and 48 feet of decomposed slates and schist. No satisfactory supply of water could be developed.[5]

Pierz

The village of Pierz is situated 12 miles due east of Little Falls. In and near the village many wells are no more than 35 to 40 feet deep. In this area the granite surface is very irregular. A short distance east of the village the rock crops out at an elevation of 1155 feet above sea level, and a few miles to the south a well 175 feet deep did not reach the granite.

A private well in the northern part of the village is typical.

[5] Data from Mr. Thelen, driller, Royalton.

Well in North Part of Pierz

		DEPTH (feet)	THICKNESS (feet)
Drift	Stony sand and gravel	0–21	21
	Bluish-gray till	21–39	18
	Sand and gravel	39–42	3

Buckman

Buckman is an inland village located 7 miles due south of Pierz. There is no public water supply system for the village and private wells are drilled as much as 200 feet deep without encountering bedrock. The sandy red drift is thick and gives up its water freely.

Center Valley

The creamery well at this village is dug to a depth of 35 feet, where it terminates on the granite surface. Wells of small diameter are not satisfactory, but most dug wells 4 feet or more in diameter give ample supplies for domestic use and for small industries.

Vawter

This village has no public water supply system. Private wells obtain their water from sandy layers in the drift. In this area a whitish clay and decomposed slate are encountered beneath the glacial deposits. Fractures in the slate may yield sufficient water for restricted use. The accompanying well section is typical.

Farm Well, Sec. 36, T. 40 N., R. 32 W., Owner, Richard Dixon

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–110	110
Pre-Cambrian	Decomposed slate	110–158	48

Similar decomposed rock was encountered in test drilling for foundations at the bridge of the Soo Line Railway over the Mississippi River southwest of Vawter. There 20 feet of hard blue clay on the floor of the river is underlaid by 10 to 20 feet of decomposed schist.

Gregory

The village of Gregory has no public water supply system. The subsurface geological relations in this vicinity are similar to those at Vawter and Royalton.

FARM WATER SUPPLIES

Logs of farm wells are given with the reports on individual municipalities, and the general underground water conditions are outlined above.

TABLE 42. — ANALYSES OF WATERS OF MORRISON COUNTY *

	1	2	3	4	5	6	7	8	9	10
Depth (feet)	60	35	...	...	...	...	...	80	110	110
Hardness	245	210	238	260	260	190	208	200	172	190
Alkalinity	252	240	239	280	280	210	160	150	200	210
Iron	2.4	.4	.8	7	7.5	6	.1	0	tr.	.55
Manganese	...	...	2	2.5	2.5	1.4	...	0	...	.44
Chlorine	1	2	...	...	...	1.7	...	39.8	1	3.4
Fluorine	...	...	...	...	...	.1	...	0	...	0
SO_4 radical	...	...	...	...	...	18	...	30	...	4.9
Turbidity	35	10	2	24	70	40	3	2	3	4
Color	45	10	20	40	40	80	10	7	2	3
Odor	a–1	...	0	...	...	...	0	...	e–1	H_2S
pH value	...	...	7.2	7.3	7.3	7.6	...	8	...	7.8

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Little Falls, 2 drilled wells, 1924.
2. Little Falls, 6 shallow wells, depths 99½ feet, 87 feet, 108 feet, 88½ feet, 104 feet, 35 feet, 1926.
3. Little Falls, 6 shallow wells, 5 drilled 74 feet to 108 feet, 1932.
4. Little Falls, pump, 11 drilled wells, 1934.
5. Little Falls, distributing system, 11 drilled wells, 1934.
6. Little Falls, Mississippi River, 1943.
7. Buckman, dug well, 1924.
8. Buckman, dug well, 1940.
9. Royalton, drilled well, 1923.
10. Royalton, drilled well, 1943.

PINE COUNTY

SURFACE FEATURES

Pine County is located east of Aitkin and Kanabec counties and south of Carlton County. The St. Croix River forms most of its eastern boundary and the surface is cut by a number of deep tributary valleys formed by the drainage of glacial lakes. Its maximum relief is more than 500 feet, with the lowest point at an elevation of less than 800 feet in the southeastern corner of the county on the floor of the St. Croix valley, and the highest points reaching an elevation of 1300 feet above sea level in the morainic hills of the northwesternmost township. The Kettle River crosses most of the county from north to south, and where it flows over the Hinckley sandstone from Willow River southward toward Hinckley it descends in a deep and picturesque gorge and cascades over rocky ledges. From a few miles east of Hinckley southeastward to the St. Croix valley, the Kettle River has cut its channel in basaltic lava flows. The river has a steep gradient, descending more than 250 feet in its course across the county. The Snake River crosses the southern part of the county from west to east, and it likewise has a steep gradient with numerous rapids from Cross Lake at Pine City eastward to the St. Croix River.

The smaller tributaries of the St. Croix to the east of the Kettle River show a pattern influenced by drainage from the south margin of the Superior lobe of the late Wisconsin glacier. This is true especially of the Tamarack River and its tributaries. The high gradients of all the rivers in the southeastern part of the county are due to the great depth of the St. Croix valley. This valley was deepened by the southward drainage of glacial Lake Duluth when it spilled over the continental divide south of Lake Superior and had its outlet by way of the Brulé-St. Croix valley through Wisconsin and thence southward to the Mississippi valley near Hastings.

Pine County is somewhat unique in that three different glaciers, each during the Wisconsin stage of glaciation, encroached upon its surface. The Patrician glacier covered most of the county, the Keewatin (Mankato) ice sheet covered a few townships at the southern end, and the Superior lobe covered a narrow strip along the northern border of the county.

The deposits of each of these ice sheets modified the topography, but the most conspicuous moraine is the red Patrician drift that enters the county northwest of Pine City and extends northeastward into the northeasternmost township. Several moraines left by the Superior lobe cross the most northern row of townships, but the morainic topography has been modified by outwash along the Kettle River south of Moose Lake and southward beyond Willow River.

UNCONSOLIDATED SURFACE MANTLE

Owing to the fact that three different ice sheets covered parts of Pine County, a variety of glacial deposits may be expected. In the townships south of Pine City gray Keewatin drift deposited by the Grantsburg lobe rests on red Patrician till. In the northernmost row of townships, to the north of the Willow River, the Patrician till is overlain by the youngest and least altered drift in the state, the red drift deposited by the Superior lobe of late Wisconsin age.

The drift is not as thick as in most of the region to the west, averaging about 75 feet for the county as a whole. Locally large areas are covered with thick deposits of outwash sands and gravels. These sediments were deposited by streams from the margin of the ice that formed delta-like plains. These have been cut into by the postglacial drainage courses, leaving the terraces that bound most of the valleys. Such terrace sediments are saturated with water which they yield freely to shallow dug and driven wells.

Thick beds of peat once covered the large swampy areas in the northwestern townships, but the great Hinckley fire some years ago swept large tracts in that region, and as a result the peat beds were burned, leaving the glacial till exposed.

ROCK FORMATIONS

The three major streams of Pine County have cut deeply into the bedrock surface and consequently there are many rock exposures along the walls of the valleys (Figure 32). In the northwestern corner of the county ancient igneous and metamorphic rocks rise in rough knobs 40 to 75 feet above the surrounding drift surface.

PRE-CAMBRIAN

The oldest pre-Cambrian rocks are the granites, schist, and slates in Birch Creek Township in the region of Denham. These have been described by Harder and Johnston. The following locations contain the most important outcrops.

"About 2 miles west of Denham a rock cut along the railroad in section 21 T. 45N., R. 21W., Pine County, shows dark-colored, schistose gneiss. The degree of metamorphism varies in different parts so that in places the rock is a perfect schist, finely laminated, consisting largely of biotite, while elsewhere it is more massive and contains abundant feldspar and quartz. . . .

"About 1¼ miles south of the locality just described, on the north and south road between sections 33 and 34, T. 45N., R. 21W., pink augen-gneiss similar to that at McGrath, outcrops at several places while a mile further south between sections 3 and 4, T. 44N., R. 21W., other exposures of the same type of rock are found. In the latter locality the gneiss shows a considerable amount of muscovite.

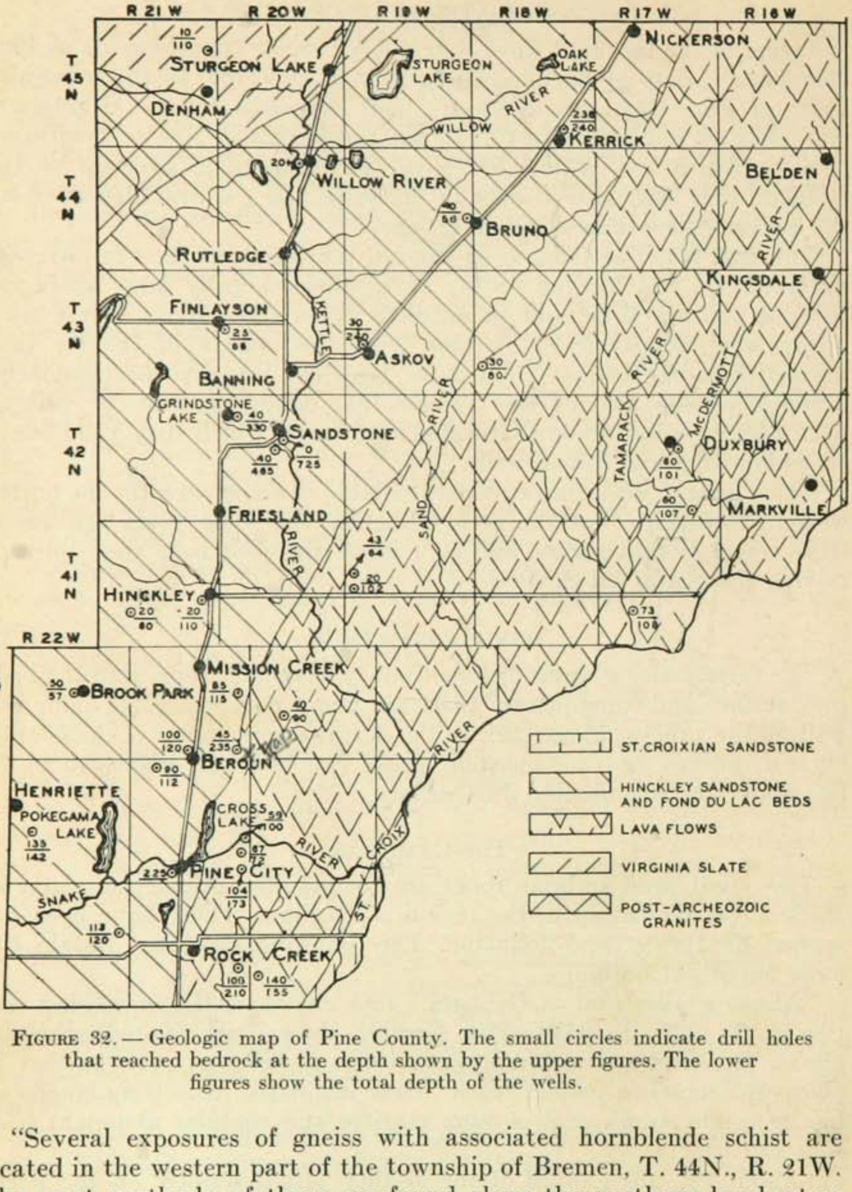

FIGURE 32. — Geologic map of Pine County. The small circles indicate drill holes that reached bedrock at the depth shown by the upper figures. The lower figures show the total depth of the wells.

"Several exposures of gneiss with associated hornblende schist are located in the western part of the township of Bremen, T. 44N., R. 21W. The most northerly of these are found along the northern headwaters of Pine River in the northeastern corner of section 17 and adjacent parts of sections 16, 8, and 9. An outcrop on the west bank of the stream near the east quarter post of section 17 consists of pink gneiss, very coarse and containing muscovite and biotite along foliation planes. The foliation strikes approximately east and west and dips about 50° S. Along the north and south section road, near the northeast corner of section 17, and extending into the adjoining sections to the east and north, are several exposures of dark reddish gneiss with closely spaced foliation planes, and of very dark, almost black, finely laminated hornblende schist. The gneiss contains abundant mica along foliation planes, the close spacing of which indicates intense deformation and metamorphism. . . .

"Several large areas of outcrops of metamorphosed sedimentary rocks are found in the northwestern part of Pine County, south, east, and northeast of Denham, these being the southernmost outcrops of this type of rock in eastern Minnesota. The rocks are principally mica schists, but hornblende schist, quartzite, and limestone occur also.

"The largest area of outcrops is that through which the Minneapolis, St. Paul, and Sault Ste. Marie Railroad passes east and northeast of Denham. The principal exposures are in the eastern half of section 19, T. 45N., R. 20W., but some are found also in the western part of section 20 and in the southeastern part of section 18. The railroad cuts through or passes over most of the outcrop.

"The rock throughout this area is quite uniform, being a quartzose mica schist. It varies slightly, however, in texture and in the relative amounts of mica and quartz which it contains in different parts. Locally it is fine-grained and quartzitic, consisting of sugary quartz with abundant fine scattered biotite flakes parallel to the schistosity. Elsewhere the quartz is present in minor amount and the mica is more coarsely crystalline, producing a very marked schistosity. Local layers consist almost entirely of mica. Small disseminated crystals of garnet are scattered throughout the rock; but are more abundant in the coarsely micaceous phases. The rock in general is dark gray, the mica being mainly biotite; but white mica is intermixed with it. . . .

"About a mile southeast of Denham is one of the most interesting groups of outcrops of metamorphosed sediments in east central Minnesota. The exposures occur principally in the E½ of SE¼ of section 25, T. 45N., R. 21W., but extend for short distances into the adjacent parts of section 30 on the east and section 36 on the south. An irregular depression with low bluffs along it runs in a southeasterly direction through this area. It varies from 200 feet to 400 feet in width, and has the appearance of being a small abandoned stream valley. The rock outcrops are found along the low bluffs on both sides of the depression. The area is wooded, the center of the depression being swampy.

"The most northerly outcrops on both sides of the depression consist of hornblende schist. To the south of these, a large outcrop of quartzite is found on the west side and an outcrop of mixed quartzite and crystalline limestone on the east side. South of the quartzite on the west side are exposures of hornblende schist, followed by more quartzite and finally mica schist, while on the east side opposite to these are outcrops of mica schist and of a dark, fine-grained igneous rock."[1]

Keweenawan basic eruptive rocks occur under the drift throughout all the eastern part of Pine County. They crop out along the Snake River below Cross Lake, along the Kettle River upstream from the St. Croix valley nearly to the mouth of the Grindstone River, and on the floor of the St. Croix valley northeast of Pine City. These rocks form a part of the area of Keweenawan lava flows which extends southwestward from Douglas County, Wisconsin, into eastern Minnesota, forming the so-called south escarpment of the Lake Superior region. The rocks are nearly all of eruptive origin, consisting of massive diabase with texture varying from medium coarse to extremely fine and of various types of amygdaloids. Locally tuffaceous layers occur, but they are not abundant. The rocks of this area have been mapped and described in detail by Grout.[2]

Upper Keweenawan sandstones and shales underlie the region to the northwest of the basic flows. The Hinckley sandstone is conspicuously exposed along the Kettle River, forming bluffs along the river banks and also forming the stream bed in many places. For a long distance north and south of the village of Sandstone, the river flows through a great gorge in which Hinckley sandstone is exposed along the bluff 75 to 100 feet above the river. The strata dip toward the southeast at a low angle. Other exposures may be seen east of the Willow River and near Rutledge.

The original type section was in the quarry wall along the bank of the Whetstone River at Hinckley. These exposures are now almost completely covered with sod and brush. More recent quarrying operations near the village of Sandstone have exposed a continuous vertical section of approximately 100 feet.

The rock is a salmon-colored, medium- to coarse-grained, poorly sorted sandstone. Some beds are arkosic and some are conglomeratic, but most of the rock is nearly pure quartz sandstone. The rock is sufficiently well cemented to be used for structural and architectural stone.

The following section of the Hinckley formation at Sandstone was measured and sampled by Dr. Samuel Goldich during a study of pre-Cambrian heavy minerals undertaken by the Geological Society of America in 1935.[3] For his purpose the section was divided into 10-foot intervals. In the section as presented here, some combinations have been made for simplicity, but the section is still essentially that of Goldich.

[1] Harder, E. C., and Johnston, A. W., Geology of east-central Minnesota: Minn. Geol. Survey Bull. 15, pp. 47–49, 65–66, 1918.

[2] Grout, F. F., Contributions to the petrography of the Keweenawan: Jour. Geol., vol. 18, pp. 633–657, 1910.

[3] Tyler, S. A., Marsden, R. W., Grout, F. F., and Thiel, G. A., Studies of the Lake Superior pre-Cambrian by accessory-mineral methods, Geol. Soc. Am. Bull., vol. 51, p. 1514, 1940.

Section of Quarries and Gorge, West Bank of Kettle River at Sandstone

	THICKNESS (feet)
11. Drift, thin cover, bedrock striated	0.7
HINCKLEY SANDSTONE	
10. Sandstone, very coarse, light yellow to buff and brown, cross-bedded, massive or thick beds	10.0
9. Sandstone, massive and coarse like that above, but with some fine-grained, thin beds. Good quarry stone	10.0
8. Sandstone, salmon-colored to brown, thin-bedded, ripple-marked, massive, coarse, and cross-bedded at the base	13.3
7. Sandstone, thin-bedded, hard, fine-grained, red to yellow	2.7
6. Sandstone, massive, medium-grained, pink to buff and red. Good quarry stone	18.0
5. Sandstone, fine to coarse, pink to reddish. A 2-foot and a 4-foot bed	6.0
4. Sandstone, massive, cross-bedded, light yellow to pink	10.0
3. Sandstone, coarse-grained, well-cemented, pink	15.0
2. Sandstone, massive to thin-bedded, ripple-marked, pink to buff	8.0
1. Sandstone, partly covered to level of Kettle River	8.0
Total	101.7

The Fond du Lac red clastic beds do not crop out in this county, but they are undoubtedly present under the Hinckley formation. Red sandstone was penetrated near the bottom of the federal prison well at Sandstone, but these red strata possess the lithologic characters of the Hinckley formation.

CAMBRIAN SYSTEM

The Cambrian is represented by the lowest member (Mt. Simon) of the Dresbach formation. White, coarse Dresbach sandstone crops out along the valley of the Snake River about a mile upstream from its junction with the St. Croix River. Other exposures may be seen at Horse Race Rapids in the St. Croix valley. The same sandstone is encountered under the drift several miles west of the St. Croix River.

SUBSURFACE STRUCTURE

The major subsurface structure in this area is the Douglas fault, which crosses the county from northeast to southwest. This fault brings the basic lava flows in juxtaposition with the Hinckley sandstone along a line from a few miles east of Nickerson southwestward roughly parallel with the track of the Great Northern Railway Company to the region 5 miles east of Hinckley. There its trend shifts southward to the east side of Cross Lake at Pine City and thence south into Chisago County. The downthrow side of the fault is to the northwest (Figure 33). There is no fault escarpment visible at the surface but the drift is thicker over the sandstone than on the flows, indicating that an escarpment existed in preglacial time. The influence of such an escarpment on valley development is shown at Pine City, where the waters of Cross Lake are ponded along the fault zone. East of the lake the flows crop out at the surface, where they show a steep dip to the southeast.

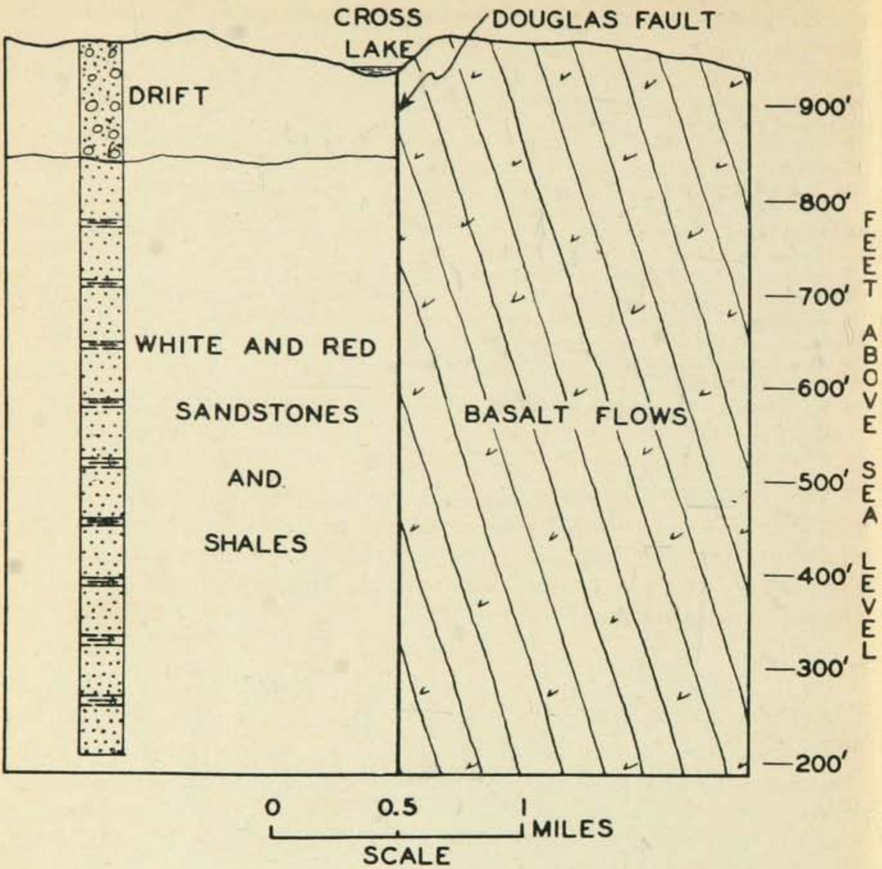

FIGURE 33. — East-west cross-section at Pine City showing the fault contact between the Middle Keweenawan basalt flows and the Upper Keweenawan sandstones and shales.

The trend and the amount of displacement along the fault has been determined by geophysical methods. A gravity-meter traverse made by Welch across the fault in Sec. 10, T. 38 N., R. 21 W., showed the throw of the fault to be about 11,000 feet.[4]

The relation of Keweenawan sandstones to the granites, schists, and slates in the northwestern part of the county has not been definitely determined. The contact is not exposed and drilling has not revealed the structural relationships. The red Fond du Lac beds may rest unconformably on the crystalline rocks as they do to the southwest in Kanabec County, or the Hinckley formation may overlap the red clastic sediments.

[4] Welch, G. I., Geophysical study of the Douglas fault, Pine County, Minnesota: Jour. Geol., vol. 49, p. 408, 1941.

The Dresbach sandstone in the southeastern part of the county overlaps the Hinckley formation and rests unconformably on the lava flows. The relation is similar to that seen in the exposures at Taylors Falls. There, however, the fossiliferous beds of the Eau Claire member of the formation were deposited on the flows, whereas in Pine County the basal or Mt. Simon member rests directly on the igneous rocks.

The upper surface of the flows slopes toward the south. It is at an elevation of about 820 feet in the creamery well at Rush City, a few miles south of the southern boundary of Pine County, and at about 925 feet at Pine City. East of Hinckley the exposures along the Kettle River stand about 950 feet above sea level and east of Askov the farm wells reach trap rock 50 feet below the surface or at an elevation of about 1050 feet. A similar elevation is shown by drilling in the southeastern part of the county a short distance west of Markville.

There is a similar southward slope of the surface of the Upper Keweenawan sandstones. In farm wells west of Pokegama Lake to the west of Pine City the upper surface of the sandstone is approximately 900 feet above sea level. Near Brook Park it is reached at an elevation of 950 feet and at the city of Sandstone the top of the cliffs reach an elevation of 1050 feet. Still farther northward in the region east of Willow River the Hinckley sandstone is exposed at an elevation of 1100 feet.

GENERAL UNDERGROUND WATER CONDITIONS

The Douglas fault, which brings vastly different kinds of rocks into juxtaposition along the fault plane, causes marked contrasts in the water-producing capacity of wells that may be only a short distance from each other at the surface. One farm well may yield copiously from the Hinckley formation, but a well on an adjoining farm, less than 100 yards away, may be on the opposite side of the fault plane where impervious lava flows lie directly beneath the drift. In most places, however, the decomposed upper part of the lava rocks is sufficiently permeable to yield enough water for farm purposes. (See the logs of municipal wells.)

In the northwestern half of the county, with the exception of the northwesternmost townships, the Hinckley sandstone, which is one of the most satisfactory aquifers in the state, occurs directly under the glacial drift. Since the drift sheets in that area were deposited by glaciers that moved from the northeast, the glacial sediments are mainly red, sandy till that is more pervious than the gray drift farther to the south. Thus Pine County serves as part of the recharge or catchment area for the waters that saturate the Hinckley formations. That this water is not mixed to any great extent with water from the Cambrian sandstones farther to the south is shown by the fact that the water in the Hinckley sandstone as far south as Minneapolis is much softer than that in the younger geologic formations.

In the areas of outwash sands and gravels in the northern part of the county and along the St. Croix River, abundant supplies of water may be obtained from shallow dug or driven wells, and most of the water is not highly mineralized.

MUNICIPAL WATER SUPPLIES

Pine City

Pine City is located on the Snake River in the southern part of the county at the south end of Cross Lake. This lake lies to the west of the lava flow escarpment formed by the Douglas fault (Figure 33). The city well is located west of the fault where the glacial drift is about 225 feet thick. The well that produces most of the water for the public supply system is 10 inches in diameter and 132 feet deep where it terminates in red glacial till. It is pumped at 275 gallons per minute with little drawdown.

The creamery well is 6 inches in diameter and 160 feet deep. It is pumped at the rate of 70 gallons per minute.

The Northern Pacific Railway Company obtains water from a well 92 feet deep. The company once drilled a well to a total depth of 700 feet. The accompanying log gives the geologic succession.

Old Well of Northern Pacific Railway Company, Pine City (elevation 950 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–230	230
Upper Keweenawan	White sandstone	230–250	20
	Red sandstone	250–260	10
	Red shale	260–282	22
	White sandstone	282–295	13
	Red sandstone	295–420	125
	White sandstone	420–440	20
	Red sandstone	440–460	20
	Hard red shale	460–480	20
	Red and white sandstone	480–700	220

A farm well 5 miles north of the city in Sec. 5, T. 39 N., R. 21 W., encountered sandstone under only 90 feet of drift, whereas about 2 miles southwest of the city in Sec. 13, T. 38 N., R. 22 W., the drift is 113 feet thick and rests on decomposed trap rock. East of Cross Lake all the deep wells terminate in the lava flows.

Hinckley

The city of Hinckley is located on the Grindstone River about 5 miles upstream from its junction with the Kettle River. The type locality of the Hinckley sandstone formation is at the north edge of the city in the abandoned quarries in the north bank of the river. The old quarries are situated between the Northern Pacific Railway Company tracks and the Hinckley–Duluth highway. The bedrock surface is very irregular.

Less than a mile south of the outcrops at the quarry, wells 100 feet deep do not reach the sandstone.

The city well is 8 inches in diameter and 110 feet deep. Its static level is 15 feet below the surface or at an elevation of 1015 feet above sea level. It is pumped at the rate of 375 gallons per minute and shows a drawdown of less than 20 feet.

A pool formed by a dam across the Grindstone River serves as an excellent recharging reservoir for the drift and underlying sandstone strata.

A well at the county poor farm east of Hinckley in Sec. 29, T. 41 N., R. 21 W., produces ample water from a depth of 60 feet. It penetrates 20 feet of drift and enters the upper part of the Hinckley sandstone.

The well at a schoolhouse 3 miles west of Hinckley in the NE¼, Sec. 29, T. 41 N., R. 21 W., obtains an ample supply of water from a well that terminates in the glacial drift at a depth of 45 feet. The top of this well is 1050 feet above sea level.

Sandstone

The city of Sandstone gets its name from the Hinckley formation that forms high cliffs along the banks of the Kettle River at the edge of the town. The city well is located on the floor of the valley about 100 feet below the level of the main street. The well is 12 inches in diameter and 725 feet deep. When not pumped the water will rise 16 feet above the surface. It is pumped 750 gallons per minute with little drawdown.

The city has an old well about 400 feet deep which did not yield sufficient water. The well has since been used by a private stone company.

The well at the federal prison, drilled in 1938, is 40 inches in diameter and 465 feet deep. Its static level is 34 feet below the surface and when tested at the rate of 350 gallons per minute it showed a drawdown of 21 feet. The accompanying log gives the lithology of the formations penetrated.

Federal Prison Well, Sandstone*

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–40	40
Hinckley	Pinkish sandstone	40–110	70
	Soft red sandstone	110–170	60
	White and yellow sandstone	170–300	130
	Soft reddish sandstone	300–345	45
	Pinkish white sandstone	345–465	120

* Data from the Layne-Western Well Company, Minneapolis.

The Douglas fault plane passes a few miles east of the city. A farm well in Sec. 15, T. 42 N., R. 19 W., enters trap rock under 62 feet of drift, whereas a well at the schoolhouse in Sec. 17 of the same township encountered sandstone at a depth of 20 feet.

Beroun

This village has no public water supply system. A well at the pickle factory penetrates 100 feet of drift and enters 20 feet of the top of the Hinckley sandstone.

A well 2 miles east of the village in Sec. 36, T. 40 N., R. 21 W., is east of the Douglas fault. It entered decomposed lava rock at a depth of 60 feet. The igneous rock was penetrated to a total depth of 160 feet but the well did not yield a satisfactory supply of water.

Askov

The village of Askov does not have a public water supply system. The accompanying logs of private wells show the subsurface geologic relations.

Well at Fernvale Nursery, Askov (elevation 1085 feet, static level 1045 feet)*

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–30	30
Hinckley	White sandstone	30–240	210

* Data from Mr. Buck, driller, Askov.

Creamery Well, Askov (elevation 1090 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–35	35
Hinckley	White and pink sandstone	35–175	140

It has been reported that the Great Northern Railway Company once used a well 700 feet deep. The Hinckley fire destroyed the tank and tower and the well was abandoned.

Willow River

The wells in and near this village are all very shallow. The creamery well is 30 feet deep and the schoolhouse well is only 20 feet in depth. The outwash sands and gravels are saturated to a static level that lies near the surface. Therefore driven and dug wells yield ample supplies of water. There is no public supply system.

Sturgeon Lake

The private wells in this village obtain water from very shallow drift wells. The public supply is taken from a well drilled in 1939 that is 3½ inches in diameter and 91 feet deep. The static level is 38 feet below the surface and when pumped at the rate of 35 gallons per minute it shows no appreciable drawdown.

West of the village in Sec. 12, T. 45 N., R. 21 W., a grayish slate was encountered at a depth of 10 feet. The well was drilled to a total depth of 110 feet, where a small yield of water was obtained from a fracture.

Bruno

In the region of Bruno the glacial drift is no more than 30 to 60 feet thick. It is underlaid by the Hinckley sandstone. The creamery well is 56 feet deep. It penetrates 39 feet of drift and 17 feet of the Hinckley formation. The well at the public school is of the same depth. Its static level is less than 20 feet below the surface.

Finlayson

The village of Finlayson is located about 4 miles northwest of Sandstone at a surface elevation of 1115 feet. The well at the depot of the Northern Pacific Railway Company is 66 feet deep. It penetrates 25 feet of drift and 41 feet of Hinckley sandstone. There is no public water supply system.

Gronigen

The village of Gronigen has no public well. The Northern Pacific Railway Company's well is 8 inches in diameter and 330 feet deep. The accompanying log gives the geologic succession.

Northern Pacific Railway Company Well, Gronigen (elevation 1135 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Red clay	0–18	18
	Fine brown sand	18–30	12
	Yellow sand	30–39	9
Hinckley	White, yellow, and pink sandstone	39–330	291

Rock Creek

The village of Rock Creek lies east of the Douglas fault and west of the Cambrian sandstones that overlap the basic lavas from the east. There is no public water supply system in the village, but private wells obtain ample supplies from the drift. A farm well 2 miles east of the village in Sec. 24, T. 38 N., R. 21 W., encountered lava flows at a depth of 108 feet. The well was drilled into the igneous rock to a total depth of 210 feet. Very little water seeped into the well. A mile farther to the southeast, in Sec. 30, T. 38 N., R. 20 W., a farm well entered Cambrian white sandstone under 140 feet of drift. The well was drilled 15 feet into the sandstone, which yielded water freely.

Mission Creek

In this region the private wells are of the dug and driven types. Only a few are drilled to bedrock, which is Hinckley sandstone. Southeast of the village, in Sec. 13, T. 40 N., R. 21 W., a farm well penetrated 80 feet of drift and encountered broken fragments of sandstone and trap. This material may represent fault breccia or residual products of preglacial weathering.

Kerrick

This village is located in the northeastern part of the county. Most private wells are shallow, but the Great Northern Railway Company has a well 238 feet deep which terminates at the contact between the drift and the Hinckley sandstone. The well is cased to within a few feet of the bottom. There is no public water supply system.

Brook Park

This village is located near the southwestern border of the county, where the Hinckley sandstone is covered with 40 to 60 feet of drift. The well at the Adam Store is 57 feet deep. It penetrates 50 feet of glacial till and 7 feet of sandstone. The static level is 20 feet below the surface.

A farm well at the north edge of the village in Sec. 15, T. 40 N., R. 22 W., entered 5 feet of sandstone under 43 feet of drift. The static level is 10 feet below the surface.

Henriette

This village is located west of Pine City near the west border of the county. The drift sheets of this region have a total thickness of 115 to 150 feet. Most private wells are shallow. The deeper drilled wells obtain water from the Hinckley sandstone. There is no village well.

A farm well south of the village is typical of the subsurface relations in this region.

Farm Well, Sec. 20, T. 39 N., R. 22 W.*

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–135	135
Hinckley	Sandstone	135–142	7

* Data from Berg Brothers, drillers, Mora.

The static level of this well is 14 feet below the surface.

Duxberry

This inland village is situated in the eastern part of the county, due east of Hinckley. In this region the basic flow rocks are near the surface and therefore the wells are shallow and of large diameter. Some wells are drilled into the flows, but the yield from the igneous rock is small. The accompanying log is typical of the deep well.

Well at Children's Campsite, Duxberry*

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–67	67
Keweenawan	Lava rock	67–101	34

* Data from the Keys Well Company, St. Paul.

The well is 6 inches in diameter and has 69 feet of casing. When pumped 12 gallons per minute it has a drawdown of 50 feet.

FARM WATER SUPPLIES

In the northwestern half of the county where the Hinckley sandstone occurs directly beneath the drift, farm water supplies are assured in every community. If shallow wells in the drift do not yield sufficient amounts, deeper wells drilled into the underlying sandstone will furnish all the water required for farm purposes.

The southeastern half of the county, east of the Douglas fault, has igneous lava flows directly under the drift. In this region it is locally difficult to obtain sufficient water from the glacial deposits. Experience has shown that it is possible to develop satisfactory wells in the upper part of the flow rocks. The following are typical of the deep wells in that area.

Farm Wells in Trap Rock in Eastern Pine County

	THICKNESS OF DRIFT (feet)	DEPTH DRILLED IN TRAP ROCK (feet)
Sec. 30, T. 43 N., R. 18 W.	30	50
Sec. 35, T. 42 N., R. 17 W.	60	47
Sec. 19, T. 41 N., R. 19 W.	20	82
Sec. 18, T. 41 N., R. 19 W.	43	21
Sec. 29, T. 41 N., R. 17 W.	73	35
Sec. 36, T. 40 N., R. 21 W.	45	190
Sec. 28, T. 40 N., R. 20 W.	40	50
Sec. 25, T. 39 N., R. 21 W.	67	25
Sec. 24, T. 39 N., R. 21 W.	59	41
Sec. 36, T. 39 N., R. 21 W.	140	33
Sec. 25, T. 39 N., R. 21 W.	40	200

TABLE 43. — ANALYSES OF WATERS OF PINE COUNTY *

	1	2	3	4	5	6	7	8
Depth (feet)	400	732	732	134	...	...	465	275
Hardness	180	43	50	210	285	280	120	450
Alkalinity	188	44	56	256	293	310	120	40
Iron	2.2	1	.4	.5	.8	.5	2.5	5.0
Manganese	...	...	.1	...	.1	.08	.14	.35
Chlorine	2	0	.29	1	0	2	21	3800
Fluorine	...	...	...	...	...	0	.1	...
SO_4 radical	...	...	...	...	...	10.1	0	85
Turbidity	25	0	2	3	...	5	15	50
Color	12	5	7	25	0	10	7	0
Odor	e–1	p–1	...	0	...	...	0	0
pH value	...	...	6.2	...	7.7	8.15	7.0	...

* Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Hinckley, drilled well, 1920.
2. Sandstone, drilled well, 1918.
3. Sandstone, drilled well, 1936.
4. Pine City, drilled well, 1921.
5. Pine City, drilled well, 1930.
6. Pine City, drilled well, 1942.
7. Sandstone, federal prison well.
8. St. Croix State Park, well.

SHERBURNE COUNTY

SURFACE FEATURES

Sherburne County is situated east of the Mississippi River in the south-central part of Minnesota. Its surface is, for the most part, undulating and gently rolling. Two areas of morainic ridges and knolls occur in the southeastern townships and another in the region north of Becker. A marginal moraine of the Grantsburg lobe extends from the northwestern corner of the county eastward into the northern part of Palmer Township. The remainder of the county has been made plain by glacial outwash and lacustrine sediments. Much of the southwestern part of the county is part of the flood plain and valley train of the early postglacial Mississippi River.

The Elk River, which parallels the Mississippi from the northwest to the southeast corner of the county, drains most of the area. It flows into the Mississippi at the town of Elk River. The eastern townships drain into the Rum River and thence to the Mississippi at Anoka. The tract of land between the Elk and Mississippi rivers is a sandy prairie, the surface of which is covered with glacio-fluvatile sediments.

The greatest relief occurs in Elk River Township, where the lowest elevation is about 850 feet above sea level. The great sandy prairie which is part of the Anoka sand plain[1] stands at about 1050 feet.

UNCONSOLIDATED SURFACE MANTLE

With the exception of the northern edge of the county, where there are a few square miles of clayey ground moraine of red drift of Patrician age, the Grantsburg lobe of the Keewatin ice sheet covered the entire county. It left a gray drift that is locally mixed with the red drift over which the glacier moved. Zones of sand and gravel outwash parallel the valley of the Elk, Mississippi, and St. Francis rivers. In the central and eastern parts of the county dune sands occur as a veneer over many of the morainic ridges and knolls.

The dunes of this area lie "three miles northwest of the town of Elk River and a mile and a half northeast of the Elk River itself at the nearest point. The part of the group having the best developed dunes is one mile in length along its northwest-southeast axis and six-tenths of a mile wide. On the southwest it merges imperceptibly into ordinary outwash sands; on the northeast a striking lee slope descends abruptly to the till surface of the Elk River morainic area. It is a complex of overlapping sand waves, arranged more or less *en échelon,* which, when active, were advancing northeastward. The waves are for the most part very closely set. Each component ridge is more or less bow-shaped and

[1] Cooper, W. S., The history of the upper Mississippi in late Wisconsin and postglacial time: Minn. Geol. Survey Bull. 26, 1935.

concave to windward, this form being decidedly more pronounced in the final series that touches the till plain on the northeast. The height of the ridges above their bases is variable, the greatest occurring along the ultimate lee slope. . . . The profiles of the ridges show the usual contrast between windward and leeward slopes. Upon the final lee slope the gradient is surprisingly steep, exceeding that at which loose sand will maintain its stability. Two measurements by clinometer gave values of 40° and 45°. The explanation seems to be that sand blown over the summit since vegetation gained general control has been held by plants, the amount decreasing from top to bottom of the slope. The contrast between the two sides is accentuated by differences in vegetation; the steep northeasterly lee slopes are densely forested with oaks, while the gentle, southwestward-facing windward slopes for the most part support prairie grasses and other herbs, with only occasional trees."[2]

Cooper reports the results of a series of mechanical analyses that show the conversion of outwash into dune sand. The following tabulation shows the percentages by size-classes for each type of sample.

TABLE 44. — TEXTURAL ANALYSES OF DRIFT SANDS

Size-Class	Size of Grain (milli-meters)	Percentages in Size-Class						
		Outwash (9 samples)	Dune Sand (6 samples)	Center of Blowout				Dunelet Traveling across Blowout
				1st ¼ in.	2nd ¼ in.	6 in. Depth	36 in. Depth	
I. Gravel	1.0+	1.9	tr.	9.9	1.8	0.5	0.1	tr.
II. Coarse sand	1.0–0.5	10.0	1.5	4.8	4.4	5.0	2.6	2.3
III. Medium sand ...	0.5–0.25	39.9	29.7	32.6	39.3	40.4	19.5	30.8
IV. Fine sand	0.25–0.10	44.0	61.7	45.4	48.7	49.1	67.6	62.8
V. Very fine sand and below....	0.10—	4.2	7.1	7.3	5.8	5.0	10.2	4.1

A comparison of the first two composite samples demonstrates in a quantitative way what is evident to the casual view: that nearly all the material of the outwash is of fineness sufficient to render it liable to removal by wind. The dune series, made up of samples taken from the deposits surrounding the blowout, seems to indicate that the upper limit for wind carriage lies near the dividing line between Classes II and III, or roughly at a diameter of 0.5 millimeter. The outwash series shows a proportion of 88 per cent below this limit.

The third percentage column shows the presence of an extremely thin surface concentrate of coarser materials, but even in this sample the proportion of particles below 0.5 millimeter in diameter, still exposed to the wind, is 85.3 per cent. Moreover, most of the particles above that limit would come under the designation of lag gravels and would be capable of being moved short distances, thus exposing the finer materials below. There are also the pebbles of various sizes that now lie scattered

[2] Cooper, *op. cit.*, p. 73.

over the floor of the blowout. It is plain, however, that the concentrate of gravel and pebbles derived from 5 to 10 feet of outwash has not attained sufficient bulk to affect seriously the removal of the fine particles by the wind. The seventh percentage column, analyzing a traveling dunelet upon the floor of the blowout, shows a striking correspondence with the dune series taken from the surrounding ridges.

We may conclude that in the Anoka sand plain there has been locally almost complete conversion of outwash into dune sand, and that the coarser residuum, even where abundant enough to produce a conspicuous concentrate, is so slight in amount as to cause very little hindrance to removal of the finer materials.

The drift varies in thickness from a few feet to more than 200 feet. On the prairie along the Mississippi valley it ranges from 0 to 100 feet. It is 75 feet to bedrock at Becker, 78 feet at Clear Lake, and 100 feet at Big Lake. The drift is thickest in the east-central townships, where some wells have been drilled to a depth of 225 feet before reaching bedrock.

ROCK FORMATIONS

Pre-Cambrian

Pre-Cambrian granites and related igneous rocks crop out at various points in Sherburne County. The largest exposures occur in the northwesternmost township near East St. Cloud. At the state reformatory in Haven Township, about 2 miles from East St. Cloud, a number of quarries are operated in a gray monzonite. About 2 miles southeast of the reformatory, in the west-central part of the township, a light gray granite, cropping out over an area of 4 or 5 acres, rises as a bare rounded knoll above the surrounding prairie.

A few miles north of Sherburne County along Estes Brook in Mille Lacs County, west of Princeton, pre-Cambrian basic, igneous, and metamorphic rocks form numerous low outcrops. (See the report on Mille Lacs County.) Granites occur directly beneath the drift as far southeast as Becker, where a farm well near the village struck the granite surface at a depth of 60 feet (Figure 34).

The granite surface is 1025 feet above sea level at the reformatory near East St. Cloud, 915 feet near Becker, and less than 400 feet at Elk River. The deepest well at Elk River terminated at an elevation of about 400 feet above sea level and no igneous rocks were encountered. The pre-Cambrian rocks near the north county line west of Princeton stand at an elevation of 1060 feet, which is higher than those of the East St. Cloud region.

Pre-Cambrian sandstones of Keweenawan age wedge out against the southeastward-sloping surface of the granites. They may be present directly under the drift in the northeastern townships, but farther southwestward they appear to be overlapped by the Cambrian sandstones. The red clastic sediments penetrated by the deep artesian well at Elk

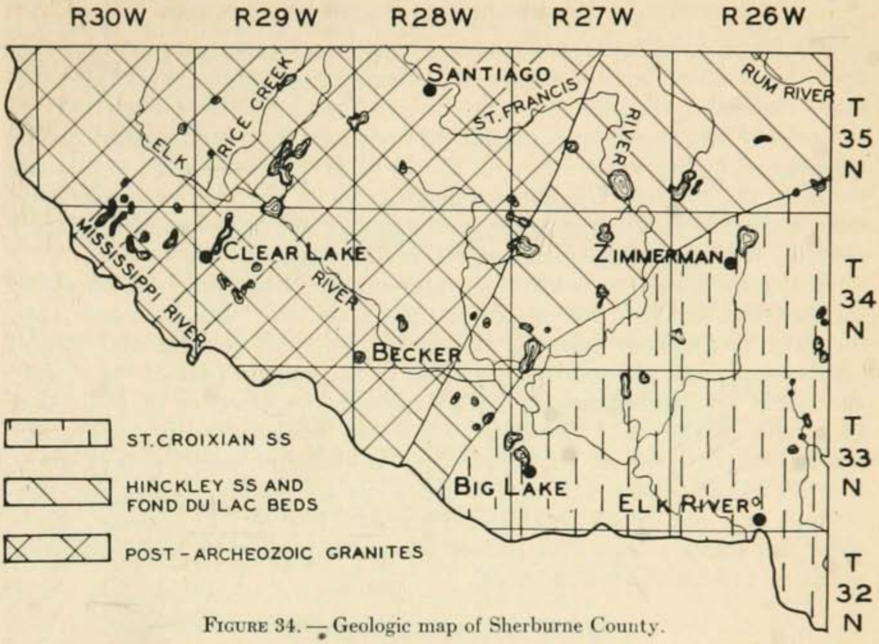

FIGURE 34. — Geologic map of Sherburne County.

River may belong to the Dresbach formation. Similar red sandstones and shales belonging to the Dresbach were encountered in a deep well at Waconia, west of Minneapolis, and at North Branch in Chisago County.

PALEOZOIC ROCKS

The Cambrian system is represented by the lower formations of the St. Croixian series. Sandstones that may belong to the Dresbach formation crop out in the east bank of the Mississippi River about 3 miles above Monticello and similar beds appear at the surface in the banks of the St. Francis River in Orrosk Township (T. 34 N., R. 27 W.).[3] Drilling has demonstrated the presence of similar white sandstone as far northwest as Clear Lake. Thus it appears that most of the southern part of the county is underlaid by members of the Dresbach formation.

Structurally, the Cambrian formations form a local basin on the northwest rim of the Twin City artesian basin. They represent the outermost northwestern margin of the catchment area. If the sandstones in central Sherburne County are the northwestward extension of the Mt. Simon sandstone that serves as an aquifer in Minneapolis and St. Paul, the difference in elevation is about 800 feet. In Minneapolis the top of the Mt. Simon is near sea level, whereas the top of the sandstone at Big Lake is at an elevation of about 825 feet.

[3] Winchell, N. H., The geology of Minnesota: Final Rept., Minn. Geol. and Nat. Hist. Survey, vol. 6, pl. 46, 1901.

GENERAL UNDERGROUND WATER CONDITIONS

The shallow wells in porous beds of sand and gravel cannot be relied upon to produce large volumes of water, but they are dependable for more restricted requirements. In the sand plain of the central part of the county the static level of the water is near the surface, and at the margins of higher morainic belts the head may be sufficient to lift the water to the surface. The alluvial deposits along the valleys usually produce moderate supplies of water, but owing to the presence of much fine silt they cannot be depended upon to produce large volumes.

In the northwestern townships water supplies must be obtained above the bedrock surface, but where the pre-Cambrian and Paleozoic sedimentary rocks occur beneath the drift, the most reliable and largest yields come from the sandstone strata. In the central part of the county the static level in sandstone wells is about the same as in wells that terminate in the drift. However, since the sandstones dip toward the southeast, the head on the water they contain increases in that direction. For that reason flowing artesian wells are common along the Mississippi and Elk rivers in the southeastern part of the county, where some wells flow as much as 15 feet above the surface or to an elevation of about 915 feet above sea level.

MUNICIPAL WATER SUPPLIES

Elk River

The city of Elk River is located at the junction of the Elk River with the Mississippi, near the southeastern corner of Sherburne County. In this area the water confined in the sandstones under the drift is under sufficient pressure to lift it to the surface. Flowing wells are common in the city and on farms west of the city.

Generalized Section of Geologic Succession at Elk River*

	DEPTH (feet)	THICKNESS (feet)
Sand and gravel	0–50	50
Sandy red clay	50–120	70
Hard blue shale	120–200	80
White sandstone	200–300	100
Red sandstone	300–515	215

*From notes by W. C. Hall.

Norling and others correlated the white sandstone with the Hinckley formation and the underlying red strata with the red Fond du Lac beds.[4] Such correlation is doubtful, but no drill cuttings are available for comparative petrographic analyses. However, the white sandstones of northwestern Isanti County to the north are unquestionably of Cambrian age, since they contain middle Dresbach fossils. Therefore, a comparatively thick Dresbach section may be expected as far south as Elk River.

[4] Norling, S. A., Report of the Water Supply Commission to the City Council, Minneapolis, June 1932.

A farm well about 3 miles west of Elk River shows that the white sandstones are thicker than the deep well at Elk River indicates. (See the accompanying log and Figure 35.)

Farm Well, Sec. 35, T. 33 N., R. 27 W., Owner, Roy Hutt*

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–120	120
Dresbach	Many-colored sandstones (white, blue, green,		
?	yellowish)	120–275	155
	White shale	275–285	10
	White sandstone	285–335	50

*Data from the Price Well Company, Buffalo. The well was drilled in 1930.

The blue, green, and yellowish sandstones of the log are suggestive of the middle or Eau Claire member of the Dresbach formation. Such strata are conspicuous in the Eau Claire beds along the St. Croix valley and its tributaries in Chisago County, and glauconitic sandstones have been penetrated also by wells in southern Isanti County.

Most of the artesian wells are about 300 feet deep. The old well at the high school is 305 feet deep and the one at the Twin City Milk Producers Plant is 285 feet deep. The old Nickerson well was drilled to a depth of 515 feet for experimental purposes, but there was no increase in volume or pressure on the water at any point beyond a depth of 300 feet. Shallower wells flow also. A well owned by J. W. Romdeen and located near the power house is only 90 feet deep. It penetrates 70 feet of alluvium and drift and enters the upper 20 feet of the sandstone. The well will flow more than 15 feet above the surface.

Most of the water for the public supply system is taken from a well 308 feet deep drilled in 1919. The well is 12 inches in diameter and reached bedrock at 175 feet. When not pumped it will flow at the surface, and when pumped at the rate of 320 gallons per minute it has a drawdown of about 5 feet.

Big Lake

The village of Big Lake has no public water supply system. Most wells for domestic supplies are driven from 20 to 30 feet into the sandy outwash deposits. The deeper drilled wells enter white sandstone at a depth of 75 to 100 feet. The accompanying log is typical.

Well at Standard Oil Company Service Station, Big Lake (elevation 935 feet)*

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–103	103
Dresbach	White sandstone	103–110	7

*Data from the Price Well Company, Buffalo.

A farm well one mile east of the village in Sec. 20, T. 33 N., R. 27 W., entered white sandstone at 110 feet below the surface, and another one

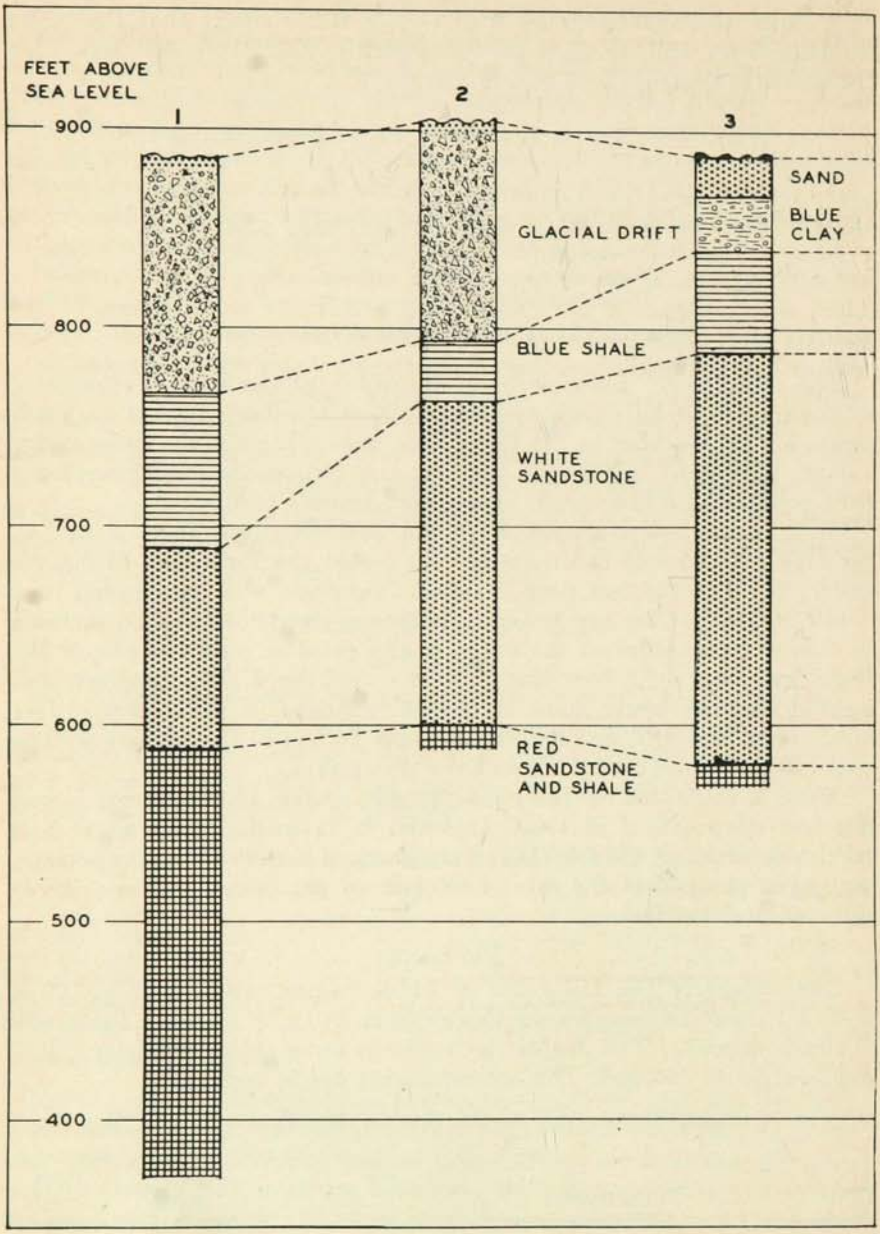

FIGURE 35. — Logs of wells at Elk River. After Meinzer.

mile west of the village in Sec. 24, T. 33 N., R. 28 W., south of the track of the Northern Pacific Railway Company, encountered the white sandstone under 70 feet of glacial drift. All the wells that terminate in the sandstone yield water abundantly.

Becker

The village of Becker is located on the sandy prairie in the south-central part of the county near the west bank of the Elk River. There is no public water supply system in the village and most private wells are driven from 20 to 50 feet into the alluvial and outwash sediments. The granite surface stands higher in this vicinity than it does to the north and to the southeast of the village. The accompanying logs of wells in and near the village are typical of the subsurface structure.

Well at Northern Pacific Railway Depot, Becker (elevation 975 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Unclassified	0–74	74
Pre-Cambrian	Granite	74–105	31

Farm Well 1 Mile Northwest of Becker, Sec. 25, T. 34 N., R. 29 W. (elevation 975 feet)

		DEPTH (feet)	THICKNESS (feet)
Drift	Sand and gravel	0–45	45
	Clayey hardpan	45–60	15
Pre-Cambrian	Granite	entered	

Clear Lake

The village of Clear Lake does not have a public water supply system. The private dug and driven wells produce ample water from a depth of 30 to 60 feet. The well at Roy's Garage is 45 feet deep and penetrates 20 feet of sand and 25 feet of gray glacial till. The well at the depot obtains an abundance of water from a gravel bed encountered at a depth of 52 feet.

A yellowish-white sandstone occurs at a depth of about 75 feet. It was reached in one well in the village and in a farm well about 2 miles west of the village in Sec. 14, T. 34 N., R. 30 W. The sandstone is poorly cemented and yields water freely.

Zimmerman

The village of Zimmerman is situated on the rolling sandy plain in the east-central part of the county. Over much of this area the static water level in water-table wells is from 10 to 20 feet below the surface.

The village has no public water supply system and water is obtained from wells driven from 30 to 60 feet below the surface. The deeper drilled wells reach white sandstone at a depth of about 160 feet. A well half a mile north of the village on the farm of Mr. Rustin entered the white sandstone at a depth of 165 feet and penetrated it to a total depth of 185 feet. The static level in this well is about 20 feet below the surface.

East of the village in the NE¼, Sec. 14, T. 34 N., R. 26 W., the drift is nearly 200 feet thick and is underlaid by a clean amber-colored gravel bed 5 to 12 feet thick. This gravel rests directly over the white sandstone and occurs over an area 2 to 3 miles wide in the eastern part of the township. It is an excellent water-producing horizon.

North and west of the village in the region of Catlin Lake a fine green, glauconitic sand occurs at a depth of 75 to 100 feet.

East St. Cloud State Reformatory

The state reformatory has a number of dug wells. The newest is 10 feet in diameter and 24 feet deep. It reaches the top of the granite surface. The static level is from 8 to 10 feet below the surface. Two older wells, also dug to granite, are located about 200 feet to the northeast of the new well. The entire group is situated outside the reformatory wall near the northeast corner. A short distance west of the wells the granite crops out at the surface at about 1020 feet above sea level.

FARM WATER SUPPLIES

Most farm wells are supplied with water from the alluvial and glacial sands and gravels. Many of these wells are driven and bored and most of them yield ample volumes of water. In the eastern half of the county the deeper drilled wells tap the water in the sandstones under the drift or the amber gravel bed that overlies the sandstone. In the north-central townships many wells encounter red sandy till under the gray drift of the Keewatin ice sheet. Such sandy till gives up its water freely and in many areas the static level in the farm wells is from 10 to 15 feet below the surface. Along the valleys of the Elk and Mississippi rivers the alluvial sands are permeable and saturated to within 10 to 15 feet of the surface.

Table 45. — Analysis of Water from City Well, Elk River*

Depth (feet)	...
Hardness	210
Alkalinity	220
Iron	.28
Manganese	.3
Chlorine	.4
Fluorine	0
SO_4 radical	5
Turbidity	3
Color	3
Odor	...
pH value	7.4

*Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

ST. LOUIS COUNTY

SURFACE FEATURES

St. Louis County embraces more than one-third of the northeastern quarter of Minnesota, its area being slightly more than 6500 square miles. It extends from the southwestern end of Lake Superior northward to Rainy Lake on the Canadian border, or from T. 48 N. to T. 71 N., a distance of more than 130 miles. Most of the county is 10 townships or 60 miles in width.

Most of the county is a tableland standing 600 to 900 feet above Lake Superior or 1200 to 1500 feet above the sea. The Giants Range and associated rock ridges rise in places to 1800 feet above the sea. A rugged moraine in the southeastern part of the county is about 1700 feet where it enters from Lake County, and the bedrock surface there is at an altitude of about 1600 feet. Along much of the eastern part of the county the rock surface has an altitude of 1500 to 1700 feet. The general elevation decreases westward from Lake County on each side of the Giants Range. That range reaches its highest elevation, about 1800 feet, in the region north of Virginia and Eveleth.

In the Vermilion district the topography is characterized by linear bluffs and ridges with numerous linear lakes in the depressions between them. The position of the ridges and depressions is determined by the character of the bedrock formations. The more resistant rocks form the ridges, the less resistant the depressions.

About 365 square miles of the surface of St. Louis County are occupied by lakes. The great majority of the lakes are small, but several within the limits of the county are of considerable size. Vermilion Lake is about 70 square miles, Kabetogama fully 30 square miles, Pelican Lake 20 square miles, and Trout Lake 11 square miles.

Most of the southern half of the county is drained by the St. Louis River and its tributaries, the chief of which are the Cloquet, Whiteface, and Embarrass rivers. The southwesternmost townships drain westward into Sandy Lake, which in turn drains into the Mississippi River. The north-central townships lie within the drainage basin of the Vermilion River. The Pike River and its tributaries extending southward as far as the Virginia horn are a part of this system. The northwestern townships drain through tributaries of the Rainy River and into the chain of lakes along the Canadian border.

The flat swampy land from Floodwood northward toward the Mesabi Range is the floor of a temporary glacial lake which formed at the northwestern margin of the Lake Superior lobe of the late Wisconsin glacier. It is commonly referred to as glacial Lake Upham or glacial Lake St. Louis. The former outlet of this lake occurs near Mirbat about

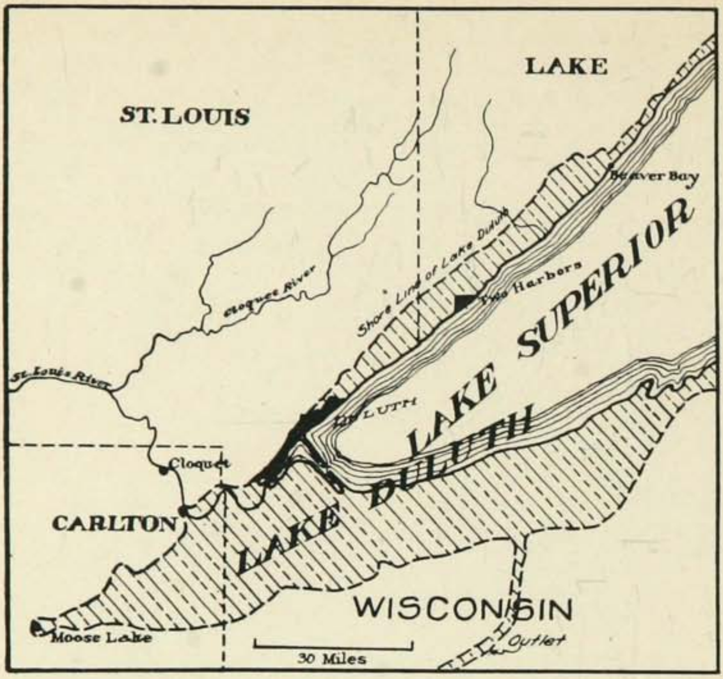

FIGURE 36. — Sketch map showing the relation of Lake Duluth to Lake Superior. After Schwartz.

3 miles below Floodwood, where a well-defined beach comes from the west along the south side of the East Savanna River.[1]

The region of the valley of the St. Louis River southwest of Duluth was at one time the bed of glacial Lake Duluth (Figure 36). The beaches of this lake are still visible, the highest one being 534 feet above the level of Lake Superior. In the region of Fond du Lac the St. Louis River has cut a valley more than 100 feet deep into the former lake bed. Similar beaches may be seen on the hillside at Duluth, where the Boulevard Drive utilizes the highest one as a roadbed. The area in this county covered by Lake Duluth is about 100 square miles. Near Duluth its highest shoreline is scarcely a mile back from the lake, but further northeastward the distance increases to fully 5 miles.

UNCONSOLIDATED SURFACE MANTLE

In the northern part of St. Louis County the drift is very scanty on the hills and ridges. This is especially true for a distance of 30 to 35 miles south of the Canadian boundary, or as far south as Pelican, Vermilion, and Birch lakes. The Giants Range is very thinly coated with drift, though its south slope and the portion west from Chisholm carry a

[1] Leverett, Frank, and Sardeson, F. W., Quaternary geology of Minnesota and parts of adjacent states: U.S. Geol. Survey Prof. Paper 161, p. 54, 1932.

relatively heavy coating. North of the Giants Range in the drainage areas of the Sturgeon and Little Fork rivers, the drift cover is thick. The same is true of the region from the Mesabi Range southward to Duluth, except in a narrow strip fronting on Lake Superior, where bare rock ledges are conspicuous.

The glacial drift that occurs at the surface in St. Louis County was deposited by three different ice sheets, all of Wisconsin age. During the Cary substage the ice moved from the Patrician district, and during the Mankato substage one ice sheet moved from the Keewatin center and another from the Labrador center. The latter is commonly called the Superior lobe. The ice from the Patrician district covered all the county and extended as far south as Minneapolis. The northern part of St. Louis County was still buried under this ice when the two other ice sheets were occupying the southern and western townships.

The Keewatin ice sheet (Mankato) extended into the county from

TABLE 46. — THICKNESS OF THE GLACIAL DRIFT ON THE MESABI RANGE IN ST. LOUIS COUNTY

Location	THICKNESS (feet)
Sec. 4, T. 57 N., R. 17 W.	35
Sec. 6, T. 57 N., R. 17 W.	50
Sec. 1, T. 57 N., R. 18 W.	30
Sec. 6, T. 57 N., R. 20 W.	95
Sec. 12, T. 57 N., R. 21 W.	265
Sec. 15, T. 57 N., R. 21 W.	220
Sec. 17, T. 57 N., R. 21 W.	187
Sec. 4, T. 58 N., R. 15 W.	126
Sec. 5, T. 58 N., R. 15 W.	103
Sec. 6, T. 58 N., R. 15 W.	140
Sec. 9, T. 58 N., R. 16 W.	31
Sec. 10, T. 58 N., R. 16 W.	60
Sec. 17, T. 58 N., R. 16 W.	40
Sec. 18, T. 58 N., R. 16 W.	55
Sec. 5, T. 58 N., R. 17 W.	20
Sec. 8, T. 58 N., R. 17 W.	118
Sec. 19, T. 58 N., R. 17 W.	55
Sec. 24, T. 58 N., R. 17 W.	60
Sec. 26, T. 58 N., R. 17 W.	180
Sec. 1, T. 58 N., R. 18 W.	80
Sec. 3, T. 58 N., R. 18 W.	25
Sec. 7, T. 58 N., R. 18 W.	38
Sec. 8, T. 58 N., R. 18 W.	108
Sec. 25, T. 58 N., R. 18 W.	155
Sec. 13, T. 58 N., R. 19 W.	100
Sec. 15, T. 58 N., R. 19 W.	92
Sec. 17, T. 58 N., R. 19 W.	40
Sec. 21, T. 58 N., R. 19 W.	165
Sec. 25, T. 58 N., R. 20 W.	108
Sec. 26, T. 58 N., R. 20 W.	100
Sec. 34, T. 58 N., R. 20 W.	89
Sec. 21, T. 59 N., R. 14 W.	18
Sec. 29, T. 59 N., R. 14 W.	50
Sec. 2, T. 59 N., R. 15 W.	55
Sec. 23, T. 59 N., R. 15 W.	15

the northwest, covering about twenty townships north of the Giants Range and a still larger area in the St. Louis basin south of the range. This ice sheet did not override the Giants Range in the area of St. Louis County. It crossed the range in Itasca County where the rocky ridge was lower, and then spread eastward along the south side of the range as far as T. 57 N., R. 14 W., in the area south of Allen Junction.

The moraine of Patrician drift that extends across the county in a northwest-southeast direction south of Vermilion Lake is correlated in age with the moraines of the Superior lobe of the southeastern townships in the region of Duluth. The Patrician drift to the south of the Giants Range was encroached upon by the Superior and Keewatin glaciers and consequently its deposits are buried beneath their respective drift sheets.

The Patrician drift is as a rule exceedingly stony both in the ridges and on the low areas. In the district between the Mesabi Range and Vermilion Lake there are rough and very stony strips interposed by nearly plane areas that are partly sand and gravel and partly stony drift similar to that in the moraines. On the Mesabi Range the drift is in places so thickly set with boulders as to form a pavement. This is especially true in the zone directly south of the Giants Range granite.

In the St. Louis basin south of the iron range much of the Keewatin (Mankato) drift is a clayey till with relatively few boulders. Near the St. Louis River and paralleling its course is a fine sandy drift deposit which borders the river for most of its course from the crossing of the Duluth and Iron Range Railroad down to the crossing of the Coleraine branch of the Duluth, Mesabi, and Northern Railroad. This same type of sandy deposit also spreads westward to within a few miles of the Mesabi Range in the drainage basin of Swan River. It apparently underlies a considerable part of the muskeg in the western part of the county.

The area of glacial Lake Upham is covered with a layer of fine-grained lake silt. The same deposit is exposed along the Floodwood River for many miles above its mouth and underlies the muskeg swamps for some distance north and west of Floodwood.

In the western part of the county on the borders of the Little Fork River and on the lower course of the Sturgeon River, there is an area of more than 200 square miles of clayey Keewatin drift deposits in which glacial boulders are not very common. Part of this area was once covered by the waters of Lake Agassiz and consequently the surface deposits are lake silts. These silts form a thin veneer over the rolling drift hills that characterize the topography.

ROCK FORMATIONS

Archeozoic

Archeozoic rocks are represented by the Keewatin greenstones, the Soudan iron formation, and later intrusives, some of which may be of

Laurentian age (Figure 38). On the Mesabi Range the ancient greenstones are exposed north and northwest of Nashwauk, northwest of Hibbing, north and northeast of Mountain Iron, and in the southerly projection of the Giants Range known as the Horn, which is bounded by the cities of Virginia, Eveleth, Sparta, and McKinley. Several large exposures occur also north of Biwabik.

In the region of Vermilion Lake the Keewatin greenstones (locally called the Ely greenstone) form a nearly continuous belt all across St. Louis County (Figure 38). They occur from the western border of the county in the region of Bear River eastward to the most westerly bays of Vermilion Lake, and from Tower northeastward through Ely and beyond to the Lake County boundary. This zone from Tower to Ely is 35 to 40 miles wide and is bordered on the north by the granites of the Vermilion batholith and on the south by the Giants Range granite. The greenstones contain smaller areas of younger sedimentary rocks and local intrusive masses of granites and porphyries.

The Keewatin greenstones are conspicuous not only because of their great extent, but also because of their influence on the topography. The rocks are resistant to weathering and consequently many of the high knobs in the topography are composed of them. Typical examples are the east-west ridges crossed by the highway between Tower and Ely.

The greenstones are mainly various types of basic lava flows that are given a general name rather than specific petrographic names because many of them have been so intensely altered by metamorphism that in the field it is often impossible to determine their true character or to discriminate between closely related varieties. Where they are less altered and less massive, the greenstone outcrops show one or more of three structures — ellipsoidal, amygdaloidal, and spherulitic. The ellipsoidal is the most conspicuous. When an outcrop is observed at a distance, the rock appears to be composed of a mass of ellipsoids varying from a few inches to several feet in diameter. These ellipsoids are set in a matrix of material not greatly different from the ellipsoids themselves, but usually of slightly different color and texture. The chief minerals are hornblende, biotite, altered plagioclase, and some chlorite and quartz. Many other minerals are present in varying amounts.

Because these highly altered rocks are very dense and compact, they are not a satisfactory source of ground water.

The Soudan iron formation is an iron-bearing chert that was deposited on and between the greenstone lavas as a laminated sediment. It thus represents the youngest unit of the Keewatin series. Geographically it is limited to the area of Keewatin greenstone, where it occurs in parallel belts half a mile wide and several miles long or in narrow stringers or patches surrounded by greenstone. These belts of outcrops parallel the general trend of the Vermilion Range and were produced by the erosion and truncation of folds. Most of them are synclinal in struc-

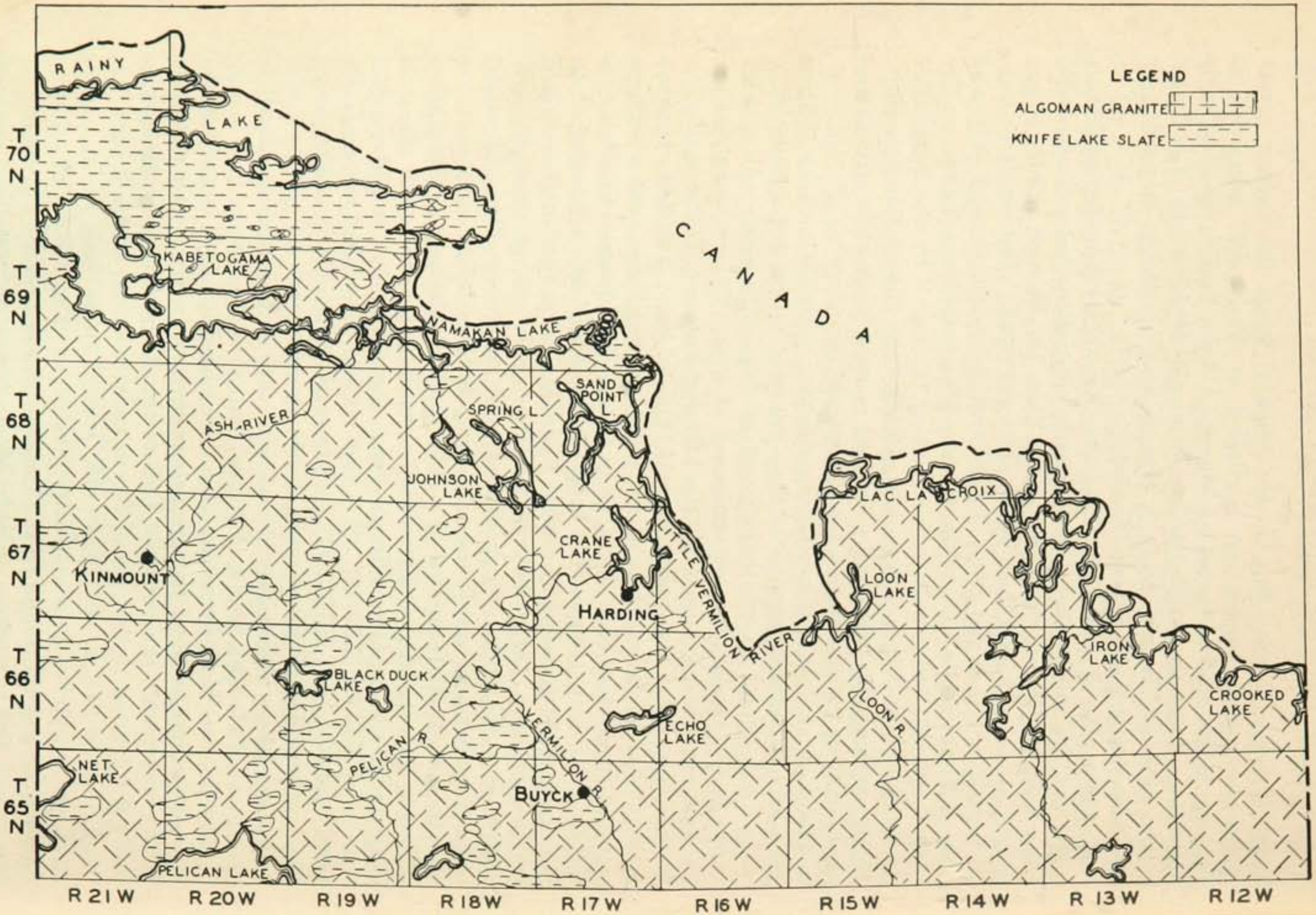
LEGEND
ALGOMAN GRANITE
KNIFE LAKE SLATE
CANADA
RAINY LAKE
KABETOGAMA LAKE
NAMAKAN LAKE
SAND POINT L.
SPRING L.
ASH RIVER
JOHNSON LAKE
LAC LA CROIX
CRANE LAKE
LITTLE VERMILION RIVER
LOON LAKE
KINMOUNT
HARDING
IRON LAKE
BLACK DUCK LAKE
LOON R.
CROOKED LAKE
ECHO LAKE
VERMILION R.
PELICAN R.
NET LAKE
BUYCK
PELICAN LAKE
T 70 N
T 69 N
T 68 N
T 67 N
T 66 N
T 65 N
R 21 W
R 20 W
R 19 W
R 18 W
R 17 W
R 16 W
R 15 W
R 14 W
R 13 W
R 12 W

FIGURE 37. — Geologic map of northern St. Louis County.

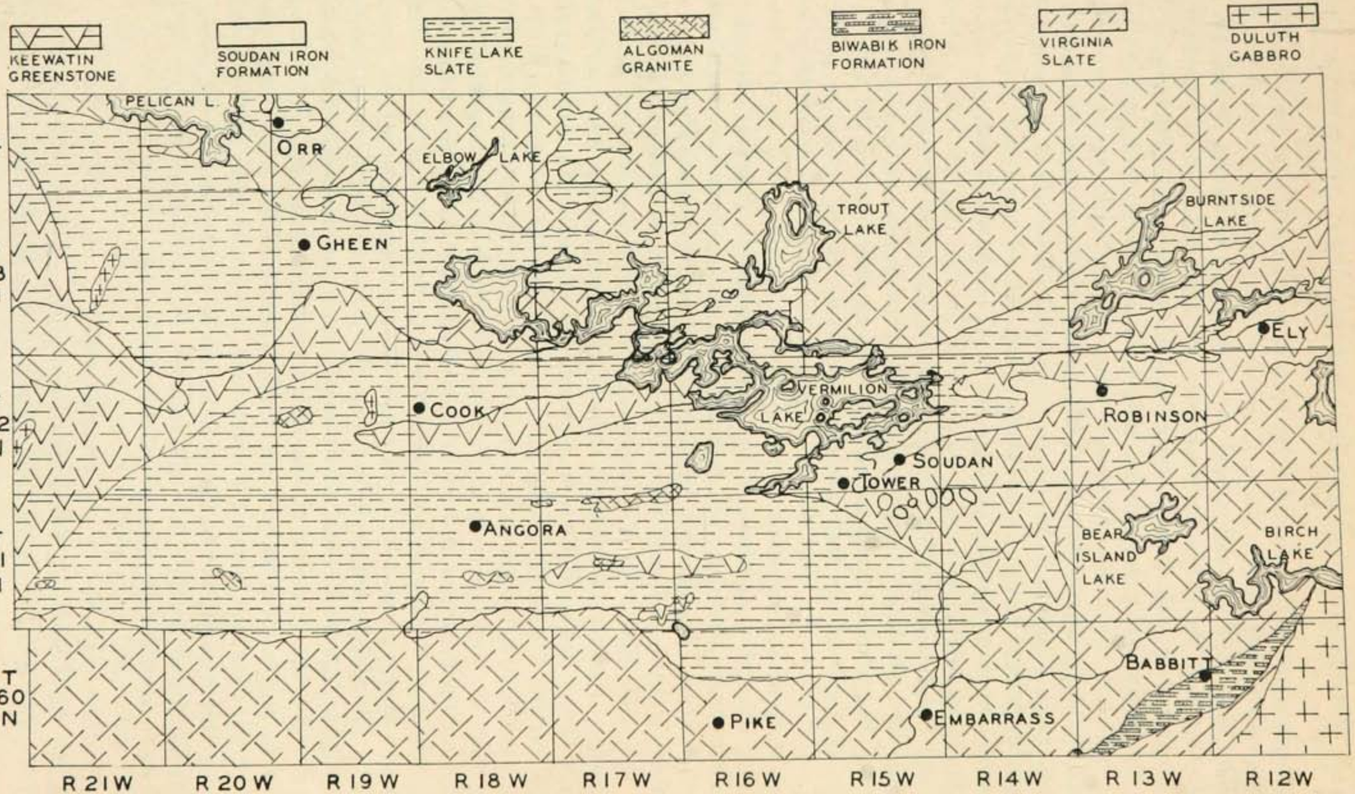

FIGURE 38. — Geologic map of north-central St. Louis County.

ture and represent the down-folded portions of folds that have not been removed by erosion.

The details of lithology and structure of the Soudan formation are well shown in the extensive exposures on Tower, Lee, and Soudan hills and on Jasper Peak east of the village of Soudan. The folding is of the most complicated character, with the major folds extending parallel to the trend of the range. However, cross-folding has been severe; many of the pitching anticlines and synclines are nearly vertical and some are overturned. The major folds and the cross-fold are all of the composite type; that is, second order folds are superposed upon the major folds in each direction, and upon these are folds of the third order, and so on down to minute plications.

The Soudan formation is composed of two quite different types of rocks. The dominant variety consists of interlaminated bands of finely crystalline quartz, iron oxides, and various mixtures of the two. This banded phase of the formation is commonly called jasper or jaspilite. At some places an argillaceous (clayey) variety is interstratified with the cherty or jaspery beds.

The banded or laminated cherts are composed of layers of material of different color which vary from a fraction of an inch to several inches in thickness. The siliceous bands may be nearly pure white, gray, red of various hues, or nearly black. The difference in color is caused chiefly by the contained iron. If hematite is present in the form of very fine particles, it produces brilliant red colors, whereas magnetite and hematite in larger particles produce gray and black cherts. The chief varieties of chert are (a) black-banded, (b) red-banded, (c) white-banded, and (d) massive gray to pink. Locally there is found a gray-banded variety that consists mainly of iron carbonate in the form of the mineral siderite.

Where fractured and shattered by faulting, the Soudan formation may produce small yields of ground water, but the bulk of the formation is too impervious to allow water to circulate freely.

The Laurentian series is represented by various felsites and porphyries that occur as dikes and small bosses. At some places in the Vermilion district the age relations of the smaller intrusive masses are extremely intricate and consequently their stratigraphic position is not established definitely. However, some are older than the Knife Lake slates, because they yielded fragments to the conglomerate at the base of the series.

None of the igneous intrusive masses of Laurentian age can be expected to produce supplies of ground water.

Proterozoic

Knife Lake Series.—The oldest Proterozoic rocks are the slates, graywackes, and conglomerates that constitute the Knife Lake or Temiskaming series. These rocks crop out in isolated areas along the north margin of the Mesabi Range between the Giants Range granite and the Pokegama quartzite. The largest area in the Mesabi district occurs north of Eveleth and northeastward toward Biwabik, extending as far as Sec. 34, T. 59 N., R. 16 W. North of the Giants Range and southwest of Vermilion Lake the Knife Lake slates are found exposed and under the glacial drift over an area covering about twelve townships. To the north of Vermilion Lake many small isolated areas occur as roof pendants in the Vermilion batholith.

The Knife Lake series is composed of many different kinds of rocks. Those found most abundantly are argillaceous slates, cherty slates, tuffaceous slates, graywacke slates, graywackes, micaceous schists, and gneisses and conglomerates. There are also all gradations between these varieties. Structurally the slates are folded in a very complex fashion. Usually the linear areas of outcrops are in synclines between anticlines composed of the Keewatin or Ely greenstones. Since the slates are relatively nonresistant, many of the lakes in the north-central part of St. Louis County are in the centers of synclines. Burntside Lake and Vermilion Lake are typical examples.

Because of the complicated folding of the Knife Lake series, the total thickness of the slates has not been determined with any degree of exactness. However, the extent of the area which is profoundly folded leaves no doubt that the formation is thousands of feet thick.

The Thomson formation, correlated with the Lower Huronian or Knife Lake series by Schwartz,[2] crops out in Sec. 20, T. 49 N., R. 15 W., near the base of an escarpment of Middle Keweenawan basalt flows. It may be seen also along the headwaters of the Midway River in Sec. 6, T. 49 N., R. 15 W., where its slaty rocks are converted into a hornfels by the intrusion of the Duluth gabbro. Figure 39 shows the field relations in the area west of Duluth.

Algoman.—The deposition of the Knife Lake series was followed by the intrusion of the Algoman granite batholiths and related intrusive masses. The granites are exposed extensively in the Giants Range and in the area of the Vermilion batholith north of Vermilion Lake. The Giants Range granite occurs in a zone from one to three townships wide from White Iron Lake southwestward across the county. At the western county line the southern limit of the granite occurs in T. 57 N., and the most northerly outcrops occur in the southern part of T. 61 N., about 5 miles south of Bear River. The belt of granite trends nearly parallel to the strike of the adjoining rocks. It is bordered on the north by the Ely greenstone and Knife Lake slate and on the south chiefly by the Animikean series of the Mesabi iron-bearing district. At the eastern border of the county the Duluth gabbro cuts across the southeastern edge. This great granite mass is composed of a succession of different facies, some grading into each other and others showing abrupt contacts.

[2] Schwartz, G. M., Correlations and metamorphism of the Thomson Formation, Minnesota: Geol. Soc. Am. Bull., vol. 53, pp. 1001–1020, 1942.

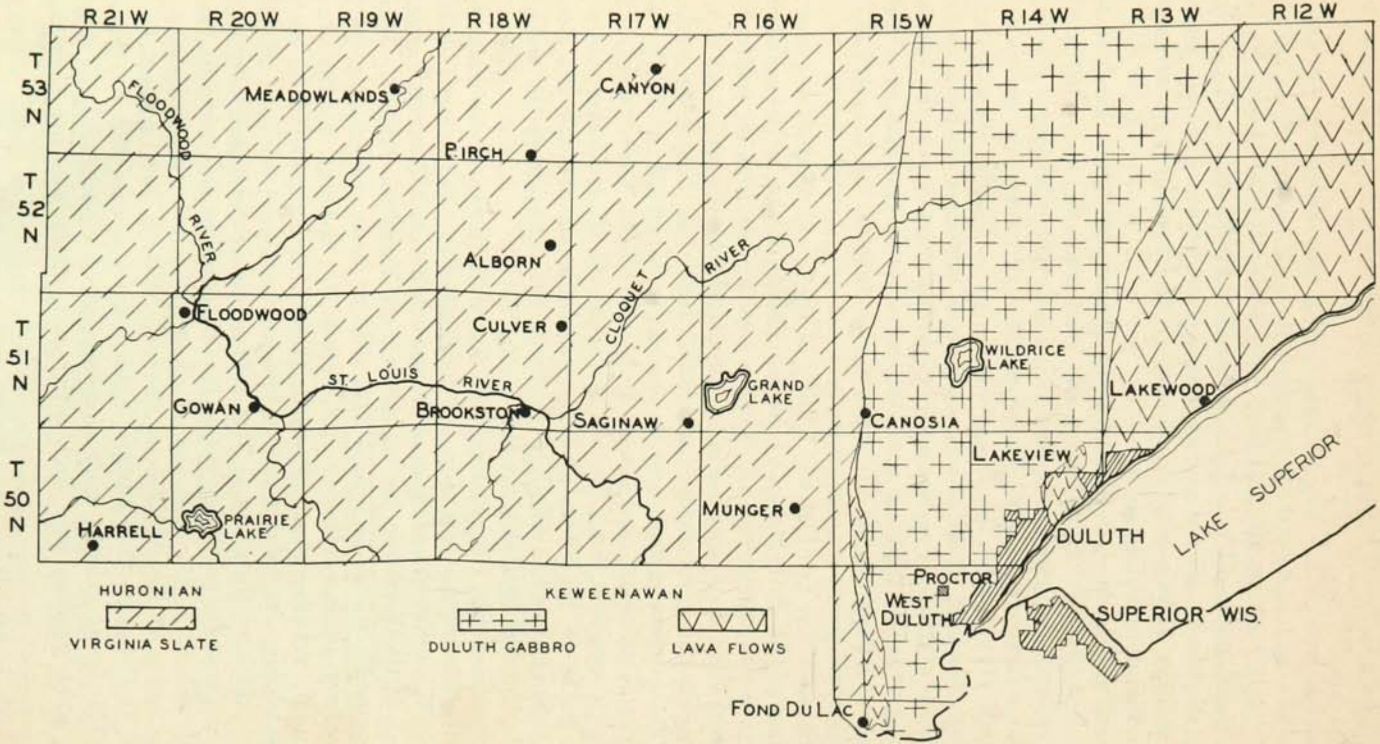

FIGURE 39. — Geologic map of southern St. Louis County.

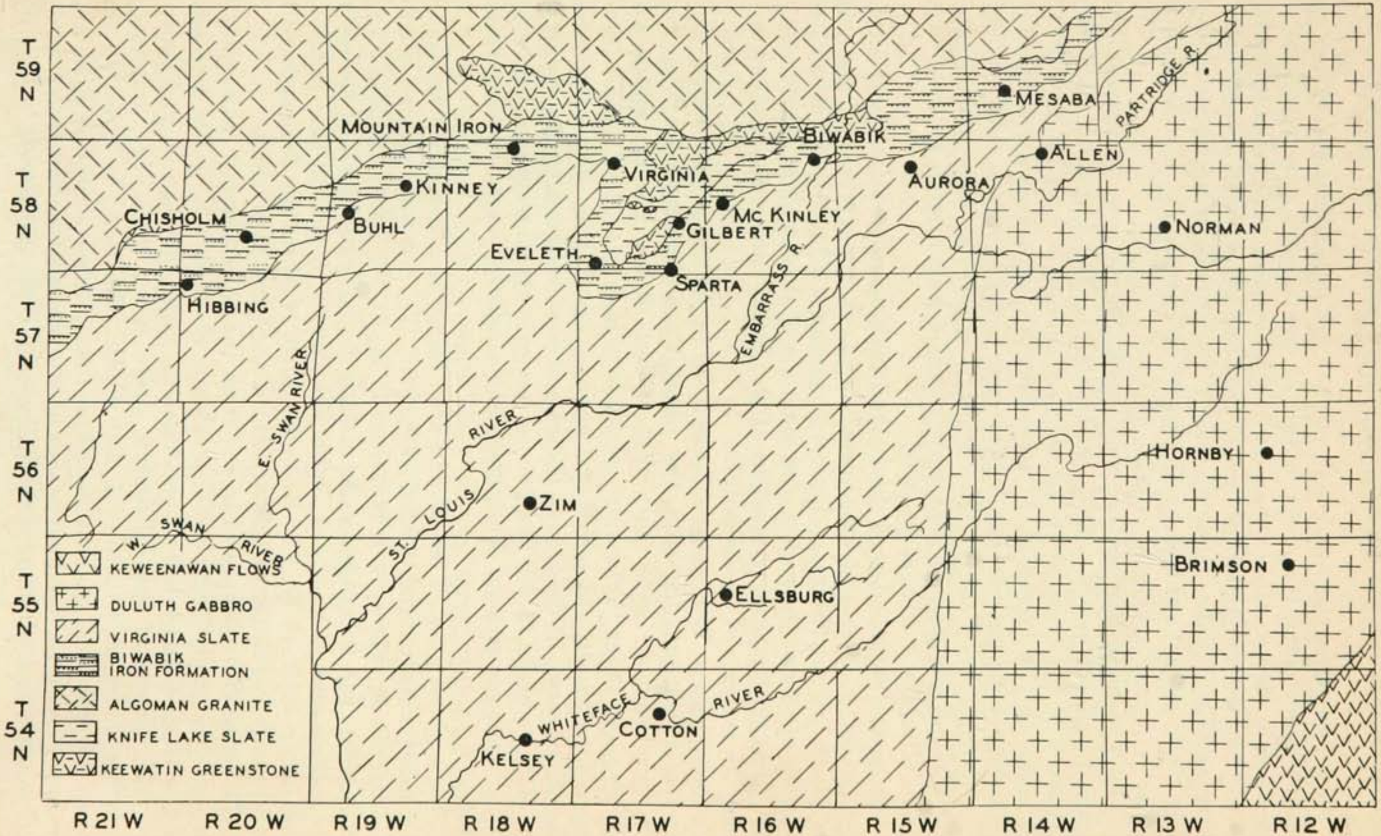

FIGURE 40. — Geologic map of south-central St. Louis County.

At a few places the south wall of the batholith is exposed. These exposures occur along the north margin of the iron-ore producing zone of the Mesabi Range, where the younger Animikean beds do not overlap on the granite. The outcrops in such locations show the Keewatin greenstone and Knife Lake slates in a nearly vertical position, indicating that they were thrust upward by the force of injection of the batholithic mass.

The Vermilion batholith occupies most of the area of northern St. Louis County from T. 63 N. northward to the Canadian boundary (Figure 37). Outcrops of the granite are numerous over an area 30 by 80 miles. In the northwestern townships the rock is largely concealed under the drift, but the granite probably extends only a short distance into Koochiching County. Mica schist is exposed at many points along the Little Fork River where granite would be expected to form even larger outcrops if it were present.

Along the south edge of the batholith the contact is so complicated by numerous dikes and other small intrusive masses that no line can be drawn as a satisfactory limit or boundary. The granite intrudes all the older rocks of the region, and inclusion of the Archeozoic greenstone, the Soudan formation, and rocks of the Knife Lake series are common near the margins of the batholith.

Animikean.—The rocks of Animikean or Huronian age, represented by the Pokegama quartzite, the Biwabik iron-bearing formation, and the Virginia slate, occur south of the Giants Range granite (Figure 40). These rocks enter the county in the east in T. 61 N., R. 12 W., and extend southwestward across the entire county. They occur in all the townships south of the Giants Range and west of the range line between R. 15 W. and R. 16 W. There are very few natural outcrops, but some of the rocks are exposed in the walls of the open-pit mines on the Mesabi Range.

Throughout most of the Mesabi Iron Range the Animikean rocks rest unconformably on the eroded surface of the Algoman granite of the Giants Range (Figure 41). However, in R. 21 W., north and northwest of Hibbing, the Animikean rocks rest on the truncated folds of Keewatin greenstone and rocks of the Knife Lake series. A similar field relationship occurs in R. 17 W., and R. 18 W., north of Mountain Iron and north of Virginia, and in the area of the Horn northeast of Eveleth.

The term *Horn* is applied to a spur on the Giants Range that projects in a southwesterly direction for 6 miles in R. 17 W. The entire core area of the Horn is composed of pre-Algoman rocks that have been exposed by the removal of the Animikean strata which were once continuous over the domelike structure of that region. This dome is in reality the northern end of a pitching anticline that pitches southwestward and extends beyond the productive zone of the Biwabik iron formation. Along the western limb of the fold the Animikean rocks dip toward the north-

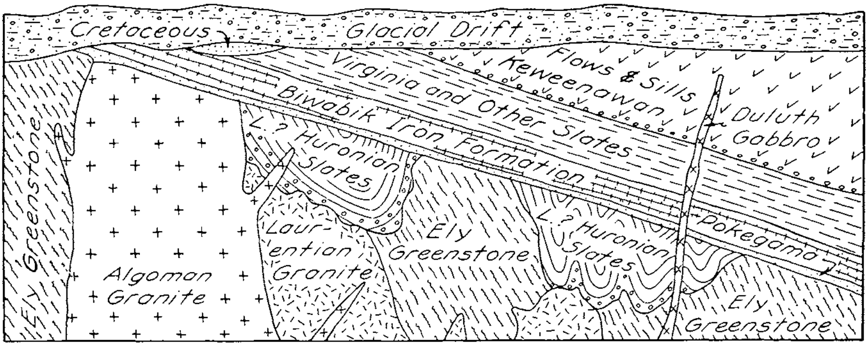

FIGURE 41. — Generalized cross-section showing the subsurface relations of the rocks of the Mesabi Range. After geologic map by Minnesota Geologic Survey.

west, producing a synclinal structure, the axis of which extends from Sec. 33, T. 59, R. 17 W., southwestward through Virginia Lake and thence in a northeast-southwest direction across T. 58 N., R. 18 W. South of Eveleth in the region of the Fayal mine the Animikean rocks dip to the south and at Genoa, Gilbert, Corsica, and McKinley the dip is toward the southeast.

The lithology of the individual formations of the Animikean series as they are exposed on the Mesabi Range is given in the report on Itasca County.

The main portion of the Animikean series in St. Louis County is the Biwabik iron-bearing formation and the Virginia slate. Below these, however, there was deposited a sand of more normal sedimentary character than the cherty iron-bearing rocks. This is the Pokegama quartzite, which has at its base a conglomerate that shows pebbles from the underlying formations. The quartzite rests with a marked angular uncon-

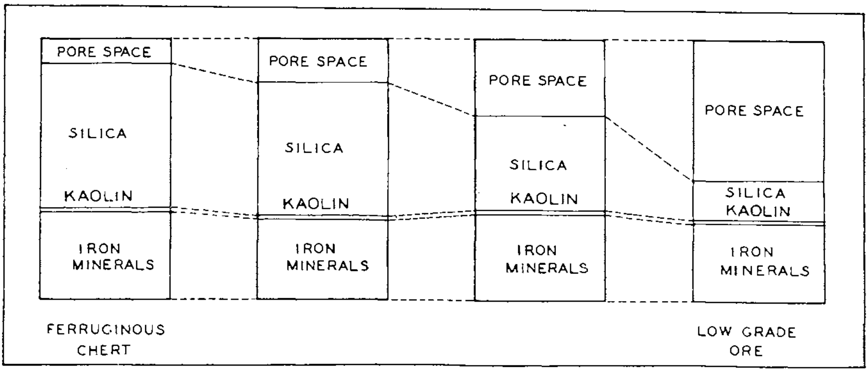

FIGURE 42. — Diagrammatic sketch showing the increase in pore space as ferruginous chert is converted to low-grade ore. After C. K. Leith.

formity on the truncated folds of the Knife Lake series of slates and graywackes, on the Algoman granites, and on the Archean greenstones. The quartzite outcrops are located in a belt between the north margin of the iron formation and the ridge of granite and older rocks of the Giants Range. The formation ranges from a few feet to over 200 feet in thickness. It includes vitreous quartzite of various colors and textures, micaceous quartz, slates, and conglomerates.

The Biwabik iron formation is composed of rocks that are classified as ferruginous cherts. They have a peculiar granular texture and consist of chert, iron silicates, iron oxides, and carbonates. They are exceedingly hard and dense and have a low porosity. However, as these cherty rocks are weathered and oxidized, the silica is leached out and the iron minerals are changed to limonite and hematite. During this process the porosity is greatly increased (Figure 42) and thus the formation may locally become an aquifer for artesian circulation or a reservoir rock for water-table wells. Where the oxidation and leaching has converted the

TABLE 47. — CHEMICAL AND PHYSICAL ALTERATION OF FERRUGINOUS CHERT*

	Chemical Composition		Approximate Volume Composition
	Fe	SiO_2	(pore space)
Series 1, Stevenson mine	29.47	52.89	8.00
	33.01	50.08	16.50
	35.26	43.44	26.30
	48.88	25.03	52.70
Series 2, Stevenson mine	44.33	34.24	38.00
	45.30	31.05	39.70
	48.51	26.42	42.40
	49.18	23.60	45.40
Series 3, La Rue mine	32.26	50.78	4.00
	38.84	42.69	23.20
	44.49	34.33	24.20

* Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior Region, U.S. Geol. Survey Mon. 52, p. 188, 1911.

ferruginous chert into iron ore, the ore body may be more than five times as porous as the original massive chert. This change in porosity is illustrated in the analyses reported in Table 47. In each series of specimens the decrease in SiO_2 is accompanied by an increase in porosity. Since the ferric iron oxides are only very slightly soluble in ground water, the oxidized cherts and iron ore bodies yield water with a low content of dissolved iron. (See Table 52.)

The Virginia slate overlies the Biwabik formation conformably, but owing to the dip of the Animikean series, the slate occurs to the south of the outcropping edge of the iron formation. The slate is gray to greenish-gray in color and varies in hardness. The total thickness of the formation is probably several thousand feet, but as a result of erosion it wedges out to the vanishing point along its north margin where it is in contact with the iron formation. The slate is exceedingly fine-grained and impervious and consequently yields very little ground water.

Keweenawan.—The three subdivisions of Keweenawan rocks are represented in St. Louis County. The Lower Keweenawan conglomerate, the Puckwunge, crops out along the St. Louis River in Sec. 1, T. 48 N., R. 16 W., where it is a quartz-pebble conglomerate. A similar conglomerate rests directly on the Thomson slates in the bed of the St. Louis River in Sec. 15, T. 48 N., R. 16 W. Farther to the north the upper part of the Puckwunge formation crops out under a massive ledge of basalt that represents the lower part of a Middle Keweenawan lava flow. At this outcrop the Puckwunge is a massive and dense quartzite. The formation as a whole is so impervious that it cannot be considered as a source of ground water.

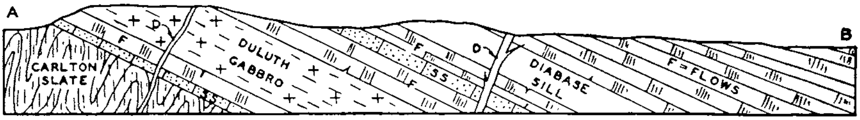

FIGURE 43.—Generalized cross-section showing the relation of the Duluth gabbro to the basalt flows and to the Thomson (Carlton) slate near Duluth. After Sandberg.

The Middle Keweenawan rocks are mainly lava flows and gabbro with local intrusive sills and dikes of diabase. These rocks occur from Duluth northeastward to the Knife River and northward to Birch Lake. They extend westward into T. 48 N., R. 15 W., near Gary, and from there northward to Birch Lake. Most of this area is occupied by the Duluth gabbro, which is too massive and impervious to produce more than very small supplies of ground water.

Lava flow rocks occur along the shore of Lake Superior from Duluth northeastward to beyond the eastern border of the county, where they extend inland for about 15 miles. The flows dip toward the lake (Figure 43) and their upper porous units allow a considerable amount of ground water to move down dip toward the lake. Thus a well drilled near the lake penetrates a number of lava flows, and the upper porous units of each contribute some water to the well. Consequently wells from 150 to 250 feet in depth may yield from 2 to 10 gallons of water per minute.

The Upper Keweenawan is represented by the Fond du Lac beds. These sediments are mainly red to pink arenaceous shales and red to brown argillaceous to arkosic sandstones. They form conspicuous cliffs along the St. Louis River southwest of Duluth. Their total thickness is not known, but the formation is undoubtedly more than 2000 feet thick. The geographic extent of the Fond du Lac beds has not been determined, but an outcrop has been reported as far north as Floodwood. However, this observation has not been verified.

The accompanying section of the Fond du Lac is exposed in the east bluff of the St. Louis River in the SE¼, Sec. 6, T. 48 N., R. 15 W., near Fond du Lac.

Section of Fond du Lac Bed, SE¼, Sec. 6, T. 48 N., R. 15 W.*

	THICKNESS (feet)
6. Sandstone, massive, medium-grained, dark red, with white mottling	11
5. Sandstone, cross-bedded, gray to yellow	10
4. Sandstone, massive, cross-bedded, gray to reddish brown, medium to fine	8
3. Sandstone, massive, cross-bedded, ferruginous. Contains thin layers of sand and grit	10
2. Sandstone, massive, ferruginous. Conglomeratic zone near top, with flat pebbles of quartz and red and green shale	8
1. Talus to level of St. Louis River	15

*Tyler, S. A., Marsden, R. W., Grout, F. F., and Thiel, G. A., Studies of the Lake Superior pre-Cambrian by the accessory-mineral methods: Geol. Soc. Am. Bull., vol. 51, p. 1514, 1940.

Section of Fond du Lac Bed in Bank of Mission Creek, Near Fond du Lac

	THICKNESS (feet)
Sandstone, light gray to red, fine-grained, coherent, massive beds of variable thickness	13
Shale with green and red sandy layers	3
Sandstone, massive, gray, medium to fine, cross-bedded	4
Shale, red, thinly laminated	4
Sandstone, gray to red with micaceous parting	3
Shale, thinly laminated, chocolate brown	2
Sandstone, massive, ferruginous	3
Sandstone, gray, medium to fine, thinly bedded, slabby, with green and red shale seams	4

The geographic relations along the St. Louis River suggest that faulting has displaced the basal beds of the Fond du Lac to a position far below the present outcrops of the Middle and Lower Keweenawan strata in that region. The Thomson slate is exposed in the bed of Little Creek just north of the center of Sec. 1, T. 48 N., R. 16 W., and other exposures of slate continue at intervals up Little Creek as far as the tracks of the Northern Pacific Railway in Sec. 35, T. 49 N., R. 16 W. Downstream from the slate exposure, at the mouth of a small creek which joins Little Creek from the north, is an exposure of quartz-pebble conglomerate. The exact contact between slate and conglomerate is not exposed here, but a similar conglomerate is found directly on the slate in the bed of the St. Louis River in Sec. 15, T. 48 N., R. 16 W. The accessory minerals in the matrix of the conglomerates at the two locations are very similar and both are undoubtedly of Lower Keweenawan age. A short distance downstream from the conglomerate on Little Creek in Sec. 1 is an outcrop of red, arkosic sandstone that has the lithologic and petrographic characteristics of the Fond du Lac beds. It is quite possible that a fault passes between the two outcrops and that the Upper Keweenawan is in contact with the Lower Keweenawan along the fault plane. This interpretation is given added support by the results of drilling for the foundation of the dam on the St. Louis River in SW¼, SW¼, Sec. 6, T. 48 N., R. 15 W. A drill hole penetrated alternating red shale and sandstone beds from an elevation of 606 feet to 500 feet without reaching the Lower Keweenawan conglomerate or the Thomson slates. The distance between the quartz-pebble conglomerate in Sec. 1 and the dam is no more than three-fourths of a mile, but the unconformable surface drops an unknown amount more than 180 feet in that short distance.

Both Winchell and Thwaites reported faults across the valley of the St. Louis River.[3] Thwaites included a photograph of a normal fault with a displacement of 14 feet in the arkosic grits and sandstones in the gully just above the railway bridge in Sec. 1, T. 48 N., R. 16 W. He states that another normal fault of at least 40-foot displacement cuts the red shales and sandstones exposed in the north bank of the St. Louis River near the line between St. Louis and Carlton counties.

It is quite possible that the grayish-green sandstone with pebbles of Middle Keweenawan basalt which crops out along Little Creek near the quartzite-pebble conglomerate in Sec. 1 is equivalent in age to the interflow sandstones that occur farther to the north in the region of the Short Line Park. If such is the case, then the Lower, Middle, and Upper Keweenawan sandstones are in direct contact with each other in Secs. 1 and 6, T. 48 N., R. 16 W. The Middle Keweenawan sediments may lie unconformably over those of the Lower Keweenawan, and the Fond du Lac beds of the Upper Keweenawan are faulted down in juxtaposition with the older strata. Since no basaltic flows are known to extend southwestward beyond Sec. 32, T. 49 N., R. 16 W., it is reasonable to suppose that sediments of Middle Keweenawan age were deposited around the outer margin of the flows.

It is equally difficult to draw a sharp boundary on contact at the top of the Fond du Lac beds. The red color that characterizes these clastic sediments is not in itself a safe criterion for establishing the lithologic boundary that separates them from the overlying Hinckley sandstone. However, a detailed study of numerous drill cuttings and outcrop samples from widely separated areas has shown a marked difference in the quantity and character of the feldspar in the two formations. These differences are discussed in the report on Carlton County.

Cretaceous System

Marine sedimentary rocks of Cretaceous age occur as a mantle over the unevenly eroded surface of the Animikean rocks. Cretaceous strata

[3] Winchell, N. H., The geology of Minnesota: Final Rept., Minn. Geol. and Nat. Hist. Survey, vol. 4, p. 13, 1899; Thwaites, F. T., Sandstones of the Wisconsin coast of Lake Superior: Wis. Geol. and Nat. Hist. Survey, Bull. 25, pl. XV, p. 70, 1912.

are exposed in the walls of the open-pit mines near Hibbing and Virginia. Bergquist gives the following field description.

"*Near Hibbing:* — Cretaceous materials occur as irregular fillings in depressions in the eroded surface of the tilted Biwabik iron formation in the Sellers townsite pit at North Hibbing. In places the initial deposit is a coarse rounded-pebble conglomerate with boulders of taconite and porphyry and pieces of quartz and highly polished pebbles and cobbles of hematite and limonite in a light-colored laminated gritty matrix. Some of the boulders are over a foot in diameter. Either above the boulder conglomerate or directly on the eroded taconite, is a flat-lying bed of light-colored, fine angular pebble conglomerate. Most of the angular fragments are only an eighth to one-half inch in diameter and are composed of red earthy hematite from the underlying formation. This bed is of variable thickness; as much as 12 feet was exposed in the east face in 1928, while along the south face a thickness of 5 to 20 feet included a thin layer of fine angular hematite-pebble conglomerate, firmly cemented in a cherty green matrix and separating overlying material of the same light-colored conglomerate. Apparently the Cretaceous sediment is of nonmarine origin. No fossils have been reported from the mine.

"In the south face of the Sellers pit the Cretaceous is overlain by 30 feet of red drift succeeded by 10 to 30 feet of stratified clay, sand and gravel with 25 feet of gray drift above. In the east face of the pit 16 feet of stratified glacial sands and gravels overlie the Cretaceous and iron formations and in turn are covered by about 35 feet of gray drift with large boulders.

"Drill records from the Scranton pit in North Hibbing indicate that the Cretaceous conglomerate was somewhat thicker than 100 feet in the middle of the pit but thinned laterally to about 10 feet on the sides. The Cretaceous sediments apparently were continental fillings of an old erosion channel, with the top beds of flat-laying materials. On the north side of the pit a bench exposed 18 feet of massive and blocky conglomerate containing coarse angular and fine round pebbles cemented by a green cherty matrix. The top 4 feet showed slight bedding.

"*Near Virginia:* — At Virginia the conglomerate occurs in local patches. A hard massive conglomerate 3 to 6 feet in thickness was encountered during operations in the south face of the Alpena pit and in the north side of the Sauntry pit. Some likewise occurred in the Missabe Mountain pit but was removed during operations. The pebbles of the conglomerate are angular and range from small fragments to pieces a foot in diameter firmly cemented in a red massive cherty matrix. This conglomerate, like that found near Hibbing, may have been deposited as continental material east of the marine beds. Fossils have not been found, and the variation in size and the angularity of rock fragments suggest short transportation."[4]

MUNICIPAL WATER SUPPLIES

Duluth

In the vicinity of Duluth the upper surface of the bedrock formation is very irregular. The Duluth gabbro crops out at elevations ranging up to approximately 800 feet above the level of Lake Superior and numerous outcrops of the Keweenawan lava flows occur on the slope of the hill, down to and beneath the level of Lake Superior. Southwestward in the valley of the St. Louis River, the bedrock surface is from 250 to 350 feet below the lake level and at Superior several wells have been drilled to a depth of 550 feet before encountering bedrock.

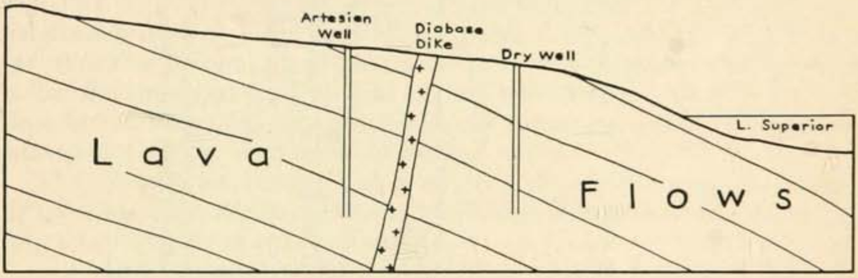

Figure 44. — Generalized cross-section showing the influence of dikes on artesian circulation along the north shore of Lake Superior.

Since most of the rock at Duluth is of volcanic origin, it is too impervious to yield large supplies of ground water. There are a large number of private wells in the city, but most of them drilled into the rock have a yield of less than 25 gallons per minute.

The city of Duluth obtains the water for its public supply system from Lake Superior. The Lakewood Pumping Station, located at the northeastern extremity of the city, is equipped with a steel intake pipe 60 inches in diameter and 1560 feet long. This pipe rests on the floor of the lake and its open end is more than 1500 feet out from shore. Here the water is 72 feet deep. The pipe is held in place by a series of rock-filled cribs and the end is covered by grating. The lake water is pumped to the Lakewood detention basin, which has a capacity of 4 million gallons. From this basin the water is distributed to a series of reservoirs and tanks, the highest of which are 916 feet above the level of the lake. Figure 45 shows the plan of construction at the Lakewood Pumping Station.

[4] Bergquist, Harlan R., Cretaceous of the Mesabi Iron Range, Minnesota: Jour. Paleontology, vol. 18, pp. 3–4, 1944.

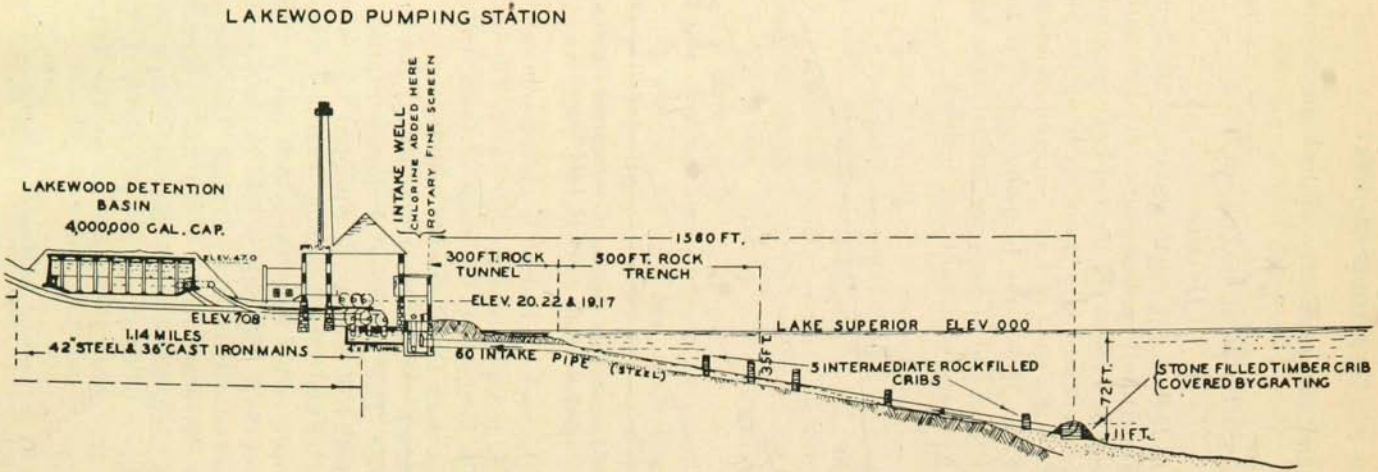

FIGURE 45. — Diagrammatic section showing the construction of the intake of water from Lake Superior at the Lakewood pumping station, Duluth. After Duluth Water Department Report.

The water is treated as follows:

"Our method at present calls for a dose of 1 ppm. residual chlorine entering the Detention Basin. This test is made by the Lakewood operators every hour and the chlorine feed is adjusted to be right on the line. Considerable variation of the chlorine feed is necessary depending on the temperature and contamination of water. The 'flash test' for 'active' residual chlorine is also taken by the operators to check the chlorine reaction. In our testing this is taken after a ten minute reaction period and has averaged up to about 90 per cent of the total residual chlorine. If the 'flash test' was less than 80% of the standard technique it would be evidence that chlorine compounds that are less active were present. This type of treatment results in a stable residual going through the detention basin and coming back as high as .8 ppm. Our average residual here in the downtown laboratory is .5 ppm. The ammonia feed to the basin return is used to check the taste and odor of chlorine and to keep up a stable residual through the distribution system. The ammonia feed has to be in a very close range to produce a uniform taste and has averaged up less than we were using in the first part of the year. Efficient sterilization is assuming greater and greater importance in the treatment of surface water." [5]

The influence of meteorological changes during the year on dosages of chlorine and ammonia and the variations in physical and biological characteristics are shown in Table 48.

A number of years ago the city of Duluth drilled a group of ten wells on the flats of the St. Louis River in New Duluth. These wells terminated in the glacial and alluvial fill of the valley at a depth of 250 to 300 feet. They produced from 20 to 50 gallons per minute, but they are no longer connected with the city water supply system. The accompanying log shows the nature of the sediments.

Well at New Duluth, Sec. 9, T. 48 N., R. 15 W. (elevation 610 feet)

		DEPTH (feet)	THICKNESS (feet)
Glacial drift and alluvium	Red clay	0–2	2
	Soft muddy sand	2–81	79
	Coarse sand	81–88	7
	Red clay	88–112	24
	Quicksand	112–200	88
	Muddy sand	200–270	70
	Fine sand	270–278	8
	Gravel and sand	278–280	2

The deepest well in the vicinity of Duluth was drilled at the Short Line Park station in 1888. The top of the well is at an elevation of about 900 feet above sea level, or 300 feet above Lake Superior. It was drilled to a total depth of 1517 feet. A condensed summary of the log follows.

[5] Water, Gas and Sewage Disposal Department of the City of Duluth, 46th Annual Report, p. 8, 1944.

TABLE 48. — WATER PURIFICATION, LAKEWOOD STATION, DULUTH, 1944

Month	Total Number of Gallons Treated	Prevailing Wind Direction	Water Temperature (Degrees F.)	Mean Air Temperature (Degrees F.)	Precipitation (Inches)	Ammonia Dosage (p.p.m.)	Chlorine Dosage (p.p.m.)	Residual Chlorine (p.p.m.)	Total Bacteria (cc., 48 Hours at 37° C.)	Turbidity	Alkalinity	Dissolved Oxygen
January	374,270,000	W.	36	21.9	.57	.219	.852	.71	2	.9	44.0	11.40
February	358,250,000	N.W.	34	14.4	.82	.216	.855	.71	2	.0	43.0	11.40
March	387,130,000	N.W.	33	21.7	1.64	.222	.840	.71	2	.0	44.0	12.50
April	387,690,000	N.E.	32	37.0	.78	.220	.843	.70	13	.4	44.0	11.60
May	399,660,000	N.E.	34	51.2	7.12	.216	.878	.70	6	1.1	43.0	11.10
June	405,330,000	N.E.	36	58.4	6.19	.201	.921	.71	8	.7	44.5	10.15
July	432,960,000	N.W.	39	64.8	1.89	.149	1.129	.73	7	.3	43.5	9.40
August	458,660,000	N.E.	46	65.0	5.90	.152	1.006	.72	15	.0	43.0	8.30
September	421,870,000	E.	51	55.9	2.43	.182	1.219	.87	6	.7	43.5	8.90
October	423,930,000	W.	47	47.4	.46	.183	1.414	1.00	18	.6	44.0	9.00
November	393,230,000	N.E.	43	34.1	2.40	.188	1.304	1.00	6	2.3	45.0	9.20
December	404,120,000	N.W.	39	15.2	.35	.188	1.342	1.00	10	.6	43.5	10.10
Average	403,925,000		39	40.6	2.55	.195	1.050	.80	8	.6	43.8	10.25

Short Line Park Deep Well*

	FEET
Drift and red sandstones	231.0
Eruptives (surface flows, etc.)	217.0
Pyritiferous quartzites and quartz conglomerate	48.0
Surface flows as at Duluth	91.0
Slates as at Thomson	930.5
Total	1517.5

*For a detailed description of samples, see N. H. Winchell, The geology of Minnesota: Final Rept., Minn. Geol. and Nat. Hist. Survey, vol. 4, pp. 567–569, 1899.

Many years ago a deep well was drilled at the brewery at 29th Avenue West and Bay Front in an attempt to find a supply of cold, artesian water to be used in the brewing of beer. The well entered the Duluth gabbro at a depth of approximately 170 feet below the surface and drilled into it for about 800 feet. Only a very limited amount of water was obtained from fractures in the gabbro, and the water became progressively more saline with depth. The most abundant salts were sulphates of sodium, magnesium, and calcium. Drilling was discontinued at a depth of 975 feet.

Wells in the Lava Flows.—From the base of Minnesota Point northeastward, most of the rock formations in Duluth are lava flows that dip toward the lake at a low angle. The upper part of many of the flows is somewhat porous and vesicular. Since such porous units crop out on the catchment area of the hillside, any appreciable amount of rain water and melt water from snow sinks into the rocks and flows underground down toward the lake. Wells drilled through a series of such lava flows intercept the water that is trapped under the impervious lower part of the individual flows (Figure 43). There the water is under sufficient hydrostatic pressure to lift it to near the surface in a drilled hole or well. Many of the wells in the northeastern part of Duluth are of this type. The yield of water is generally small but quite permanent. The following well is a typical example.

Golf Club Well, 34th Avenue, East Duluth*

		DEPTH (feet)	THICKNESS (feet)
Drift and fill	Sand and clay	0–8	8
Keweenawan	Basalt	8–380	372

*The yield of water is 3 to 5 gallons per minute. Data from E. W. Dotten, Cromwell.

Wells in the Duluth Gabbro.—The Duluth gabbro occurs directly beneath a thin mantle of glacial drift in the area west of Miller's Creek and southward toward New Duluth. In this area ground water must be obtained from the glacial drift. A number of deep wells have been drilled into the gabbro, such as the deep brewery well in Duluth, but the yield is very meager and of poor quality.

At the Duluth Homestead Resettlement Project in T. 50 N., R. 15 W., the gabbro crops out at the surface on several of the small farm plots. Where the rock is covered with drift, the glacial deposits are too thin to yield a large supply of ground water. Thirty wells have been dug or drilled in this area and nearly all terminate on the upper surface of the gabbro. None produce satisfactory quantities of water from the gabbro.

A number of wells have been drilled into the gabbro on the small farms along the Hermantown Road to the west of the city in Sec. 27, T. 50 N., R. 15 W. No adequate supply of water was obtained. The accompanying log is typical of that area.

Gabbro Well, Sec. 27, T. 50 N., R. 15 W.*

		DEPTH (feet)	THICKNESS (feet)
Drift	Red sandy clay	0–9	9
Duluth gabbro	Dark gray rock	9–275	267

*Data from Ray Lacy, driller, Duluth.

Wells in the Glacial Lake Sediments.—The waters of glacial Lake Duluth (Figure 36) once covered the hillside where the city now stands to an elevation of more than 500 feet above the present level of Lake Superior. Great quantities of glacial sediments were deposited on the floor of the lake during that period. This was especially true in the area of West Duluth, where the glacial St. Louis River deposited delta-like sediments over what are now the flats along the river. As the water level of the lake was lowered, the velocity of the inlet streams was accelerated and deep valleys were cut into the glacial sediments that were once under the lake water. The valley of the St. Louis River in Jay Cooke Park is entrenched more than 100 feet in such sediments. The gravels, sands, and clays eroded during such entrenchment were transported northeastward and redeposited in the lake. Thus in and around the bay near the mouth of the St. Louis River reworked sediments were deposited in a thickness of 300 to 500 feet.

During recent geologic time the area of the south shore, opposite Duluth, and the area east of Fond du Lac have subsided, allowing the waters of the lake to occupy the valley of the St. Louis River. The valley now has all the characteristics of a drowned valley as far westward as New Duluth.

Numerous wells have been drilled in these sediments around the southwestern bay. A log of one of the city wells drilled in New Duluth is given on page 231. A well at the steam plant of the Minnesota Power and Light Company at 50th Avenue West and the St. Louis River terminates in coarse sand and gravel at a depth of 265 feet. Similar conditions exist along the south side of the valley. The accompanying log of the Great Northern Railway Company at Superior, Wisconsin, illustrates the nature and thickness of the sediments over the bedrock surface.

Well No. 2, Great Northern Railway Company, Superior, Wisconsin, Drilled 1942*

		DEPTH (feet)	THICKNESS (feet)
Lake and glacial sediments	Sand and gravel	0–7	7
	Red clay	7–47	40
	Red clay and gravel	47–100	53
	Red clay and sand	100–135	35
	Boulders	135–137	2
	Red clay and fine sand	137–270	133
	Boulders	270–271	1
	Red clay	271–285	14
	Boulders	285–286	1
	Red clay	286–319	33
	Boulders	319–320	1
	Sandy red clay	320–346	26
	Hard fine sand	346–495	149
	Hard red clay	495–527	32
	Very coarse gravel	527–543	16
	Red clay	543–550	7
	Rock	entered	

*Data from the Layne-Western Well Company.

Wells near the North Shore of Lake Superior

Wells at and near Palmers Station.—The well at the station is 5 inches in diameter and 176 feet deep. It penetrates 55 feet of glacial drift and 121 feet of basaltic lava rock. The hole is cased to a depth of 74 feet. The average yield is 3 gallons per minute.

A well on the farm of J. Huhta near Palmers encountered rock at a depth of 45 feet and was drilled to a total depth of 125 feet. It produces about 2½ gallons per minute from a casing 5 inches in diameter.

On the farm of M. Aketh near Palmers the glacial drift is 143 feet thick. A well terminating at a total depth of 202 feet produces 20 gallons per minute. The static level is 85 feet below the surface.

A short distance west of the Sucker River a well on the property of F. J. Young penetrates 18 feet of drift and 152 feet of basaltic rock. The yield of water is from 2 to 5 gallons per minute.

Wells at and near French River.—The well on Paul Gilmore's property has a total depth of 192 feet. It penetrates 40 feet of glacial drift and 152 feet of basaltic lava flows. The static level is 65 feet below the surface, and when pumped at the rate of 20 gallons per minute it shows a drawdown of 25 feet.

The well on John Mattson's property at French River encountered basaltic rock at a depth of 26 feet below the surface. It was drilled to a total depth of 125 feet and produces 10 gallons per minute.

A well owned by Walter Johnson is located a short distance west of

French River, where there is only 10 feet of glacial drift over the basaltic rock. The well has a total depth of 90 feet and produces about 10 gallons per minute.

The well on Carl Anderson's property flows at the surface. It penetrates 11 feet of glacial drift and 110 feet of basaltic lava. When pumped at 10 gallons per minute it shows a drawdown of 18 feet.

Hibbing

The city of Hibbing obtains the water for its public supply system from a group of shallow wells south of the city and from the Scranton mine. All the wells terminate in the glacial drift and each is cased with steel casing and equipped with a standard screen. The wells have a total capacity of more than 4000 gallons per minute. Table 49 gives the depth and capacity of the individual wells.

Table 49. — City Wells at Hibbing

Well	Depth (feet)	Capacity (G.P.M.)	Static Level (feet below surface)	Drawdown (feet)
1A	112	700	5	44
2A	118	500	5	20
3A	148	700	30	28
4	88	300	23	47
7	115	250	42	44
9	129	150	29	90
11	128	450	5	30
12	138	450	18	115

The pumping equipment at the Scranton mine consists of one 192-foot-head, deep well pump connected to a 200-horsepower electric motor which is connected in series with a 350-foot-head, centrifugal pump. The combined capacity from the Scranton mine is 1400 gallons per minute.

During 1941 the average daily production from the wells and mine was 2,251,649 gallons with a maximum production on August 4 of 3,458,000 gallons.

Aurora

The city of Aurora pumps its water from an undeveloped ore body at the north edge of the city. It has several wells, the deepest of which terminates at a depth of 455 feet. When mining operations are inactive the water level is about 45 feet below the surface, but when the mines are being operated the static level is lowered to 218 feet. When pumped at the rate of 175,000 gallons per day the wells show a drawdown of 50 feet. The subsurface formations penetrated are shown in the accompanying log.

City Well, Aurora

		DEPTH (feet)	THICKNESS (feet)
Glacial drift	Sandy clay	0–76	76
Virginia slate	Greenish slate	76–312	236
Biwabik formation	Altered taconite	312–377	65
	Iron ore	377–447	70
	Dense taconite	447–455	8

The Virginia slate thickens rapidly southward from the city. A hole drilled approximately half a mile south of the city penetrated 2700 feet of slate and failed to reach the bottom of the formation.

Biwabik

The city of Biwabik obtains most of its water from two pits 24 feet square and approximately 30 feet deep that were excavated near Embarrass Lake. The pits are cased with cement and are open at the bottom. They produce 500 gallons per minute.

Additional water is obtained from a group of shallow drilled wells. Four of these are 6 inches in diameter and one has a diameter of 16 inches. All are 45 feet deep.

Buhl

The water for the city of Buhl is taken from two wells, one 372 feet deep and the other 220 feet deep. The accompanying log gives the subsurface formations penetrated by the deeper well.

City Well No. 1, Buhl

		DEPTH (feet)	THICKNESS (feet)
Glacial drift	Clay and sand	0–70	70
Virginia slate	Bluish slate	70–95	25
Biwabik formation	Ore	95–170	75
	Taconite	170–372	102

The lower 200 feet of the well has a casing that is 12 inches in diameter and the upper part has a 10-inch casing. The static level is about 160 feet below the surface. When pumped at the rate of 400 gallons per minute it has a drawdown of 48 feet.

Chisholm

The city of Chisholm has a group of wells 16 inches in diameter that terminate in the glacial drift. The wells numbered 1 to 4 are 77, 51, 77, and 50 feet deep respectively. The largest supply of water is obtained at or near the contact between the drift and bedrock.

The city uses from 400,000 to 600,000 gallons per day.

Eveleth

The city of Eveleth obtains water for its public supply system from St. Mary Lake, a short distance south of the city. The water is pumped from the lake to a filtration plant and from there to the storage tank on a tower which is erected on a hill at the east margin of the city.

Gilbert

The city of Gilbert has a well 16 inches in diameter and 372 feet deep that draws water from the taconite and iron ore of the Biwabik formation. The static level is 108 feet below the surface, and when pumped at the rate of 50 gallons per minute it has a drawdown of 200 feet. The formations penetrated are shown in the accompanying log.

City Well, Gilbert

		Depth (feet)	Thickness (feet)
Glacial drift	Soil and fine sand	0–8	8
	Clay and boulders	8–30	22
	Sandy clay	30–70	40
Virginia slate	Bluish slate	70–130	60
Biwabik	Iron ore	130–170	40
	Shaly taconite	170–200	30
	Iron ore	200–300	100
	Hard taconite	300–372	72

Mountain Iron

For many years the water for the city supply system at Mountain Iron was taken from a shaft 6 by 8 feet that was dug into the Biwabik iron formation to a depth of 150 feet. More recently most of the water for the city has been pumped from a well that is 10 inches in diameter and 225 feet deep. It is equipped with a pump that has a capacity of 300 gallons per minute.

Ely

The city of Ely obtains water for its public supply system from the east end of Burntside Lake. The water is pumped to a filtration reservoir located on the flats near Long Lake at the northwest margin of the city. From the reservoir it is pumped to a storage tank for distribution.

Tower

Water for the public supply system at Tower is pumped from Stuntz Bay on Vermilion Lake. The water is treated chemically in a large storage reservoir that is located on Soudan Hill about a mile and a half northeast of the city. From the reservoir it passes through filter beds and into a pipe through which it flows by gravity to the city of Tower.

Alborn

This village does not have a public water supply system. Ample water for domestic purposes is obtained from shallow drift wells. Several wells have been drilled to a depth of 190 feet without encountering bedrock formations.

Cook

The village of Cook does not have a public water supply system. The private wells average about 100 feet in depth. A short distance west of the village igneous rock is encountered at a depth of 35 feet.

Corsica Mine

A well at the Corsica Mine near Elcor is 30 inches in diameter and 160 feet deep. It penetrates 158 feet of ore and paint rock and terminates in massive taconite. When pumped at the rate of 850 gallons per minute it has a drawdown of 40 feet.

Cotton

The village of Cotton does not have a public water supply system. A well at the village store is 105 feet deep and terminates in the glacial drift. The static level is 20 feet below the surface.

Locally the drift contains beds of large boulders. A well drilled at the forestry lookout station was abandoned after encountering numerous large boulders at a depth of 57 feet.

Culver

In the region of Culver the glacial drift is sufficiently thick and permeable so that ample supplies of water for domestic purposes may be obtained readily. Several wells are more than 150 feet deep, but most of them are from 50 to 120 feet.

Floodwood

The region of Floodwood is underlain by the Virginia slate, which is covered by approximately 150 feet of glacial drift. Eight miles north of the village the slate was encountered at a depth of 170 feet.[6]

A test well was drilled in the village a block northwest of the schoolhouse and about 400 feet from the river. The accompanying log shows the formations penetrated.

Test Well, Floodwood*

		DEPTH (feet)	THICKNESS (feet)
Glacial drift	Loamy soil	0–3	3
	Red clay	3–25	22
	Hardpan	25–58	33
	Gray clay	58–62	4
	Fine muddy sand	62–72	10
	Fine clean sand	72–84	12
	Coarse sand	84–103	19
	Fine sand	103–106	3

*Data from C. K. Handschu, engineer, Moose Lake.

[6] Data from E. W. Dotten.

The static level in the test well was 20 feet below the surface or at an elevation of 1235 feet above sea level.

The well at the creamery is 6 inches in diameter and 90 feet deep.

The village pumps the water for its public supply system from a well that is 10 inches in diameter and 104 feet deep. The static level is 18 feet below the surface, and when pumped at the rate of 275 gallons per minute it shows a drawdown of 50 feet. The formations penetrated are shown in the accompanying log.

Village Well, Floodwood

		DEPTH (feet)	THICKNESS (feet)
Glacial drift	Red sticky clay	0–59	59
	Hardpan	59–86	27
	Sandy clay	86–96	10
	Sand and gravel	96–104	8

Gheen

The village of Gheen does not have a public water supply system. Most private wells are dug from 30 to 50 feet in the glacial drift. A well drilled at the public school penetrated 75 feet of glacial sediments and 31 feet of granite. No satisfactory yield of water was obtained.

Kinney

The village of Kinney has a well 16 inches in diameter and 65 feet deep. It terminates near the base of the glacial drift. The static level is 25 feet below the surface, and when pumped at the rate of 40 gallons per minute it has a drawdown of 5 feet.

Meadowlands

In the region of Meadowlands the glacial drift varies in thickness from 75 to 125 feet. It is underlain by the Virginia slate. Wells drilled into the slate yield a very limited supply of water, whereas those finished in sand lenses in the lower part of the drift produce enough for domestic purposes. The static level is about 15 feet below the surface.[7]

Orr

The village of Orr is located in the northwestern part of the county, where the granites of the Vermilion batholith are covered with a thin mantle of glacial drift. Water for the public supply system is taken from a well 10 inches in diameter and 40 feet deep. Granite was encountered at a depth of 36 feet. The static level in the well is 10 feet below the surface, and when pumped at the rate of 75 gallons per minute it has a drawdown of nearly 20 feet.

A well at the schoolhouse entered granite at a depth of 25 feet and was drilled to a total depth of 136 feet. It produces 5 gallons per minute.

[7] Data from J. Nenman, driller.

Taft

In the region of Taft the glacial drift is more than 200 feet thick. A well 2 miles north of the village penetrated 220 feet of drift below which the Keweenawan basic igneous rock was encountered. Most shallow drift wells produce an ample supply of water.

Twig

The village of Twig does not have a public water system. The private wells are dug from 10 to 50 feet deep, while the drilled wells are from 45 to 75 feet deep. All terminate in the glacial drift.[8]

WELLS AT CIVILIAN CONSERVATION CORPS CAMPS

During the years from 1934 to 1940 numerous camps were established for the Civilian Conservation Corps in the forests of northern St. Louis and Lake counties. A number of these camps were in the area where there is no more than a thin veneer of glacial drift over the granites of the Vermilion batholith and over the Duluth gabbro. Some of the wells produced ample supplies of water. Others yielded no more than 1 or 2 gallons per minute. The accompanying logs are typical of the area.

Wells at CCC Camps

Location		Depth (feet)	Thickness (feet)
Camp 704, 10 miles south of Ely*			
Glacial drift	Sandy clay	0–5	5
Algoman	Gray granite	5–230	225
Camp 711, 30 miles north of Ely†			
Glacial drift	Sandy clay	0–4	4
Algoman	Pink granite	4–36	32
Camp 1720, 20 miles southeast of Ely‡			
Keweenawan	Gabbro	0–190	190
Camp 1775, 18 miles north of Hibbing§			
Glacial drift	Clay and sand	0–6	6
Algoman	Pink granite	6–45	39
Knife Lake	Mica schist	45–208	163
Camp near Cascade, Cook County£			
Glacial drift	Sand and gravel	0–5	5
Keweenawan	Lava flows	5–405	400
10 miles north of Ely, on Echo Trail**			
Algoman	Pink granite	0–233	233
28 miles northeast of Buyck, on Buyck Trail††			
Glacial drift	Clay and sand	0–8	8
Algoman	Pink granite	8–98	90

*Yield 7 gallons per minute.
†Static level 18 feet; yield 40 gallons per minute.
‡Yield 4 gallons per minute.
§Static level 40 feet; yield 12 gallons per minute.
£Well flows 5 gallons per minute, pumps 13 gallons per minute; drawdown 100 feet.
**Static level 40 feet; yield 6 gallons per minute.
††Static level 16 feet; yield 12 gallons per minute.

[8] Data from Swanson Brothers, drillers, Superior, Wisconsin.

TABLE 50. — SEASONAL FLUCTUATIONS OF GROUND WATER LEVEL NEAR EVELETH*
(Water level, in feet below land-surface datum, 1943)

Date	Feet	Date	Feet	Date	Feet	Date	Feet
July 27	6.78	Sept. 5	7.26	Oct. 17	7.50	Nov. 28	7.67
Aug. 1	6.97	Sept. 12	6.92	Oct. 24	7.51	Dec. 5	7.55
Aug. 8	6.82	Sept. 19	7.10	Oct. 31	7.58	Dec. 12	7.67
Aug. 15	6.63	Sept. 26	7.25	Nov. 7	7.44	Dec. 19	7.67
Aug. 22	6.01	Oct. 3	7.69	Nov. 14	7.39	Dec. 26	7.75
Aug. 29	7.14	Oct. 10	7.50	Nov. 21	7.63		

*Well located on property of Herman A. Katola, Lot 3, Sec. 4, T. 56 N., R. 17 W., near Eveleth, in basement of residence. Dug domestic well, diameter 16 inches, depth 9.55 feet. Measuring point, filed mark on pump pipe, at about land surface. Observation recorded by Corps of Engineers, U.S. Army.

Source: United States Department of the Interior, Water levels and artesian pressure in observation wells in the United States in 1943, Part 3. North-Central States: Geol. Survey Water-Supply Paper 988, p. 163.

TABLE 51. — PUMPING REPORT ON IRON MINES OF VERMILION AND MESABI RANGES*

Type of Pump	Total Head (feet)	Rated Capacity	Per Cent of Time in Operation	Average G.P.M. (yearly)
	TOWER, SOUDAN MINE			
Plunger	1000	175	26.2	45.8
Plunger	1000	175	27.2	47.5
Centrifugal	850	350	32.4	113.0
	ELY, PIONEER MINE			
Plunger	1400	216	43.8	94.8
Plunger	1400	216	38.6	83.4
Centrifugal	1400	450	14.1	63.5
	EVELETH, SPRUCE MINE			
Plunger	750	450	59.0	266
Plunger	750	450	63.2	284
Plunger	750	450	48.5	218
	LEONIDAS			
Plunger	750	250	44.2	111
Plunger	750	300	39.9	120
Plunger	750	300	54.8	164
Plunger	650	300	50.6	152
	HIBBING, HULL-RUST			
Centrifugal	300	600	28.5	171
Centrifugal	450	1250	55.5	694
Centrifugal	450	1250	18.1	226
	CHISHOLM, GODFREY			
Centrifugal	375	225	16.7	376
Plunger	300	50	90.0	45
Centrifugal	300	450	38.8	152
Centrifugal	260	750	48.0	360
Centrifugal	475	225	33.8	200
Centrifugal	460	550	24.1	135
	FRASER, HARTLEY MINE			
Centrifugal	45	225	47.8	102
Centrifugal	450	750	13.1	96
Centrifugal	450	750	38.1	286

*Data from Oliver Iron Mining Company.

UNDERGROUND WATER IN IRON MINES

Table 51 is a summary of the amount of water that is taken from the iron-ore bodies in order to depress the regional static level to below the level of operation in the mines. In the impervious rocks of the Vermilion Range the underground flow of water is far less than on the Mesabi Range. This difference may be noted by comparing the rate and volume of water pumped at the Soudan Mine at Tower as compared with the Spruce Mine at Eveleth.

Variations in the amount of water encountered in the iron mines is indicated by the following statement from Mr. Pearsall of the Mesabi Mineral Association.

"In July, 1936, new drifts were put in at the Susquehanna Mine and water was encountered at the 560 foot level. The flow was measured at 2,800 G.P.M. at this time. The rate of flow went up to 3,000 G.P.M. in August, 1936, and continued to flow at this rate until January, 1937. During 1937 water was pumped at an average rate of 2,500 G.P.M. During 1938 the rate increased to 2,675 G.P.M. During the first six months of 1939 the rate was 2,800 G.P.M., but this decreased to 2,400 G.P.M. at the end of 1939. 2,400 G.P.M. was the average for 1940. During 1941 the rate gradually increased until it reached a maximum of 3,300 in November, 1941. During the first six months of 1942 the mine made an average of 3,200 G.P.M."

TABLE 52. — ANALYSES OF WATERS OF ST. LOUIS COUNTY *

	1	2	3	4	5	6	7	8	9	10
Depth (feet)	42	91	120	68	340	800	...	...	...	...
Hardness	45	570	310	230	58	180	180	240	157	190
Alkalinity	43	500	190	290	71	180	160	190	156	170
Iron	.5	.8	.8	.2	.02	tr.	.05	8.5	1	.3
Manganese	.05	2	.02	.03	0	0	.05	2.4	...	.15
Chlorine	..	.04	2.2	3	1.6	7.7	13	3.7	120	7.5
Fluorine	..	.1	.4	.3	0	0	...	...	...	0
SO_4 radical	..	110	7.5	17	0	.97	...	...	...	53
Turbidity	2	7	6	3	.5	0	.1	14	5	2
Color	15	10	7	6	3	0	0	32	30	7
Odor	..	...	8.9	...	...	...	...	...	0	7.2
pH value	6.3	7.4	...	8.2	7.4	7.5	7.6	7	...	...

*Data from State Board of Health Laboratory. Hardness, alkalinity, iron, and chlorine in terms of parts per million (1 grain per gallon = 17.1 p.p.m.). For key to turbidity and items following, see standards in Section II.

1. Babbitt, drilled well, 1933.
2. Cook, drilled well, 1939.
3. Floodwood, drilled well, 1942.
4. Meadowlands, drilled well, 1939.
5. McKinley, drilled well, 1939.
6. Buhl, drilled well, 1939.
7. Virginia, 4 drilled wells and mine drainage, 1939.
8. Chisholm, 3 drilled wells, 1936.
9. Mountain Iron, 3 drilled holes, 1919.
10. Aurora, drilled well, 1944.

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