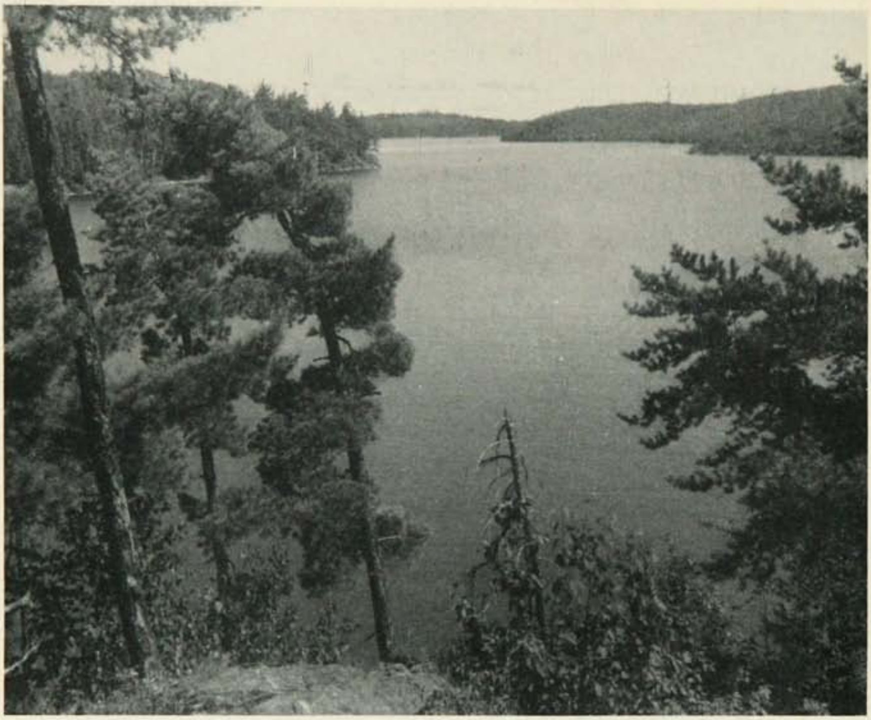
THE LAKES OF MINNESOTA
THEIR ORIGIN AND CLASSIFICATION

To Helen and
Harry

from
Elaine



Looking east from the west end of Mica Bay, an arm of Namakan Lake in northwestern St. Louis County. (Photograph by the author.)

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G. M. SCHWARTZ, DIRECTOR

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The Lakes of Minnesota
THEIR ORIGIN AND CLASSIFICATION

BY

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To the memory of
FRANK LEVERETT
a pioneer in Minnesota glacial geology

FOREWORD

The most distinctive features of the surface of Minnesota are the thousands of lakes scattered irregularly over the state. Even casual observation reveals the fact that these lakes vary greatly in their character. This means that they have been formed in different ways closely related to the geologic history of the region. There are scattered references to the origin of specific lakes particularly in the Annual Reports and the volumes of the Final Reports of the Geological and Natural History Survey of Minnesota. There has been, however, a lack of any single systematic treatment of the geologic factors involved in the formation of the lakes. It is evident that such a geologic basis is desirable for all scientific and practical work on the lakes which form such a valuable resource.

For this reason Dr. Zumberge was supported in his field work by funds allotted by the University of Minnesota to the Minnesota Geological Survey, a unit in the College of Science, Literature, and the Arts. Appreciation is due Dr. Zumberge for his painstaking work, particularly in revising his doctoral thesis to make it into a bulletin for the Geological Survey series — a task performed without remuneration. The Director also wishes to express his thanks to all who helped Dr. Zumberge in his work.

G. M. Schwartz

ACKNOWLEDGMENTS

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For the use of maps and unpublished data the writer is indebted to the Division of Lands and Minerals (Cuyuna Branch office) and the Division of Game and Fish, both of the Minnesota Department of Conservation. To the general staff of the United States Corps of Engineers in St. Paul, Minnesota, the writer also expresses his thanks for their cheerful cooperation in supplying information concerning borings along the Mississippi River.

J. H. Z.

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I. INTRODUCTION

The value of Minnesota's ten thousand lakes cannot be estimated in dollars and cents, although the income from resorts and recreation areas, which depend largely on lakes for survival, ranks below only that from agriculture and mining in the state. Besides this monetary value to the state's economy, the lakes of Minnesota provide rest and relaxation to thousands of people every year. For these reasons it is not surprising that systematic studies of Minnesota's lakes have been made from time to time, each resulting in a clearer understanding of some particular function of the lakes with respect to their utilization. Eddy[1] and Moyle[2] have made studies of lakes and their relation to fish productivity and aquatic vegetation, respectively. Besides these biological studies, other investigations have dealt with the geologic phase of lakes — the marl deposits[3] and the peat resources.[4]

The previous investigations of the lakes in Minnesota have not resulted in a general classification from the geologic point of view, and since such an investigation would be of interest to a large group of people, the Minnesota Geological Survey supported a geological investigation of the lakes in the state. The field observations were made during the summer months of 1948, 1949, and 1950. This bulletin is a summary of the results of the work carried out in those years, and is based on the writer's dissertation submitted to the University of Minnesota in partial fulfillment of the requirements for the degree of doctor of philosophy.[5]

WHAT IS A LAKE?

In order to determine the scope of the investigation, the writer was confronted with the question, "What constitutes a lake?" Webster defines a lake as ". . . an inland body of standing water," with no qualifications as to size or depth. Welch, an authority on lake terminology, suggested that a distinction be made between the terms *lake* and *pond*.[6] The latter term he would confine to the following: ". . . that

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[1] Samuel Eddy, "Minnesota Lake Survey and Fish Management," *Minnesota Academy of Science Proceedings*, 47:325–334 (1940).

[2] J. B. Moyle and N. Hotchkiss, *The Aquatic and Marsh Vegetation of Minnesota and Its Value to Waterfowl* (Minnesota Dept. of Conservation, Technical Bulletin 3, 1945).

[3] G. A. Thiel and C. A. Stauffer, *The Limestones and Marls of Minnesota* (Minnesota Geological Survey Bulletin 23, pt. 2, 1933).

[4] E. K. Soper, *The Peat Deposits of Minnesota* (Minnesota Geological Survey Bulletin 16, 1919).

[5] James H. Zumberge, *The Origin and Classification of the Lakes of Minnesota* (Ph.D. thesis, June 1950, available at University of Minnesota Library and Geology Dept.).

[6] P. S. Welch, *Limnology* (New York: McGraw-Hill Book Company, 1935), p. 15.

class of very small, very shallow bodies of standing water in which quiet water and extensive occupancy by higher aquatic plants are common characteristics." All larger bodies he would refer to as lakes.

Other definitions indicate that a lake should have ". . . an area of open, relatively deep water sufficiently large to produce somewhere on its periphery a *barren wave-swept shore*."[7] This would eliminate smaller bodies of standing water conventionally referred to as ponds or swamps.

In all definitions of a lake no attempt has been made to impart quantitative limitations insofar as area and depth of water are concerned. This in itself allows the individual worker considerable leeway in the use of the terms *lake, pond,* and *swamp.* Furthermore, a rigid definition of these would lead to much confusion since what was originally considered a lake might be modified by natural processes within the course of a few years to a dry basin.

In the geological study of lakes it was soon realized that the most important factor in the definition of a lake is not the water, but the basin in which the water is confined. Thus the maximum areal extent as well as the depth of the water in a lake is determined by the dimensions of the basin itself. Furthermore, these dimensions may change with time so that any working definition of a lake must provide for such changes. Therefore, the following definition of a lake is proposed which, admittedly, may not suit the biologist or limnologist, but which is more acceptable to the geologist interested primarily in the origin of the lake basin.

A lake is a basin *filled or partially filled with standing water.* It will be noted that the terms *lake, pond,* and *swamp,* as they are commonly used, will fall within the limits of this definition.

PURPOSE OF THE STUDY

This study presents a classification of the lakes of Minnesota based on the geologic origin of the lake basins. This classification provides for lakes extant during the time the field investigations were carried out as well as for those potential lake basins that might come into existence in the future after certain geological processes now in operation have had time to form them. For each kind of lake a "type-lake" is cited and described, and the general distribution of the various types of lake within the state is also considered.

A secondary phase of this report deals with the subject of lake modification, in which the effects of waves, currents, ice, and the accumulation of sediment are considered.

Before discussing the subject of lake classification, the writer offers in the next chapter a brief review of the glacial history of the state, inasmuch as the majority of lake basins came into being as the result of continental glaciation during the Great Ice Age.

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[7] *Ibid.*

II. THE GLACIAL HISTORY OF MINNESOTA

Within the last million years most of the middlewestern states and much of Canada were covered at one time or other with an ice sheet. This continental glacier had a profound effect on the surface features of the area over which it moved. Vast quantities of rock and soil were scraped from the glacial centers to its margins by the slowly moving ice and redeposited as "drift." Much of this drift was dumped into old preglacial river valleys, while some of it was heaped into belts of hills (end moraines) at the margin of the glacier. The chief result of glaciation has been the modification of the preglacial topography by the deposition of drift over the countryside. However, continental glaciers possess great power of erosion and may actually modify the preglacial land surface by scouring and abrading rather than by the deposition of drift.

Minnesota would have a vastly different topography were it possible to remove the marks of glaciation. Probably the most significant difference would be in the character and extent of the drainage. In preglacial times there is every reason to believe that most of the rain water or meltwater from snow was quickly carried back to the ocean. Today, however, much of the precipitation is retained temporarily on the surface in nature's storage basins, the lakes. Streams meander from lake to lake, and only part of the total precipitation is carried away by the rivers. One might describe such topography as immature because the streams have not yet been able to establish themselves into a network that quickly and efficiently drains the land. True, the Mississippi River has cut for itself a deep valley below St. Anthony Falls, but even the waters of this large river do not flow freely to the ocean because of Lake Pepin, which acts as a storage basin for some of the water. Streams have been actively engaged in their erosive work only for the last eleven thousand years, the estimated length of time since the last glacier began its final retreat. This span of time is relatively insignificant to the geologist, who reckons time in millions of years rather than in centuries.

It is quite necessary, therefore, that any study of the lakes in this state be preceded by a summary of the glaciation of Minnesota, since almost all of the lakes are either directly or indirectly related to this significant event.

SEQUENCE OF GLACIAL EVENTS

Minnesota played host to four major ice advances during the Pleistocene Ice Age, named, from the oldest to the youngest, Nebraskan, Kansan, Illinoian, and Wisconsin. The ice moved into Minnesota at different times from three glacial centers, the Labradorian center in northern Quebec and Labrador, the Patrician center just southwest of Hudson Bay, and the Keewatin center northwest of Hudson Bay.

Deposits left by the continental ice sheets advancing from these three centers reflect the characteristics of the rocks over which they passed. The Keewatin ice encountered the Cretaceous limestones and shales of Manitoba and the Red River Valley, whereas the Patrician and Labradorian ice moved over Pre-Cambrian crystalline rocks of the Canadian shield.

PRE-WISCONSIN GLACIATION

There are few areas in which the earlier drifts are exposed at the surface, and, therefore, not a great deal need be said about the deposits of the Nebraskan, Kansan, or Illinoian glacial stages in Minnesota. The extreme southeastern and southwestern portions of Minnesota have extensive areas of pre-Wisconsin drifts, but they are masked almost everywhere by a surficial covering of loess (wind-blown silt). Furthermore, these regions of older drift are maturely drained, because the streams have had a longer time to get integrated into an efficient drainage system as compared with the streams flowing in areas covered by the younger glacial deposits. Natural lakes, other than those related to the Mississippi River, therefore, are not found in the areas where the pre-Wisconsin drifts occur, and we need not consider them further.

WISCONSIN GLACIATION

The Wisconsin glacial stage has been subdivided into four *substages,* each representing an advance and retreat of the ice. The substages, named from oldest to youngest, are the Iowan, Tazewell, Cary, and Mankato. Only the Iowan, Cary, and Mankato drifts are recognized in Minnesota, but current studies by Ruhe indicate that the Tazewell drift may be present in southwestern Minnesota.[1]

The Iowan drift occurs extensively at the surface only in southwestern and southeastern Minnesota, and contains few if any lakes because of the relatively mature surface drainage. The Tazewell drift of Ruhe in southwestern Minnesota is also devoid of lakes; in fact, the criterion of drainage was used by Ruhe to distinguish Tazewell from Cary drifts.

Nearly all of the lakes in Minnesota are found within the borders of the Cary and Mankato drifts. For this reason, it is necessary to consider in some detail the nature and distribution of these two drift sheets.

Cary substage. Figure 1 shows the maximum advance of the Cary ice in Minnesota from the Patrician center. Because it reached somewhat south of Minneapolis, Cooper proposed the name "Minneapolis lobe."[2]

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[1] R. V. Ruhe, *Reclassification and Correlation of the Glacial Drifts of Northwestern Iowa and Adjacent States* (unpublished Ph.D. thesis, University of Iowa, 1950).

[2] W. S. Cooper, *History of the Upper Mississippi River in Late Wisconsin and Postglacial Time* (Minnesota Geological Survey Bulletin 26, 1935), p. 7.

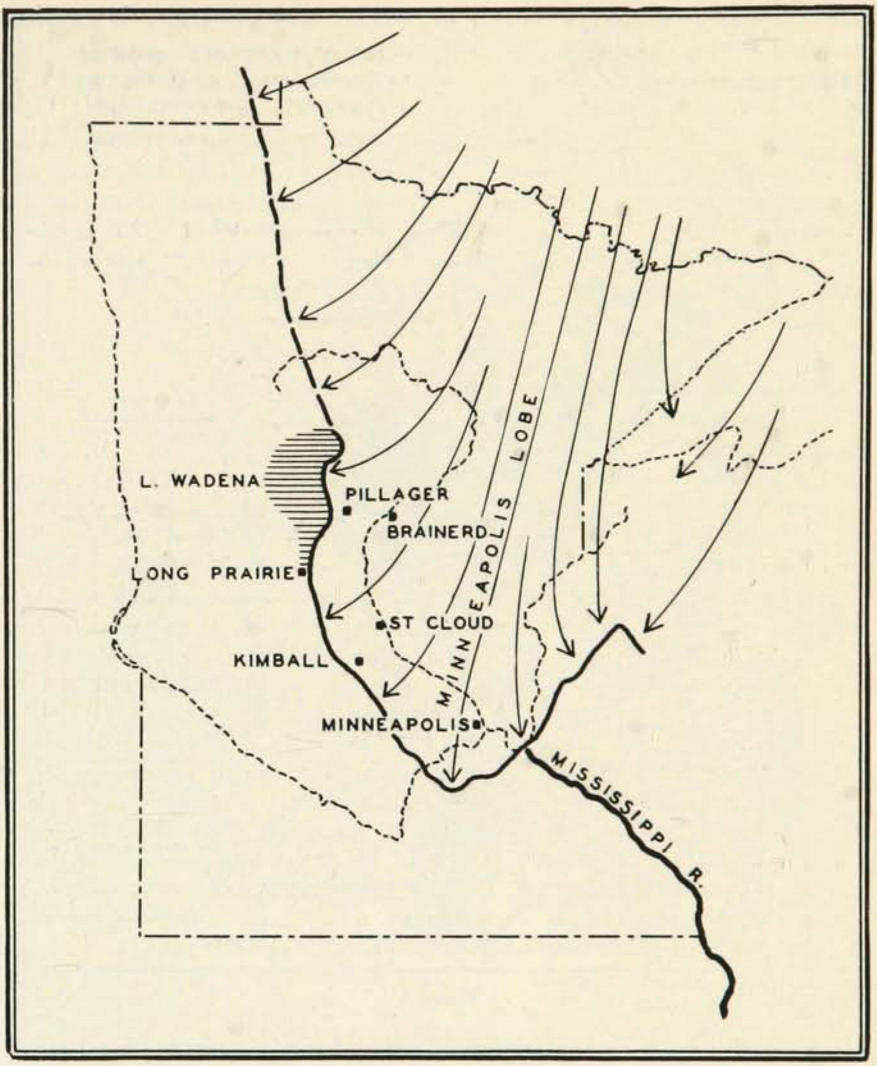

FIGURE 1. — Position of the ice margin during the maximum advance of the Cary glacier from the Patrician Center of glaciation. (After Leverett.)

The St. Croix morainic system (Plate 1) marks the maximum expanse of the Minneapolis lobe. In places this Cary terminal moraine is covered by younger drift, but even there its distinctive topography is only slightly modified. A prominent recessional moraine of the Minneapolis lobe is the Mille Lacs moraine, which borders Mille Lacs Lake on the south and west and extends across Aitkin, Mille Lacs, Kanabec, Crow Wing, and Pine counties in east-central Minnesota (Plate 1). The drift of the

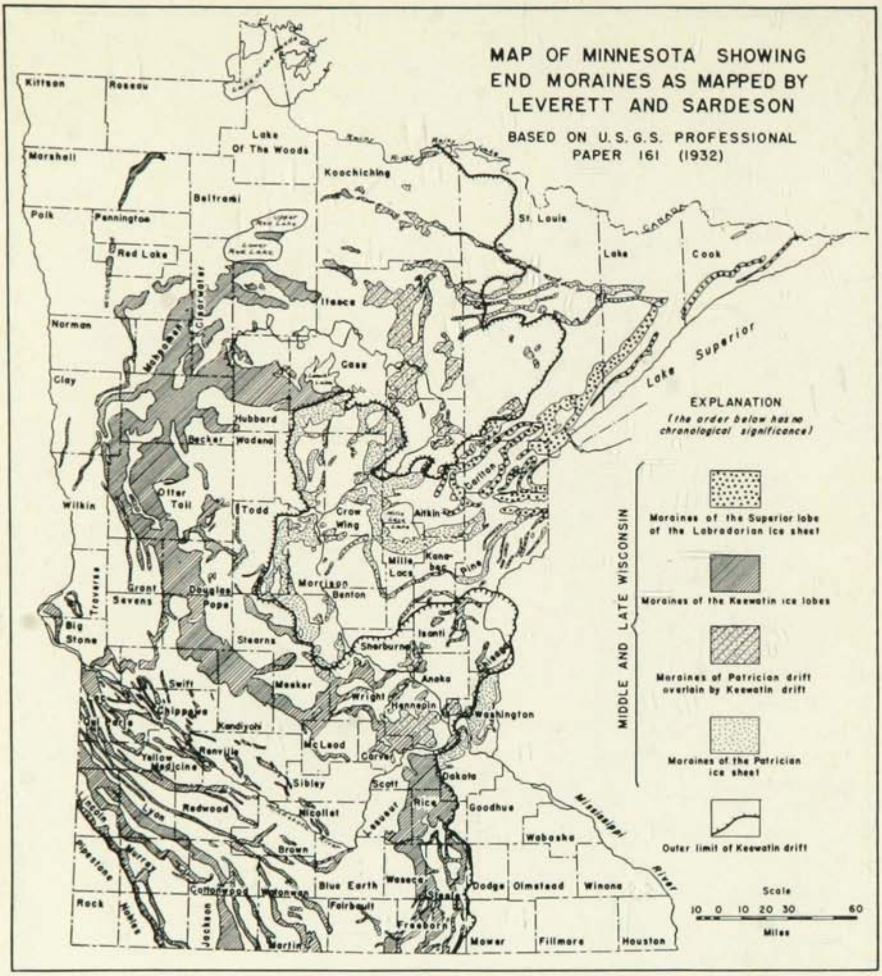

PLATE 1

Minneapolis lobe is characteristically red and sandy because of red sandstone and shale source rocks to the north and northeast; it may be recognized as well by pebbles of basalt, gabbro, red syenite, felsite, red sandstone, and iron formation from northeastern Minnesota.

Mankato substage. With the retreat of the Patrician ice the stage was set for the final phase of the Wisconsin glaciation in Minnesota. The last major advance of the continental glacier in Minnesota culminated in a lobe that reached as far south as Des Moines, Iowa. The Des Moines lobe produced a northeast-moving projection known as the Grantsburg sublobe (Fig. 2). Also protruding from the main Keewatin ice sheet was the St. Louis sublobe. The drift of these ice lobes is generally gray or

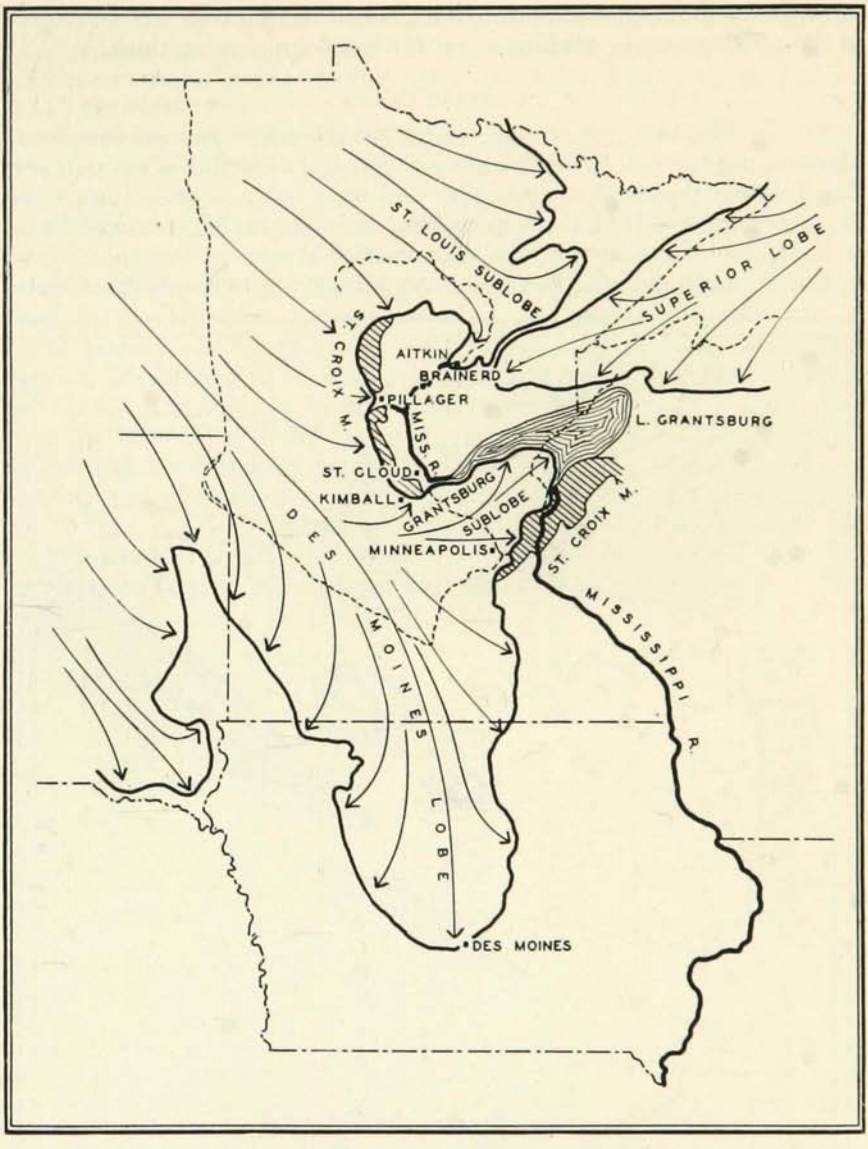

FIGURE 2. — Position of the ice margin during the maximum advance of the Mankato glacier in late Wisconsin time. (Modified after Leverett.)

buff, clayey, and calcareous because of shale and limestone source rocks to the northwest.

The Superior lobe also developed during Mankato time and advanced as far west as Aitkin County. The exact relationship of these several advances of ice from different centers is still not known, and a solution to the problem seems contingent on further field investigations.

GLACIAL LAKES

As the Mankato ice shrank, meltwaters became ponded in several places along the margin of the glacier. Some of these lakes covered several hundred thousand square miles and have left a definite imprint on the topography. All of them have since been drained by natural forces or have shrunk considerably from their original size.

Glacial Lake Duluth. This name has been given to the body of water

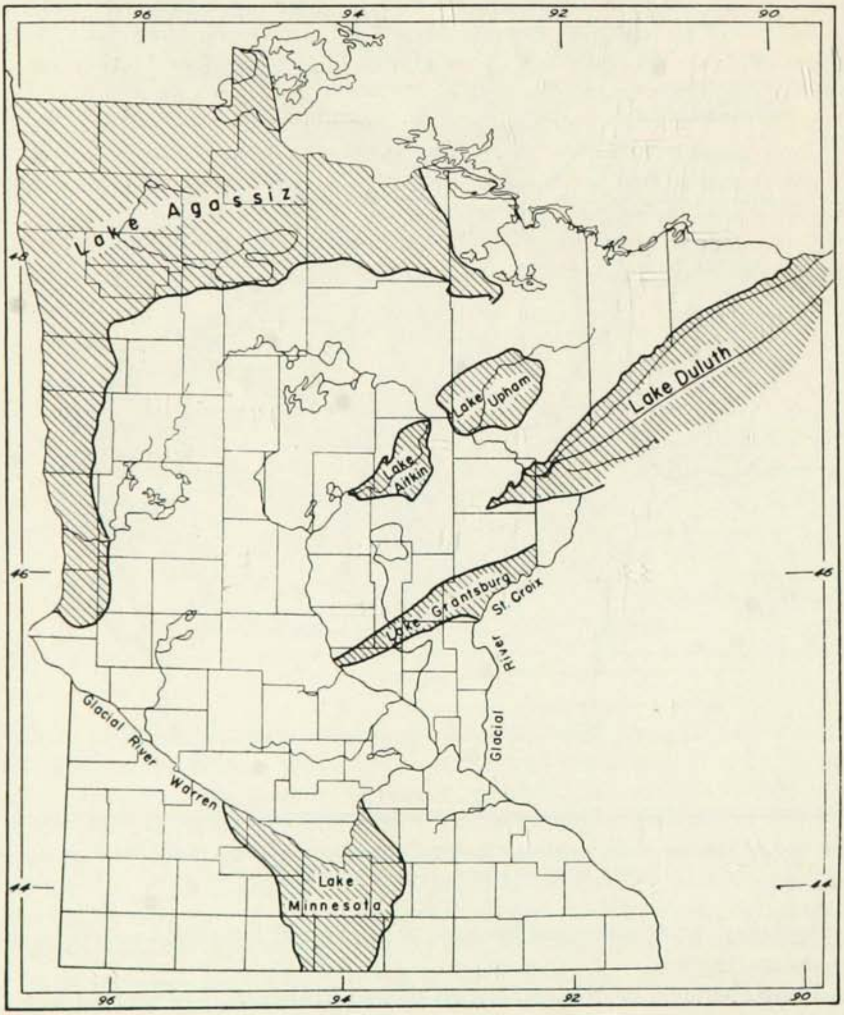

FIGURE 3. — Glacial lakes.

which formed at the southwestern margin of the Superior lobe and occupied a much larger area than the present Lake Superior (Fig. 3). Its shore lines stand nearly 500 feet above the level of its modern successor, Lake Superior.

During its early history Lake Duluth drained into the Mississippi River via the St. Croix River Valley. Later, however, when the Superior lobe had retreated farther to the northeast, the waters of Lake Duluth merged with those in the Michigan and Huron basins, and the southern outlet was abandoned in favor of a lower one to the east.

Glacial Lake Agassiz. The largest of all the proglacial lakes was Lake Agassiz, a small part of which occupied the present Red River Valley in Minnesota and North Dakota (Fig. 3). This lake drained through the present Minnesota River Valley at first, but later, after further retreat of the ice into Canada, lower outlets were uncovered to Hudson Bay, and the Minnesota Valley outlet was abandoned.

Several other smaller proglacial lakes developed during the general deglaciation of Minnesota, and some of them are important in explaining the origin of a few modern lake basins. When such modern lakes are encountered in the course of the discussion on lake classification, the proglacial lakes to which they are related will be considered in more detail.

III. CLASSIFICATION

The ensuing classification of Minnesota lakes is an attempt to group them into categories on the basis of their origins. The classification follows one proposed by I. C. Russell in 1895, although the two classifications are similar only in the major groups.[1]

Since the classification is genetic, the major geologic processes themselves are the headings for the main categories. Russell included such lakes as were formed by volcanic agencies, the impact of meteors, earthquakes, landslides, and diastrophism, but none of these groups occur in the classification of Minnesota lakes simply because these processes are not known to have produced any lake basins in the state.

Any one lake in Minnesota should fall into one of the following five categories, the first three of which include 99 per cent of all lakes in the state:

1. Continental glaciation
2. Stream action
3. Processes of lake modification[2]
4. Basins due to organic agencies
5. Minor geologic processes in Minnesota

A brief outline of the classification is given below, followed by a more detailed description of the process involved. In order to facilitate reference in the text to a certain kind of lake, each distinct type is numbered independently of the notation used in the classification skeleton. For instance, in referring to an ice-block basin in outwash localized by a preglacial valley, instead of using the cumbersome notation Category 1, Class A, group 3, heading a, subgroup (1), or a similar use of the letters and numbers from the outline skeleton, it is more expedient to assign a type number to that particular kind of lake, which in the case above is type 3. Thus, the orderly arrangement of lakes in the classification emphasizes their relation to each other, whereas the independent designation of each type lake by numbers is designed to avoid unnecessary wordiness when reference is made to a type lake in the text of the descriptive material.

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[1] I. C. Russell, *Lakes of North America* (Boston: Ginn and Company, 1895).

[2] All lakes undergo some degree of modification during their history, and the type of modification may be such that part of the original lake basin may be isolated or cut off from the main water body, thus forming a new basin from part of an older one. The importance of this process becomes more apparent when the reader bears in mind that, in this classification, attention is focused on *any* process whereby a closed basin is formed, even if that process involves the formation of a separate smaller basin from part of a larger one.

OUTLINE OF LAKE CLASSIFICATION

Category 1. Lake basins due to continental glaciation. This category includes all lakes which are the result of continental glaciation, whether they are produced by glacial deposition, glacial erosion, or a combination of erosion and deposition.

CLASS A. Basins produced by glacial deposition

Type 1	1. Irregular deposition of till
Type 2	2. Moraine dam
	3. Ice-block basins
	a. Localized by preglacial valleys[3]
Type 3	(1) Ice-block basins in outwash
Type 4	(2) Ice-block basins in till
	b. No apparent relation to preglacial valleys
	(1) Basins in outwash
Type 5	(a) Pitted outwash plain
Type 6	(b) Esker trough
Type 7	(2) Basins in till
Type 8	(3) Basins in till and outwash

CLASS B. Basins produced by glacial erosion

	1. Bedrock basins
Type 9	a. Localized by preglacial valleys
Type 10	b. No apparent relation to preglacial valleys

CLASS C. Basins produced by glacial erosion and glacial deposition

Type 11	1. Bedrock basins partially dammed by drift

Category 2. Lake basins due to stream processes. This category includes all lake basins formed by stream deposition or a combination of stream deposition and erosion.

CLASS A. Basins produced by stream deposition

	1. Floodplain lakes
Type 12	a. Related to natural levees
Type 13	b. Uneven aggradation of a floodplain
Type 14	2. Master stream dammed by tributary
Type 15	3. Tributary dammed by master stream
Type 16	4. Delta lakes

CLASS B. Basins produced by stream erosion and stream deposition

Type 17	1. Meander scrolls
Type 18	2. Oxbow lakes

Category 3. Lake basins due to the modification of larger basins. This category provides for all lakes that were once segments of larger

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[3] The term *preglacial valley* in this classification can mean pre-Pleistocene, but more often it simply means that the valley existed before the glaciation which produced the basin involved.

bodies of water. The processes involved in the formation of lakes in this major group involve such agents as waves, currents, and lake ice. Remnants of large glacial lakes are also considered in this category because they are the end products of a large lake which has been modified owing to a rapid loss of water, a phenomenon associated with many of the proglacial lakes that were transient features at the margins of a retreating ice sheet.

Type 19 CLASS A. Basins that are remnants of proglacial lakes which were drained in late-glacial time

CLASS B. Basins produced by shore processes
Type 20 1. Isolation of a small bay by the construction of a natural barrier across its mouth
Type 21 2. Segmentation of one large basin into two or more separate basins
Type 22 3. Basins formed behind cuspate bars

Category 4. Lake basins due to organic agencies

CLASS A. Basins produced by animal activity
Type 23 1. Beaver-dam lakes
Type 24 2. Lakes formed by artificial dams
Type 25 3. Lakes formed by mining and quarrying operations

Category 5. Lake basins, potential or real, formed by geologic processes of minor importance in Minnesota

CLASS A. Basins produced by wind processes
Type 26 1. Blowouts

CLASS B. Basins produced by the action of ground water
Type 27 1. Sinkholes

EXAMPLES OF LAKE TYPES

Category 1. Lake Basins Due to Continental Glaciation

CLASS A. BASINS PRODUCED BY GLACIAL DEPOSITION

Type 1. Basins produced by irregular deposition of till

When debris is deposited directly by glacial ice, either at the base of the ice sheet as ground moraine or at the margin of the ice sheet in the form of end moraine, closed depressions may be formed. In end moraines it is difficult if not impossible to differentiate the depressions formed by irregular deposition of till from those which are formed by the melting of stagnant ice blocks. But in typical ground moraine topography of the "swell and swale" type, such basins are easily recognized. A lake of type 1 in ground moraine is always shallow because its depth is determined by the maximum relief of the local topography which, in ground moraine, rarely exceeds 20 or 30 feet. Usually in lakes of this type the land forming the shore area slopes very gently toward the lake. Thus, if the water and accumulated sediment were removed from the lake basin, the lake bed would occupy a natural position in the terrain as another "swale" in the general ground-moraine topography.

Heron Lake in northwestern Jackson County is an excellent example of this type of lake. It is located entirely within the ground moraine of the Mankato drift and has a maximum depth of five or six feet. The topography of the immediate vicinity is that of typical ground moraine and has a maximum relief of about 20 feet. The lake is elongate in a northwest-southeast direction, parallel to the general trend of the end moraines of southwestern Minnesota (Plate 1). The position of the lake, like the position of the end moraines, was controlled by the direction of ice movement (northeast to southwest). If morainic ridges have their long axes at right angles to the direction of ice movement, it seems likely that depressions associated with those ridges would be similarly aligned.

Type 2. Moraine-dam lakes

If an end moraine or recessional moraine is sufficiently lobate and the land surface near its margin slopes toward the moraine, then conditions are favorable for the formation of a moraine-dam lake. Sometimes a small trough exists between two small morainic ridges, both of which are part of a larger morainic system. This trough may also be considered a moraine-dam lake since it is the presence of the two parallel ridges that determines the closure of the intervening basin.

Mille Lacs Lake in northern Mille Lacs County and southern Aitkin County (Fig. 4) is one of the best examples of a moraine-dam lake in Minnesota. This lake, nearly 200 square miles in area, is impounded to a maximum depth of 35 feet behind the rugged Mille Lacs moraine, which rises abruptly 130 feet above the lake south of Garrison. In contrast to the western and southern shores are the northern and eastern shores, which are marked by swamps, a vestige of a former lake level about 15 feet above the present.

Type 3. Ice-block basins in outwash localized by preglacial valleys

That deposition by a continental glacier causes the general disruption of preglacial drainage is an accepted fact. Occasionally, however, a preglacial valley is not completely filled with drift, and it may even contain a meltwater stream after the retreat of the ice has uncovered the old valley. Residual ice masses in such a valley are likely to become buried by the outwash deposited by the meltwater stream. Subsequent melting of the ice block causes collapse of the overlying and surrounding strata, a process which produces an ice-block basin localized by a preglacial valley (type 3). Very small pits of this type may be the result of buried icebergs or buried river ice, but it is questionable whether meltwater streams possess a sufficiently large volume to transport the blocks of ice that result in the formation of lakes of this type. The shape and depth

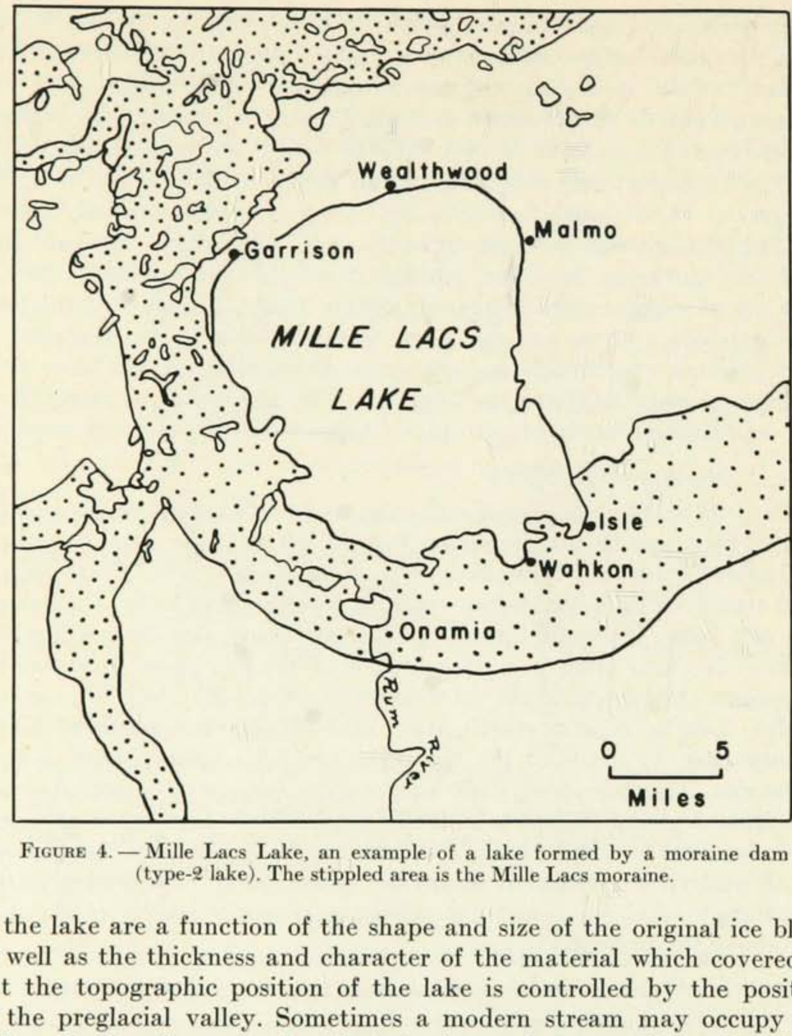

FIGURE 4. — Mille Lacs Lake, an example of a lake formed by a moraine dam (type-2 lake). The stippled area is the Mille Lacs moraine.

of the lake are a function of the shape and size of the original ice block as well as the thickness and character of the material which covered it, but the topographic position of the lake is controlled by the position of the preglacial valley. Sometimes a modern stream may occupy the valley, flowing from one ice-block basin to the next. The valley itself generally contains a thick accumulation of coarse outwash, too coarse, in fact, to have been deposited by the modern stream.

Barrett Lake in Grant County (Figs. 5 and 6) is an example of an ice-block basin localized by a preglacial valley. The lake has a maximum depth of 25 feet and is one of a chain of lakes of similar origin, all connected by the Pomme de Terre River. Barrett Lake and others in the chain lie in outwash (Fig. 5) which attains a thickness of 65 feet in some parts of the valley.[4] The presence of the gravel outwash is proof that

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[4] F. W. Sardeson, *U.S. Geological Survey Geologic Atlas, No. 210 Herman-Morris Folio* (1919), p. 7.

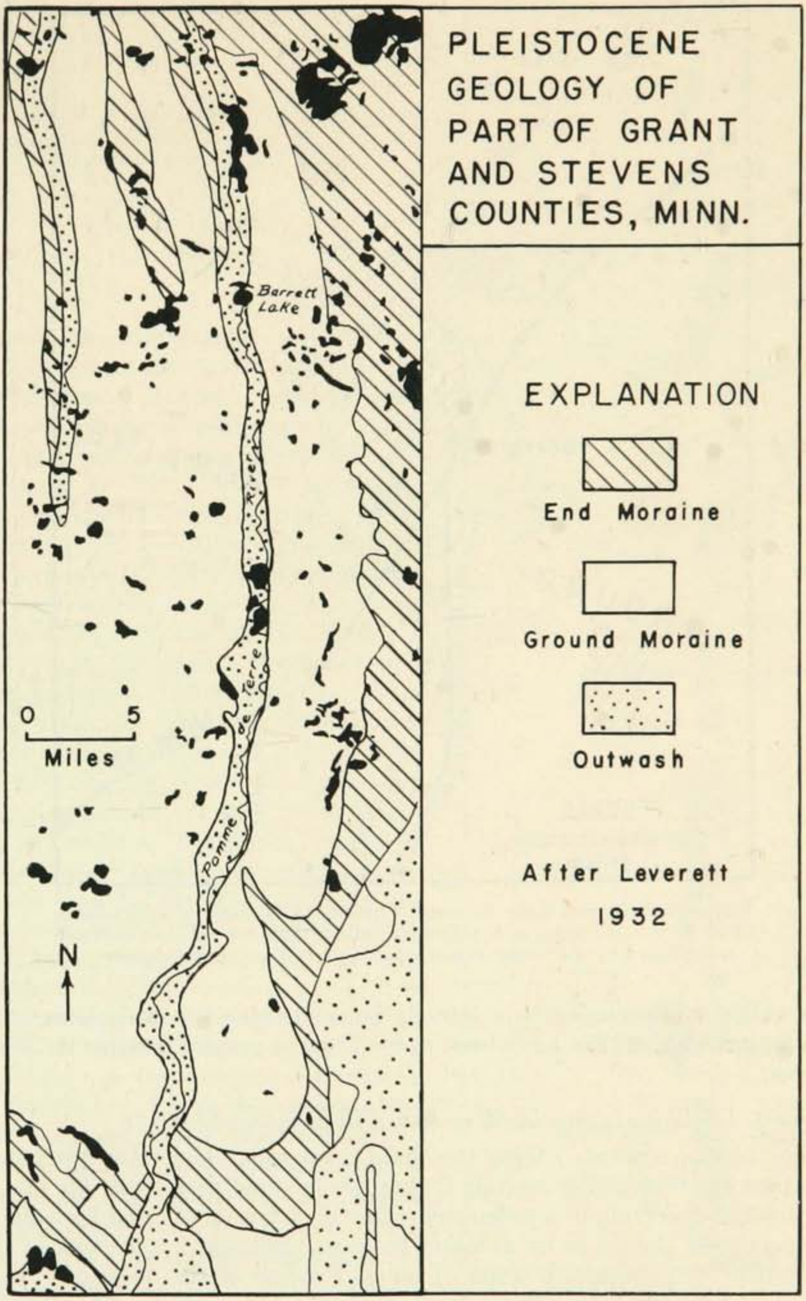

FIGURE 5. — Pomme de Terre outwash train in which ice-block basins localized by a preglacial valley are found (type-3 lakes).

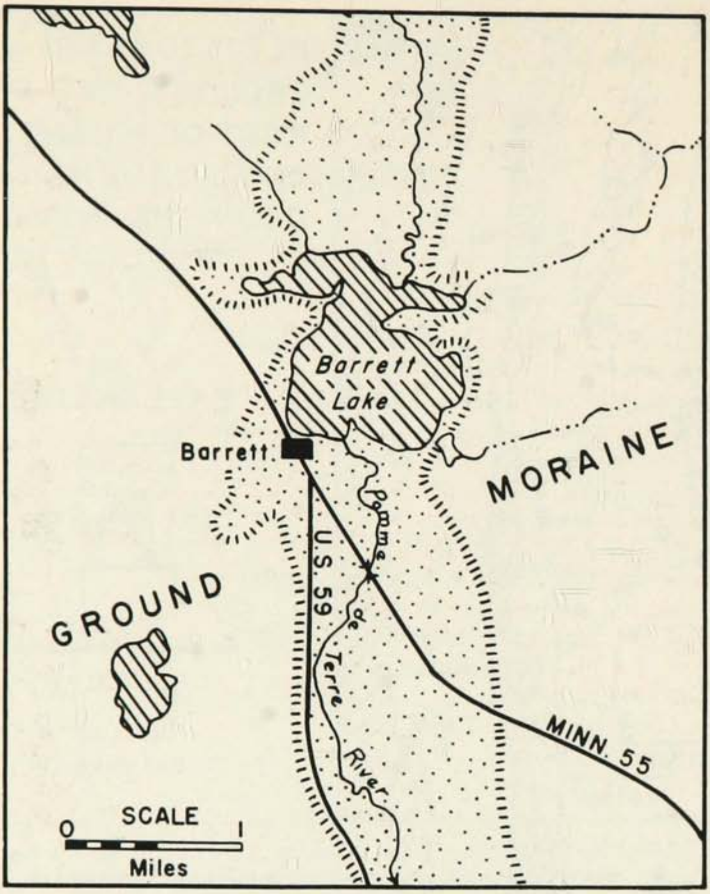

FIGURE 6. — Barrett Lake in Grant County, an example of an ice-block basin in outwash lying in a preglacial valley (type-3 lake). The outwash, deposited by meltwater streams, is shown in the stippled pattern.

the valley was occupied by a late-glacial meltwater stream because such coarse gravel could not have been carried by the present Pomme de Terre River.

Type 4. Ice-block basins in till localized by preglacial valleys

Ice blocks separated from the main mass of a glacier by downward wastage are retarded in melting if they are covered with drift. Ice blocks so isolated and lying in a preglacial valley may become buried by a slight readvance of the ice or by ablation moraine.[5] Subsequent melting of the ice blocks will produce a series of lakes. Because of the uneven manner in which the till is laid down on top of and between the stagnant ice

[5] Debris concentrated on the surface of a glacier by downward melting of the ice.

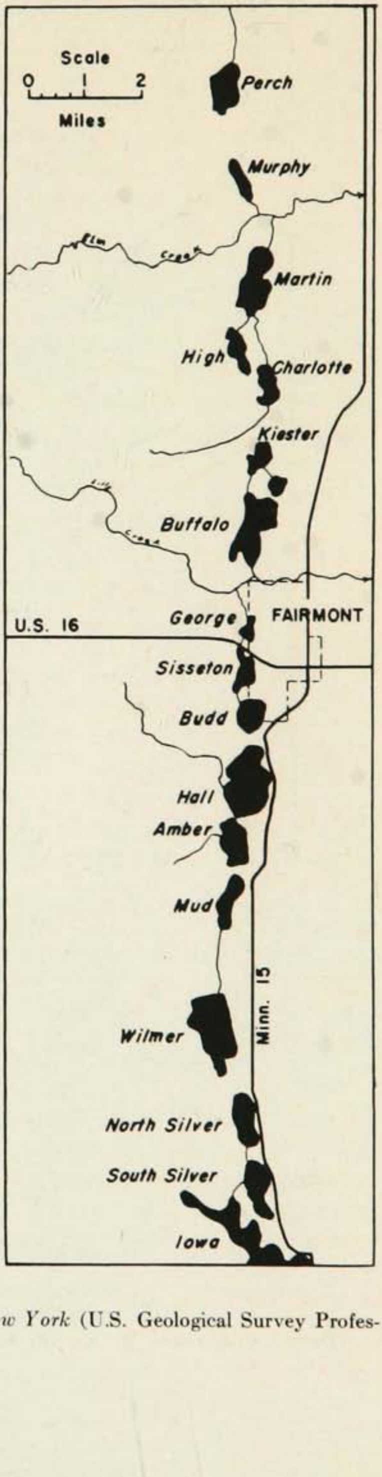

FIGURE 7. — A chain of lakes in Martin County, examples of ice-block basins in till, lying in a preglacial valley (type-4 lakes).

masses, the characteristics of the original valley are destroyed so that it will not contain a flow of meltwaters from the retreating glacier. Such a valley is different in appearance from the Pomme de Terre Valley previously described because the material in the valley is till instead of outwash. For this reason the lakes in the chain are not necessarily connected by a single stream; in fact, the modern drainage may have no relation whatsoever to the preglacial valley but may actually cross the axis of the preglacial valley at right angles.

The melting of ice blocks not entirely buried in till may result in the formation of a "kettle rim," a rim of outwash or boulders around an ice-block basin.[6] The stratification of the outwash in the rim dips away from the basin, suggesting that the outwash was derived from debris held in the upper part of the protruding ice mass. If a kettle rim can be identified, the ice-block origin of the basin is established. Those basins formed by the collapse of till that completely covers an ice block will not have a kettle rim and therefore may not be perceptibly different from a basin formed by irregular deposition of drift.

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[6] M. L. Fuller, *The Geology of Long Island, New York* (U.S. Geological Survey Professional Paper 82, 1914), p. 41.

A remarkable chain of lakes persists in central Martin County, and it is believed that these lakes are examples of ice-block basins in till. The chain is over 20 miles long and contains 18 lakes (Fig. 7). Upham noted the pronounced alignment of the lakes and concluded that they reflected an interglacial drainage course, thereby leaving the impression that *uneven deposition of till* in the pre-Mankato valley was responsible for the modern lakes, and that *no ice blocks* were involved in their formation.[7]

The writer has examined the shore area of these lakes in detail and found a segment of what appears to be a kettle rim south of Hall Lake. The rim is composed of coarse sand and gravel; it is 15 or 20 feet above the level of the lake and slopes gently southward. Cross-bedding in the outwash also dips south, indicating that the source was an ice block which once occupied the present site of Hall Lake. This evidence suggests that other lakes in the chain also may have had an ice-block origin.

Unlike the case of the Pomme de Terre, no modern stream occupies the position of the former valley. The main drainage in central Martin County crosses the trend of the central lake chain at right angles, and the surface of the till between individual lakes of the chain rises to the level of the surrounding till surface. Thus the only clue to the existence of a buried valley marked by the chain of lakes is the pronounced alignment of the lakes themselves. There is little doubt that this alignment is definitely related to a pre-Mankato valley and not just the chance orientation of several ice blocks.

Another well-known example of a chain of lakes that marks the course of a buried river valley is the chain formed by Lake Harriet, Lake Calhoun, Lake of the Isles, and Cedar Lake in Minneapolis. These four lakes mark the position of a bedrock valley which may have been occupied by the ancestral Mississippi River. Another bedrock valley, now filled by glacial drift, is marked by Powderhorn, Hiawatha, and Nokomis lakes. In St. Paul, the position of the Phalen-Spoon-Gervais chain of lakes also was determined by a bedrock valley now buried.[8] These bedrock valleys contained stagnant ice blocks buried by glacial drift. Melting of the ice blocks produced the depressions now filled with water.

Type 5. Ice-block basins in an outwash plain

The separation of stagnant ice blocks from the main mass of a retreating glacier and their partial or complete burial by outwash has long been known to produce lake basins. Fuller believes that several different types of ice-block pits are identifiable in the outwash of the Long Island region.[9] The difference between them depends on the size of the ice block

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[7] Warren Upham, *Geological and Natural History Survey of Minnesota* (1882), vol. 1, p. 484.

[8] G. M. Schwartz, *The Geology of the Minneapolis-St. Paul Metropolitan Area* (Minnesota Geological Survey Bulletin 27, 1936), plates 7 and 8.

[9] *Op. cit.*, p. 39.

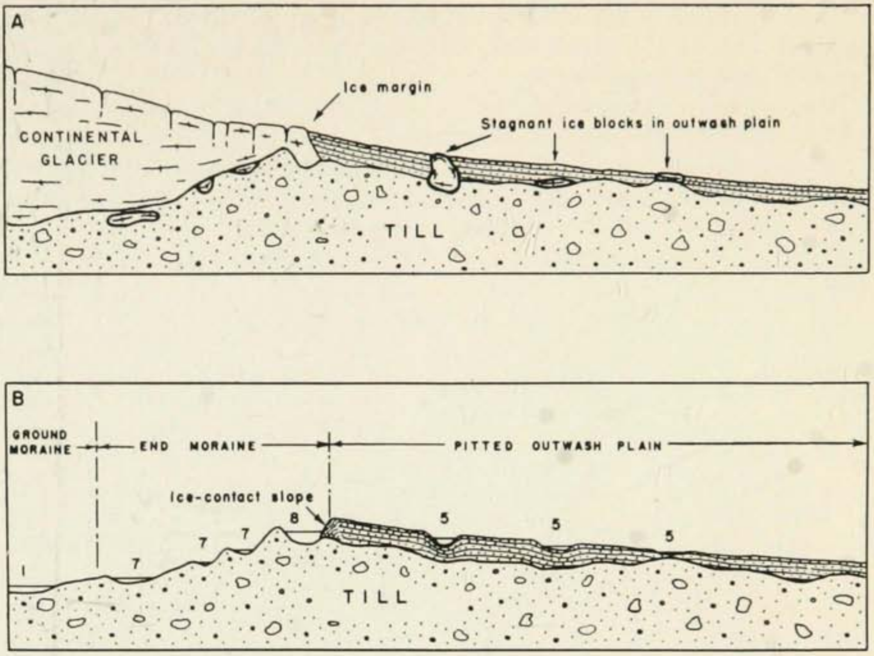

FIGURE 8. — Generalized diagrams showing the formation of different kinds of lakes related to glacial deposition. (A) Lodgment of ice blocks during glacial retreat. (B) The melting of ice blocks forms basins. The numbers indicate the lake type: (1) basin formed by the irregular deposition of till; (5) ice-block basins in an outwash plain; (7) ice-block basins in till; (8) ice-block basin in till and outwash.

and the extent to which it was buried by outwash. Figure 8 illustrates three ice blocks which vary not only in size but in degree of burial by outwash as well. All three produce a depression at the surface, and it would be difficult if not impossible to differentiate one from the other by surface form alone. Therefore, all such depressions will be treated as a single type, and no attempt will be made to differentiate them on the basis of the degree of burial of the ice mass.

The usual name assigned to an area of extensive outwash that is characterized by many ice-block pits is a pitted outwash plain. The pits may be filled or partially filled with water, in either of which instances a type-5 lake is formed.

One of the best-known examples of a pitted outwash plain in Minnesota is in Crow Wing County near Brainerd. As the last glacier retreated westward from the Brainerd area, meltwaters issuing from the ice deposited outwash that surrounded and in some cases completely buried stagnant ice blocks. Some of the lakes which were formed in this manner have depths up to 70 feet (Lake Edward, north of Merrifield), but the average is closer to 20 or 30 feet (Fig. 9). Many of these ice-block pits are not completely filled with water, a fact which accentuates the "pitted" character of the outwash plain.[10]

Ice-block pits are commonly circular or elliptical in outline, a feature which is the result of shore modification rather than the result of the original shape of the ice block. A very common term used for such a lake is *kettle* or *kettle hole*. Some geologists restrict the term *kettle* to lakes of type 5, but here the term is used in the broader sense, that is, any drift depression whether or not it was of ice-block origin.

Type 6. Esker trough

There seems to be widespread agreement that eskers (gravel ridges) are deposits of subglacial streams during a late phase of deglaciation when the ice under which the streams flowed was stagnant or nearly so.[11] Associated with some eskers are marginal kettles or troughs which apparently have a genetic relationship to the eskers with which they occur. Thwaites calls these *esker troughs*.[12] A lake of this type may occur at the base of either flank of a single esker or it may lie within a braided system of eskers. The kettles are usually elongate in a direction parallel to the long axis of the adjacent esker or eskers.

The origin of esker troughs was explained by Norman, and is based on his studies in the Lake Chibougamau district in Quebec.[13] Writing in regard to the streams occupying the subglacial channels he says: "The streams with slackened velocity, would cut laterally into their ice walls while depositing material to aggrade their floors. Lateral cutting accompanied by deposition would slowly raise and widen the ice channel of the subglacial streams and at the same time would bury linear strips of the ice of the older, lower walls. These strips of ice would be protected from immediate melting as the ice receded by being buried in the deltas at the ice front. Their subsequent melting would produce the regular rows of depressions or kettle holes . . ." This explanation seems applicable to this type of kettle in Minnesota.

Only a fraction of the eskers in this state have been mapped, and of these only a few exhibit good esker troughs. In southeastern Crow Wing County, south of Deerwood, examples of esker troughs are present. Several marginal kettles occur on either side of the esker which parallels the Nokasippi River from Wang Lake to Eagle Lake.[14] The writer has observed other esker troughs in eastern Mahnomen County and in eastern Polk County in northeastern Minnesota. Eskers of northern Cook

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[10] See the Brainerd Quadrangle, U.S. Geological Survey topographic map.

[11] R. F. Flint, *Glacial Geology and the Pleistocene Epoch* (New York: John Wiley & Sons, 1947), p. 151.

[12] F. T. Thwaites, *Outline of Glacial Geology* (Ann Arbor: Edwards Bros. Lithoprinters, 1946).

[13] G. W. H. Norman, "The Late Pleistocene Ice-Front in Chibougamau District, Ontario," *Royal Society of Canada Proceedings and Transactions*, Section IV, pp. 78–80 (1942).

[14] See the Deerwood Quadrangle, U.S. Geological Survey topographic map.

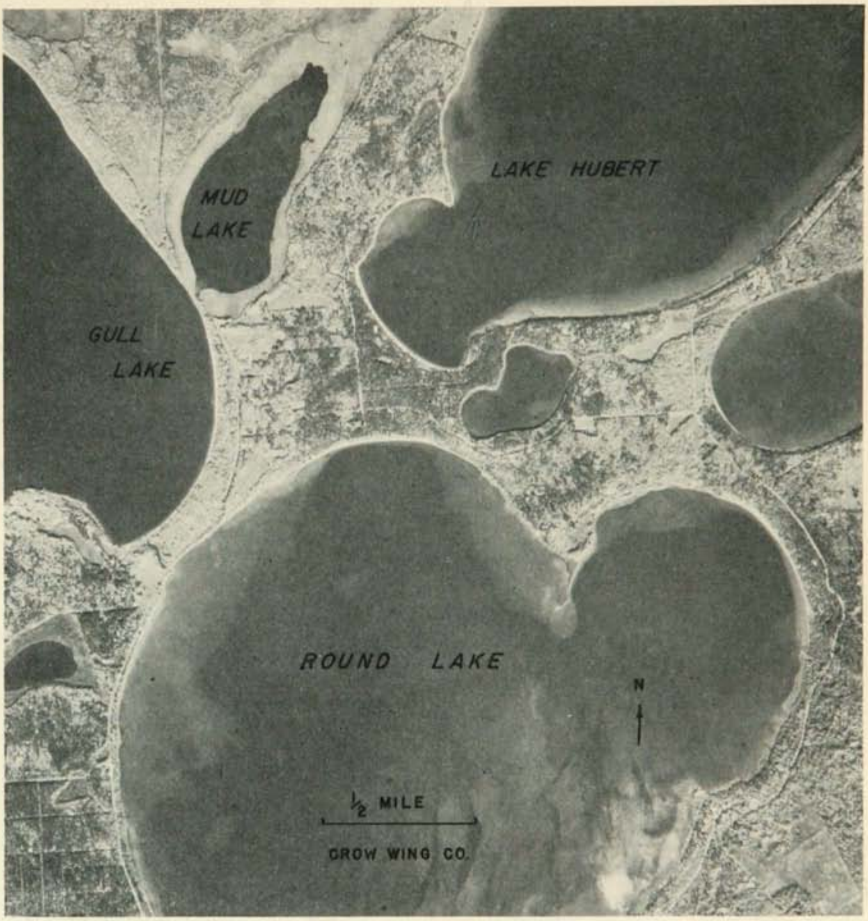

FIGURE 9. — Ice-block basins in an outwash plain (type-5 lakes) near Brainerd, Crow Wing County. Mud Lake (type 20) was formerly a bay of Gull Lake. (U.S. Department of Agriculture photograph, October 1939.)

County in northeastern Minnesota have several marginal kettles associated with them. A detailed mapping of the known eskers in the state and the discovery of new ones will undoubtedly disclose more lakes of this type.

Type 7. Ice-block basins in till

Depressions in till, especially those found in end moraines characterized by knob and kettle topography, can usually be attributed to one of two origins. Either they are ice-block pits or they are the result of the irregular deposition of till. The steeper-sided pits (i.e., the deeper lakes) are generally considered to be of ice-block origin, and the kettle rims of outwash help to distinguish the true ice-block pits. From a map study alone such a distinction can rarely be made, and even field investigations do not always disclose the presence of the outwash or boulder rims. There is also the possibility of mistaking a knob and kettle topography developed in outwash from one developed in till. In the former the kettles are all of ice-block origin, but the ice masses were so numerous and closely spaced that extensive areas of outwash plain did not develop. Or if they did develop by a complete burial of the ice blocks, the flatness was destroyed by the subsequent melting of the ice blocks and the extensive collapse of the overlying outwash. At such places the only evidence of a formerly extensive outwash plain would be flat-topped knobs of accordant elevations. These can usually be distinguished from knobs of till in end moraine topography which have rounded crests, the tops of which do not approach accordance in elevation. The distinction between knob and kettle topography developed in end moraines and that developed from the collapse of outwash plains is necessary if the origin of the kettles is to be understood.

The area west of Gull Lake in Cass County is part of the St. Croix morainic system of central Minnesota and contains hundreds of minor depressions in a knob and kettle topography.[15] Green Bass Lake, Bass Lake, Long Lake, and Shafer Lake, within the St. Croix moraine, are kettles of ice-block origin which are good examples of type 5.

Type 8. Ice-block basins partially in till and partially in outwash

If the margin of an ice sheet remains fixed for some time, the meltwater streams issuing from its surface are apt to build an extensive outwash plain, provided, of course, the newly uncovered land slopes away from the ice margin. If the frontal area of the ice which supports the outwash deposits becomes stagnated because of thinning, and becomes isolated because of a retreat of the main ice-mass, conditions are favorable for the formation of an ice-block basin. This ice-block basin differs from others in the classification because it may lie partially within the till of an end moraine and partially in the deposits of a frontal outwash plain. That portion of the resulting depression that has its rim area in the outwash will be a steep ice-contact slope, which may be partially submerged below the level of the lake which occupies the basin (Fig. 8).

Lake Minnewaska, an example of this type of lake, is located in the north-central part of Pope County, in west-central Minnesota, near the town of Glenwood. Glenwood lies at the base of a steep ice-contact slope which forms the northeastern shore of the lake and which rises 230 feet above the present lake level to an extensive outwash plain. This plain parallels the border of the Altamont-Gary morainic complex of Mankato age. The major part of the Lake Minnewaska basin is situated within the morainic mass itself and thus has the greater part of its shore area bounded by till instead of outwash.

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[15] See the Pilager Quadrangle, U.S. Geological Survey topographic map.

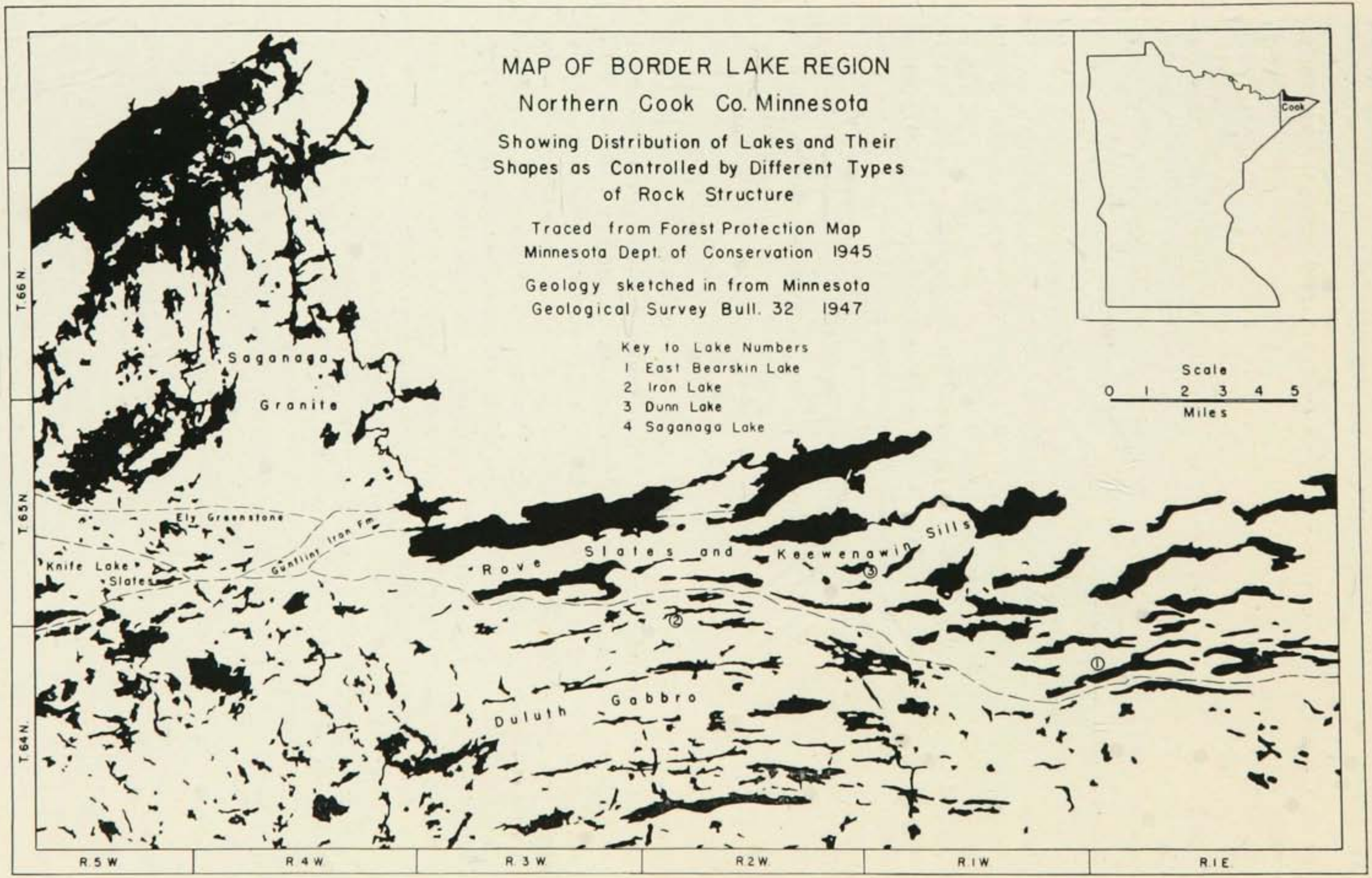
MAP OF BORDER LAKE REGION
Northern Cook Co. Minnesota
Showing Distribution of Lakes and Their Shapes as Controlled by Different Types of Rock Structure
Traced from Forest Protection Map Minnesota Dept. of Conservation 1945
Geology sketched in from Minnesota Geological Survey Bull. 32 1947
Key to Lake Numbers
1 East Bearskin Lake
2 Iron Lake
3 Dunn Lake
4 Saganaga Lake
Scale
0 1 2 3 4 5
Miles
Cook
Saganaga
Granite
Ely Greenstone
Gunflint Iron Fm.
Knife Lake Slates
Rove Slates and Keewenawin Sills
Duluth Gabbro
T.66 N.
T.65 N.
T.64 N.
R.5 W.
R.4 W.
R.3 W.
R.2 W.
R.1 W.
R.1 E.

PLATE 2

CLASS B. BASINS PRODUCED BY GLACIAL EROSION

Type 9. Bedrock basins localized by preglacial valleys

In the Border Lakes region of northern Cook County the glacial deposits are thin and widely scattered. Unlike what has happened in most of Minnesota, glacial erosion rather than glacial deposition has been responsible for the major topographic features, especially the lakes. Plate 2 shows the distribution and form of the lakes in this area. Each of the major types of bedrock is characterized by lakes of a distinctive configuration. In the area underlain by the Saganaga granite many of the lakes have linear segments which reflect the attitude of the joints in the rock.[16] In the area of the Duluth gabbro, except in the western part where the drift cover may be thicker, the lakes are narrow and elongate and lie in bands of rock which are mineralogically unlike adjacent bands.[17] Differential erosion of the banded gabbro has resulted in the present east-west "grain" of the topography in the eastern part of the gabbro. The lakes near the northern border of the eastern gabbro area have an average depth of 20 or 30 feet and have bottom configurations that are symmetrical. Iron Lake (Fig. 10) is typical of the lakes in this part of the gabbro.

The Rove area,[18] however, shows the most interesting relation of bedrock to topography, and it deserves more extensive consideration because of the information it gives regarding the behavior of the ice sheet which helped to shape its surface.

The Rove area is characterized by distinct east-west valleys eroded in the Rove slate and by intervening ridges of diabase sills which intrude the slates. The rock layers are inclined to the south at an angle of 4°–15° from the horizontal such that the edges of the rock layers are exposed at the surface (Fig. 11). Most of the valleys are occupied by chains of elongate lakes, many of which are bordered by solid rock on all sides. The elevation of the individual lakes ranges from 1,525 feet (Rose Lake) to 1,745 feet (Loon Lake) above sea level, and lakes on the opposite sides of a single ridge may differ in surface elevation by as much as 200 feet.

A typical ridge is asymmetrical in cross section and is generally underlain by a thick sill, although it might consist of several sills that alternate with thin beds of slate.[19] The gentle slope of the ridge conforms to the inclination of the sill which caps it, but the steep north-facing slope forms an escarpment which may rise from 200 to 400 feet above the surface of the lake at its base. Huge talus blocks cover the lower part of the escarpment. Some of the lakes show bifurcations or abrupt termina-

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[16] F. F. Grout, *Structural Features of the Saganaga Granite of Minnesota-Ontario* (Sixteenth International Geological Congress, Report 1, 1933), p. 255.

[17] F. F. Grout, "A Type of Igneous Differentiation," *Journal of Geology,* 26:626–658 (1918).

[18] A narrow strip of land in Cook County between the international boundary and the Gunflint Trail, extending from Pigeon Point to a few miles west of Gunflint Lake.

[19] F. F. Grout and G. M. Schwartz, *The Geology of the Rove Formation and Associated Intrusives in Northeastern Minnesota* (Minnesota Geological Survey Bulletin 24, 1933), p. 36.

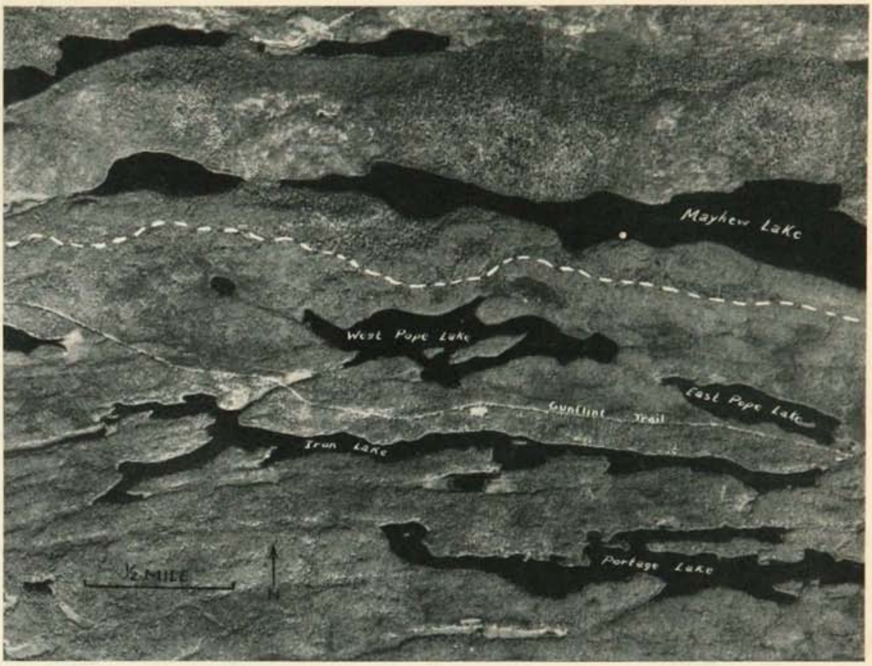

FIGURE 10. — Elongated lakes in northern Cook County. Iron Lake lies in the Duluth gabbro, while Mayhew Lake lies in the Rove slate. The approximate contact between the Duluth gabbro and the Rove area is shown by the dashed line. Note the diabase ridge north of Mayhew Lake. (U.S. Forest Service photograph.)

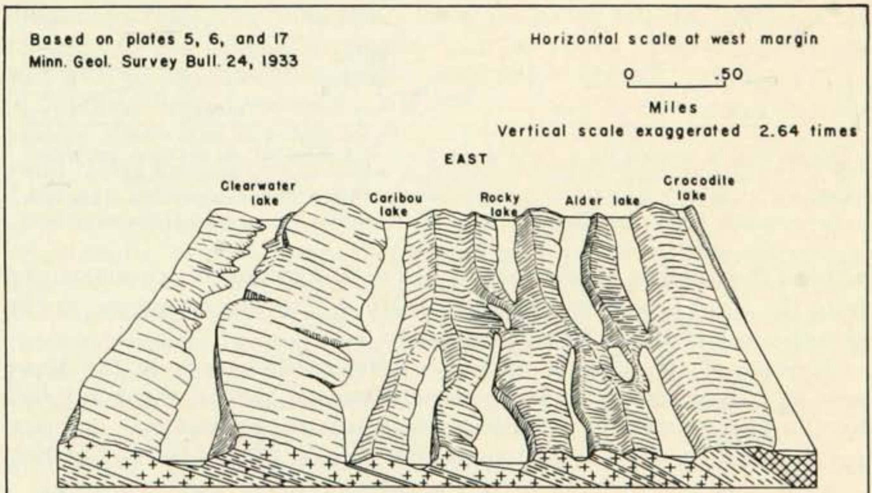

FIGURE 11. — A block diagram of part of the Rove area showing the bedrock control of topography. The ice moved from north to south (left to right).

tions and offsets because of the pinching out of the sills and slates, as, for example, East Bearskin Lake (Plate 2).

The slate layers generally consist of a series of thin beds and are usually jointed in coordinate systems; one set of joints trends parallel to and the other at right angles to the east-west valleys.[20]

An examination of maps showing the shape of the lake bottoms in the Rove area has revealed that many of the rock-bound lakes have depths of about 100 feet and a few are over 200 feet deep.[21] Most of the lakes in this area for which maps are available show an asymmetrical bottom configuration. Both Dunn Lake and East Bearskin Lake, for example, are deepest near the south shore (Figs. 12 and 13).

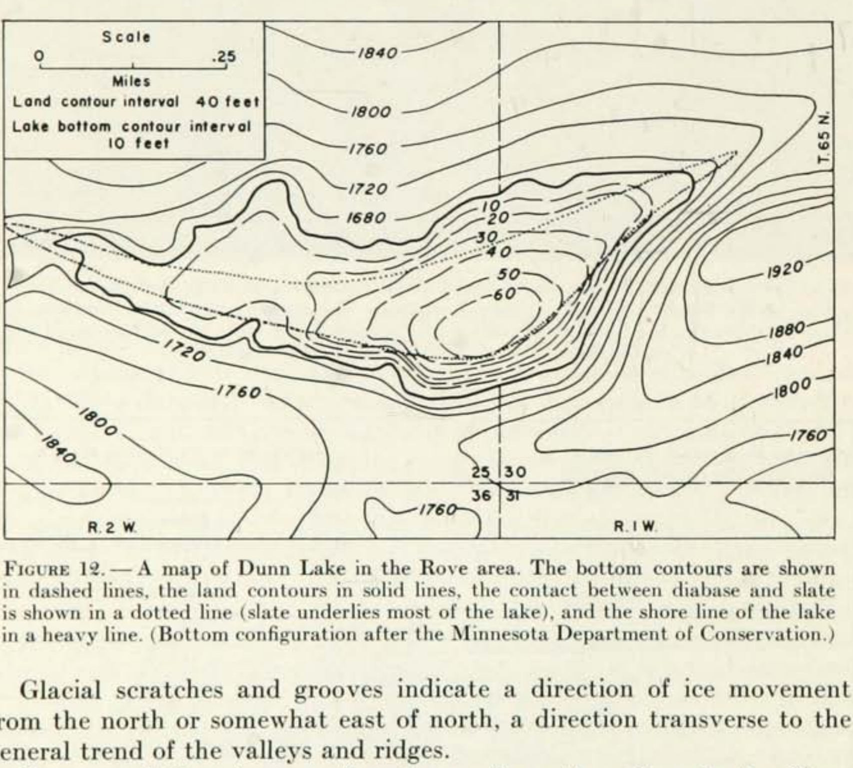

FIGURE 12. — A map of Dunn Lake in the Rove area. The bottom contours are shown in dashed lines, the land contours in solid lines, the contact between diabase and slate is shown in a dotted line (slate underlies most of the lake), and the shore line of the lake in a heavy line. (Bottom configuration after the Minnesota Department of Conservation.)

Glacial scratches and grooves indicate a direction of ice movement from the north or somewhat east of north, a direction transverse to the general trend of the valleys and ridges.

Because of the absence of major north-south valleys in the Rove area, it is apparent that the preglacial drainage pattern was controlled by the rock structure. Ver Steeg reconstructed a preglacial drainage pattern that shows major streams flowing east in the belts of slate.[22]

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[20] *Ibid.*, p. 13.

[21] This information is on record in the files of the Minnesota Department of Conservation, Division of Game and Fish, St. Paul, Minnesota.

[22] Karl Ver Steeg, "The Influence of Geologic Structure on the Drainage Pattern in Northeastern Minnesota," *Journal of Geology*, 55:359 (1947).

Short tributaries and short north-south segments of the major streams cut across ridges, forming small gaps that are still preserved today but are features of minor significance when compared with the east-west valleys and ridges.

Because the deep bedrock basins which occupy the former stream valleys cannot logically be ascribed to normal stream erosion, they are considered to be the product of glacial erosion. The lakes in the Rove area are different from other well-known linear bedrock lakes in North America in that their long axes lie *transverse* to the general direction of ice movement. It is important, therefore, to see how the effects of an ice sheet on the Rove area compare with the effects observed elsewhere, and whether any difference can be explained logically.

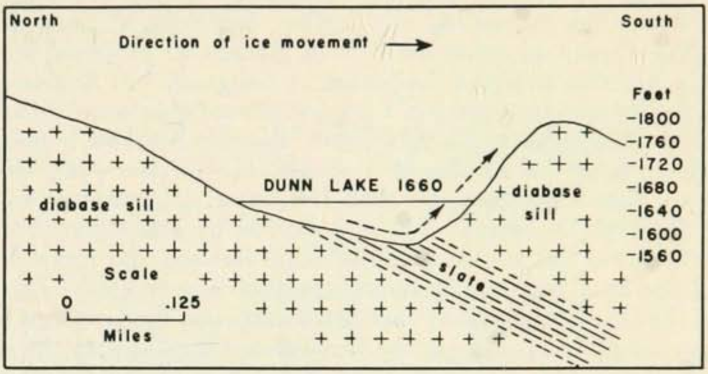

FIGURE 13. — A cross section of Dunn Lake along the north-south section line in Figure 12. The dashed arrows indicate the direction of the extrusion flow of the basal ice.

Modern thought concerning the effects of an ice sheet on preglacial valleys oriented at different angles to the general direction of ice movement stems from studies in the Finger Lakes region of New York. Cayuga Lake and Seneca Lake are the largest of the group; glacial erosion deepened the former at least 850 feet and the latter about 1,500.[23] Both lakes are elongate in a north-south direction and are nearly 30 miles long. The bedrock in which the Finger Lakes occur consists of Devonian shales and sandstones dipping gently to the south.[24] Von Engeln concluded that the great amount of deepening of the Finger Lakes was due to vigorous glacial erosion, greatly enhanced because the major valleys were parallel to the southward direction of ice movement.[25] At the same time, the tributary valleys, which were transverse or oblique to the direction of ice movement, experienced little if any erosion by the ice. Because of this, an

[23] R. S. Tarr, "Hanging Valleys in the Finger Lakes Region of Central New York," *American Geologist*, 33:284 (1904).

[24] O. D. Von Engeln, *The Finger Lake Region* (Sixteenth International Geological Congress, Guidebook 4, 1933), p. 50.

[25] *Ibid.*, p. 54.

emphasis on *topographic* control of glacial erosion has predominated in the explanation of a great number of land forms produced by glacial denudation. The writer believes that too little emphasis has been placed on *bedrock* control of glacial erosion.

Because of the studies made in the Finger Lakes region the idea has prevailed that preglacial valleys which lie transverse to the direction of ice movement will become filled with stagnant ice, over which the upper ice will flow, thus preventing any further deepening of the transverse valley. The theory of extrusion flow in glaciers as proposed by Demorest[26] in America and later supported by Seligman[27] in England states that ice flowage can take place in a glacier because of pressure differentials induced by differences in ice thicknesses. Because basal ice is more plastic than ice near the surface of a glacier, the former will yield more rapidly to differential pressure than the latter. If, however, extrusion flow of this type is obstructed in any way, as by a topographic barrier, the conditions of differential pressure cause forward and upward movement of the basal ice so that the obstruction is overridden. The writer believes that the hypothesis of obstructed extrusion flow can best explain the results of glacial erosion in the Rove area. Coupled with the concept of differential erosion as controlled by bedrock, it presents a more plausible explanation of the present topography than could be deduced from a comparison of the Rove area with the Finger Lakes region.

In order that the present surface configuration of the Rove area be understood, certain points must be emphasized: (1) The jointed and thin-bedded character of the slates made them especially well suited for glacial quarrying, much more so than the contiguous sills. (2) A cuesta topography was already developed at the beginning of the Pleistocene and was dominated by major east-west valleys with few pronounced gaps in the intervening ridges.

When conditions of continental glaciation were imposed on the Rove area, the ice was a few thousand feet thick and its surface sloped gently southward from the Patrician center to the north. The base of the ice sheet encountered a cuesta topography having a relief of a few hundred feet. Inasmuch as the ice over the valleys would be thicker than the ice over the ridges, obstructed extrusion flow would operate and would result in the removal of the easily quarried slates of the valleys (Fig. 14). On the other hand, the ridges would not be appreciably eroded, partly because the ice would be thinner over the ridges and therefore less plastic, and partly because of the resistance of the diabase to both quarrying and abrasion by the ice. The fact that some of the gentle-dip slopes of the ridges still have patches of slate on them is proof that the diabase has undergone little erosion in comparison with the slate.[28] R. P. Sharp

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[26] Max Demorest, "Ice Sheets," *Bulletin of the Geological Society of America*, 54:305–324 (1943).

[27] G. Seligman, "Extrusion Flow in Glaciers," *Journal of Glaciology*, 1:12–18 (1947).

[28] G. M. Schwartz, personal communication.

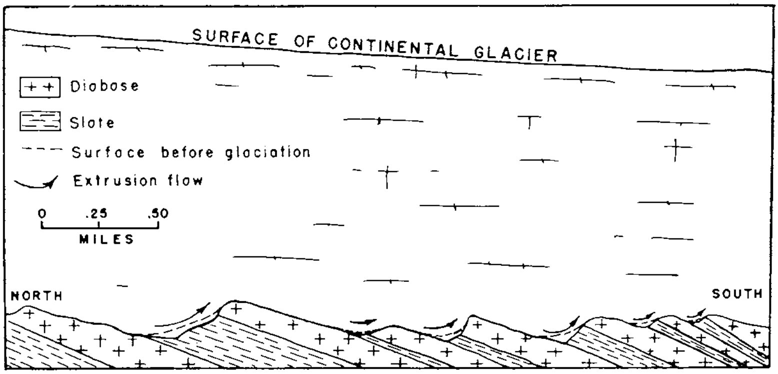

FIGURE 14. — A diagram showing the extrusion flow of the glacial ice as it crossed the preglacial valleys eroded in the Rove slate. (The vertical scale is greatly exaggerated.)

noted that the till in the vicinity of the Rove formation consists up to 90 per cent of slate fragments, which is further evidence that the ice was more able to erode the slate than the diabase.[29] The writer proposes the term *selective erosion* for this process.

One might argue with Holmes that the basal ice, being more plastic than ice higher up in the glacier, hence more mobile and more capable of adjusting its flow to irregularities in topography, would escape transverse valleys by flowing out the ends; or, if the pressure gradient toward either end was too small for ice flowage, the ice would flow through saddles at the heads of tributaries to those transverse valleys.[30] Thus one might consider that the deepening of the east-west valleys was accomplished because the basal ice was directed *along* the valleys instead of *across* them as proposed here. But there is no field evidence for this suggestion because none of the known striae show an east-west alignment. Furthermore, one would still have to explain how the basal ice got out of a valley even if it did flow parallel to it, because many of the east-west valleys in the Rove area terminate abruptly at either one or both of the ends because the bordering sills may merge together. If the basal ice were moving along the valley, it still would have to surmount a barrier at the end, and that barrier would be an obstruction of no less magnitude than the basal ice would encounter if it moved directly across the valley. The basal ice might move laterally along the valley and escape through a preglacial gap in a ridge, but such gaps are uncommon and show no evidence of concentrated glacial erosion. Even though the gaps that did exist were aligned parallel to the direction of ice movement, the resistance of the diabase in which they were cut was sufficient to counteract the favorable topographic alignment of the gaps. We must

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[29] Personal communication.

[30] C. D. Holmes, "Hypothesis of Subglacial Erosion," *Journal of Geology,* 52:184–190 (1944).

therefore look to the differences in rock structure as the real reason for the present topography rather than find the explanation in an alignment of preglacial channels with respect to direction of ice movement.

The importance of this factor in erosion by mountain glaciers has been stressed by Matthes for the origin of the rock steps in Yosemite Valley.[31] The strongly jointed zones of the granite bedrock were more easily quarried by the valley glacier than the intervening zones of less strongly jointed rock, and the valley profile was converted to what Matthes called a "glacial stairway."

A final point in support of the theory of selective erosion is the fact that the lakes themselves show a bottom configuration that is definitely controlled by rock structure. Note the asymmetry of Dunn Lake (Fig. 13) and the fact that several others in the Rove area show the same configuration, namely, a steep subaqueous slope on the south shore. Had ice moved laterally along the valleys the bottom configuration of the lakes should be U-shaped instead of an asymmetrical V.

In summary, then, it is concluded that the direction of movement of the basal ice was not appreciably altered by the transverse valleys in the slate, but the basal ice crossed the valleys at right angles under conditions of obstructed extrusion flow and, in the process, produced the rock basins. The differential resistance of slate and diabase to glacial excavation cannot be overemphasized. This factor coupled with the hypothesis of obstructed extrusion flow seems to provide a satisfactory explanation for the alignment of bedrock basins at right angles to the general direction of ice flow.

Type 10. Bedrock basins not related to preglacial valleys

Bedrock lakes do not necessarily have to lie in a position formerly occupied by a segment of a preglacial valley, for there are several rock-bound lakes in Minnesota that cannot be related logically to a preglacial drainage system. The position of these lakes is in most cases a function of the bedrock control of glacial erosion.

Kabetogama Lake in the northeastern corner of St. Louis County is apparently bounded by bedrock on all sides. The bedrock over a wide area in northern St. Louis County consists of a granite (Algoman) intruded into a mica schist, the schistosity of which has a pronounced east-west alignment. On the west shore of Kabetogama Lake the headlands are formed by the granite and pegmatite, whereas the small bays and indentations are underlain by the schist. Many of the islands of the lake are underlain by pegmatite which shows signs of glacial polish and striae on the orthoclase crystals. The striae have a northeast-southwest trend, a direction oblique to the strike of the schistosity.

Namakan Lake just east of Kabetogama has several arms and bays which are rock-bound on all sides by granite and pegmatite, a condi-

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[31] François Matthes, *Geologic History of Yosemite Valley* (U.S. Geological Survey Professional Paper 160, 1930), pp. 94–98.

tion which strongly suggests that the rock at the bottom of the arms and bays is schist which has been selectively eroded. Mica Bay (Frontispiece) is an east-west arm of Namakan Lake that clearly illustrates this point.

On the Canadian side of the international border many of the islands in Rainy Lake show a distinct east-west alignment. Although it cannot be definitely stated that Rainy Lake is completely rock-bound, there is every reason to believe that much of the basin is the result of glacial erosion of the mica schist and other metamorphic rocks in which it lies.

CLASS C. BASINS PRODUCED BY GLACIAL EROSION AND GLACIAL DEPOSITION

Type 11. Bedrock basins partially dammed by drift

The amount of water which can be held in a bedrock basin is determined by the lowest point on its rim. If the closure of the basin is increased because of a drift dam on a low portion of the bedrock rim, the size of the lake is increased over what it normally would be if the lake were confined to the bedrock basin alone.

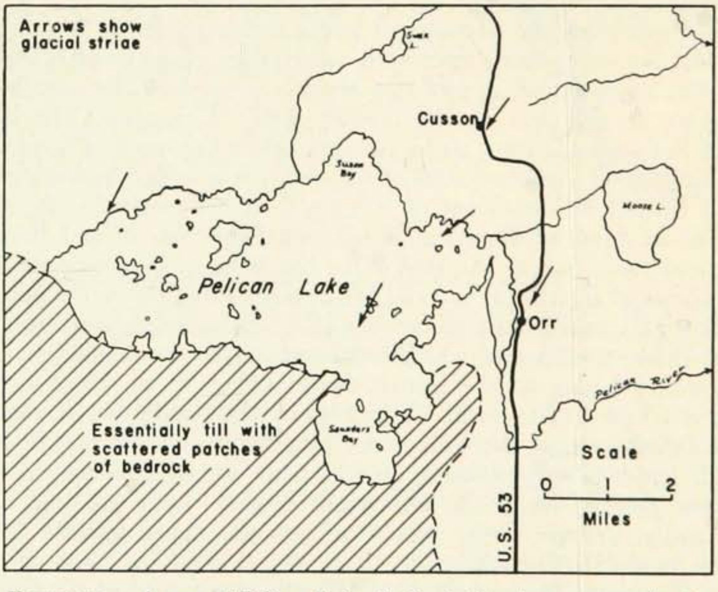

FIGURE 15. — A map of Pelican Lake, St. Louis County, an example of a bedrock basin partially dammed by glacial drift (type-11 lake).

Pelican Lake near Orr in northeastern St. Louis County (Fig. 15) is rock-bound on the northern and eastern shores. Most of the islands on the lake are bedrock and contain glacial striae and glacial polish. The lake has a maximum depth of 35 feet but averages about half of that. The till which borders the lake on the south and southeast is thin and of local derivation. A shallow bedrock basin would persist if the drift were completely removed, but there is little doubt that the presence of the till has increased the closure of the original basin.

Category 2. Lake Basins Due to Stream Processes

CLASS A. BASINS PRODUCED BY STREAM DEPOSITION

Type 12. Lakes related to natural levees
Type 13. Lakes formed by uneven aggradation of a floodplain
Type 14. Master stream dammed by tributary
Type 15. Tributary dammed by master stream
Type 16. Delta lakes

The segment of the Mississippi River from Fort Snelling to a point below the mouth of the Chippewa River of Wisconsin, along with two major tributaries, the Minnesota and St. Croix, comprises a geomorphic unit with which are associated examples of lakes of type 12 through type 16. Inasmuch as these lakes are intimately related to the above segment of the Mississippi, it is more logical to consider them together than separately.

The segment of the Mississippi under consideration is 80 miles long (Fig. 16). Its floodplain slopes with an average gradient of 0.3 foot per mile from an elevation of 692 feet above sea level at the mouth of the Minnesota to 668 feet at the mouth of the Chippewa. The bedrock floor of the valley is from 80 to 175 feet below the modern floodplain.

The nature of the alluvial fill of the valley is revealed by borings made by the United States Corps of Engineers in connection with the construction of dams at Hastings (Lock and Dam No. 2) and Red Wing (Lock and Dam No. 3). At Red Wing the borings show a layer of blue clay at least 50 feet thick, with its top about 15 feet below the floodplain. A boring at Hastings shows the top of a layer of clay and silt at least 20 feet thick, the base of which is 50 feet below the floodplain surface. Still another boring at the Robert Street bridge in St. Paul shows the top of a 7-foot clay layer at 65 feet below the floodplain. It cannot be stated definitely that these clays are genetically related, but their presence indicates a depositional environment unlike modern conditions along the present floodplain. Overlying the clay strata are beds of sand and, locally, gravel. These sands and gravels grade upward into the modern floodplain deposits.

The Mississippi River from Red Wing to the mouth of the Chippewa River is occupied by Lake Pepin, an example of a type-14 lake. It was formed by the building of an alluvial fan at the mouth of the Chippewa River. The lake has a maximum depth of 50 feet, a width that ranges from 1½ to 3 miles, and a length of 22 miles. There is no appreciable current in Lake Pepin even during high water stages, and it therefore acts as a natural settling basin for sediment carried into it by the Missisipi and smaller streams. That it is a true lake is shown by the typical

FIGURE 16. — A map of the Minnesota-Wisconsin border area showing the Mississippi River from the mouth of the Minnesota River at Fort Snelling to the mouth of the Chippewa River. The hachures indicate the modern valley limits.

lake shore features and by the delta at its head near Red Wing. Lakes of type 16 are associated with this delta. They were originally part of the main lake, but have been isolated by the deposition of alluvium along the various distributaries of the Mississippi in its course through the delta area.[32]

The lower part of the Minnesota River occupies the valley of Glacial River Warren and flows on a floodplain which is characterized by several shallow lakes that are classified as type 12. These lakes are rectilinear in outline and are separated from the present river channel by natural levees (Fig. 17). The lakes are usually flooded in the spring during the high stages of the Minnesota River, but are normally very shallow and sometimes swampy during other seasons of the year. At least one of

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[32] See Wabasha and Red Wing quadrangles of the U.S. Geological Survey topographic map series.

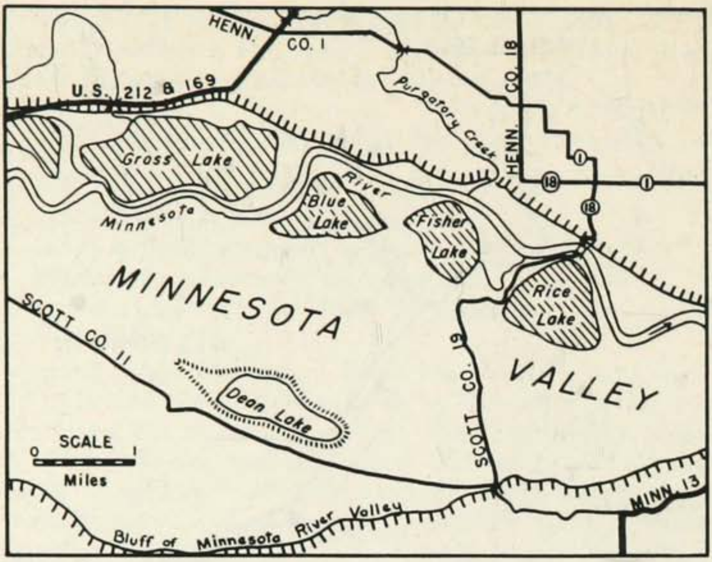

FIGURE 17. — These shallow lakes along the Minnesota River between Chaska and Fort Snelling are separated from the present river by natural levees formed during the flood stages of the Minnesota River in the spring (type-12 lakes).

these lakes has developed since 1894. At that time, when the St. Paul quadrangle was surveyed, no lake was shown southwest of Pike Island,[33] but on a 1940 aerial photograph a lake does exist on the left flank of the Minnesota River near its confluence with the Mississippi (Fig. 18). The lake is clearly visible from the Mendota bridge.

Other floodplain lakes between St. Paul and Red Wing and below the mouth of the Chippewa on the Mississippi are the result of high stages of that river. These lakes, type 13, mark the positions of minor sloughs and temporary channels of the floodwaters. Deposition of clastic and organic material has caused the segmentation of the abandoned channels into their present forms. Good examples of type-13 lakes may be seen on the Winona quadrangle.[34]

The lower St. Croix was dammed by alluvium of the Mississippi to form Lake St. Croix, which is 23 miles long and from ¼ to 1½ miles wide and has a maximum depth of over 40 feet (Fig. 19). This is an example of a type-15 lake.

Martin described the modern features along the Mississippi and St. Croix rivers in Wisconsin, but he did not stress the close interrelation of the features.[35] The writer wishes to propose a hypothesis that will

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[33] U.S. Geological Survey topographic map.

[34] U.S. Geological Survey topographic map.

[35] Lawrence Martin, *The Physical Geology of Wisconsin* (Wisconsin Geological and Natural History Survey Bulletin 36, 1916), pp. 120–171.

FIGURE 18. — A lake (type 12) formed since 1894 on the Minnesota River floodplain. (U.S. Department of Agriculture photograph, June 1940.)

explain the relationship of the lakes of the lower Minnesota River, the floodplain lakes of the Mississippi valley, the delta lakes at the head of Lake Pepin, Lake Pepin itself, and Lake St. Croix. Actually, this hypothesis is an extension of what has been generally agreed upon by those familiar with the late-glacial and postglacial history of the area under consideration.

During late-glacial time, the Minnesota-Mississippi Valley was occu-

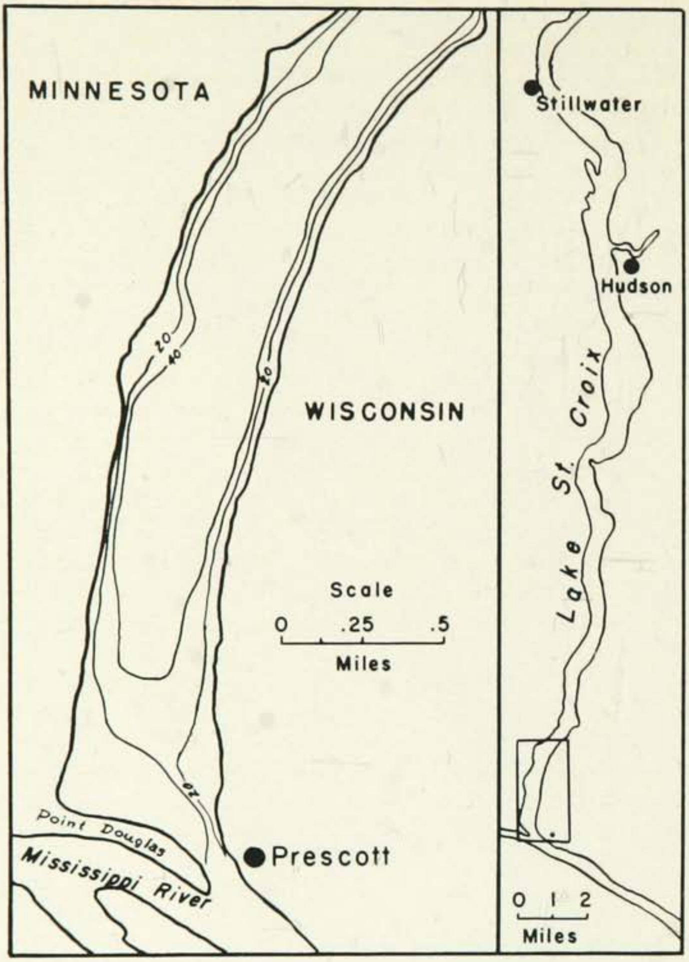

FIGURE 19. — A map of Lake St. Croix showing the bottom configuration at the lower end. (After Martin, 1916.)

pied by the Glacial River Warren, which served as an outlet for Glacial Lake Agassiz. Because of its large volume and relatively small load, River Warren was able to transport all of the sediment added to it from the Chippewa River and other tributaries in southwestern Wisconsin and southeastern Minnesota, and, in fact, cut its bed to a gradient at least 50 to 100 feet below the modern floodplain. The volume of relatively clear water was augmented by the large contribution from Glacial River St. Croix, which served as the early outlet for Glacial Lake Duluth. But as the ice sheet retreated and the outlets of Lake Agassiz and Lake Duluth shifted to the north and east respectively, River Warren lost its large volume of water and the modern Minnesota-Mississippi and St. Croix rivers came into existence.

With a reduced volume and therefore a reduced velocity, the Mississippi no longer was able to transport the relatively coarse load supplied by the Chippewa River. In response to the loss in volume of the Mississippi, the alluvial fan was constructed across the Mississippi at the mouth of the Chippewa. Ponding behind this alluvial dam resulted in the formation of Lake Pepin. The original extent of the lake upstream is unknown, but the writer believes that it was probably near the Robert Street bridge in St. Paul, some 50 miles upstream from the present head at Red Wing. Thus a longitudinal section of early Lake Pepin would be wedge-shaped with the shallow part of the wedge upstream and the deepest part near the mouth of the Chippewa. The shallow part would be filled very rapidly by coarse sediment as the Mississippi formed a delta at the head of the new settling basin, and the clay and silt fraction would be deposited in the deeper, quieter part of the lake. As the delta expanded, it would advance down the long axis of the lake and progressively bury the bottom sediments of clay and silt. Figure 20 shows the sequence of events from the time the Chippewa fan first started its growth to the present time. The diagrams also show the manner in which the present sediments found in borings by the United States Engineers came into being.

Because the St. Croix valley was cut to a low gradient by the waters of Glacial Lake Duluth, the rise in the base level of the Mississippi at the mouth of the Chippewa also caused the lower reaches of the St. Croix to pond. Thus Lake St. Croix was formed as an arm of early Lake Pepin. But when the delta at the head of Pepin progressed downstream to a point beyond the mouth of the St. Croix, this arm of Lake Pepin was cut off from the rest of the lake. Continued alluviation all along the Mississippi above the Pepin delta caused the waters of the St. Croix to rise higher and higher until the present level was attained.

Both Lake Pepin and Lake St. Croix will be continuously diminished in size by the advance of the deltas at their heads as well as the filling of the basin with silt and clay.

Further support for the writer's interpretation of the post-River Warren history of Lake Pepin is drawn from a study by Todd of the heavy minerals found in the clay, silt, and sand in the borings for the Hastings dam.[36] He concluded that the upper 150 feet of fill in the Mississippi River at Hastings was derived from both Cary and Mankato drifts. This indicates to the writer that the clay and silt as well as the overlying sands were deposited, not by outwash from these glaciers, but by postglacial streams which derived their sediment from the surface drifts.

Another significant point which supports the writer's hypothesis is

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[36] J. H. Todd, *A Contribution to the Study of Pleistocene History of the Upper Mississippi River* (unpublished Ph.D. thesis, University of Minnesota, 1942).

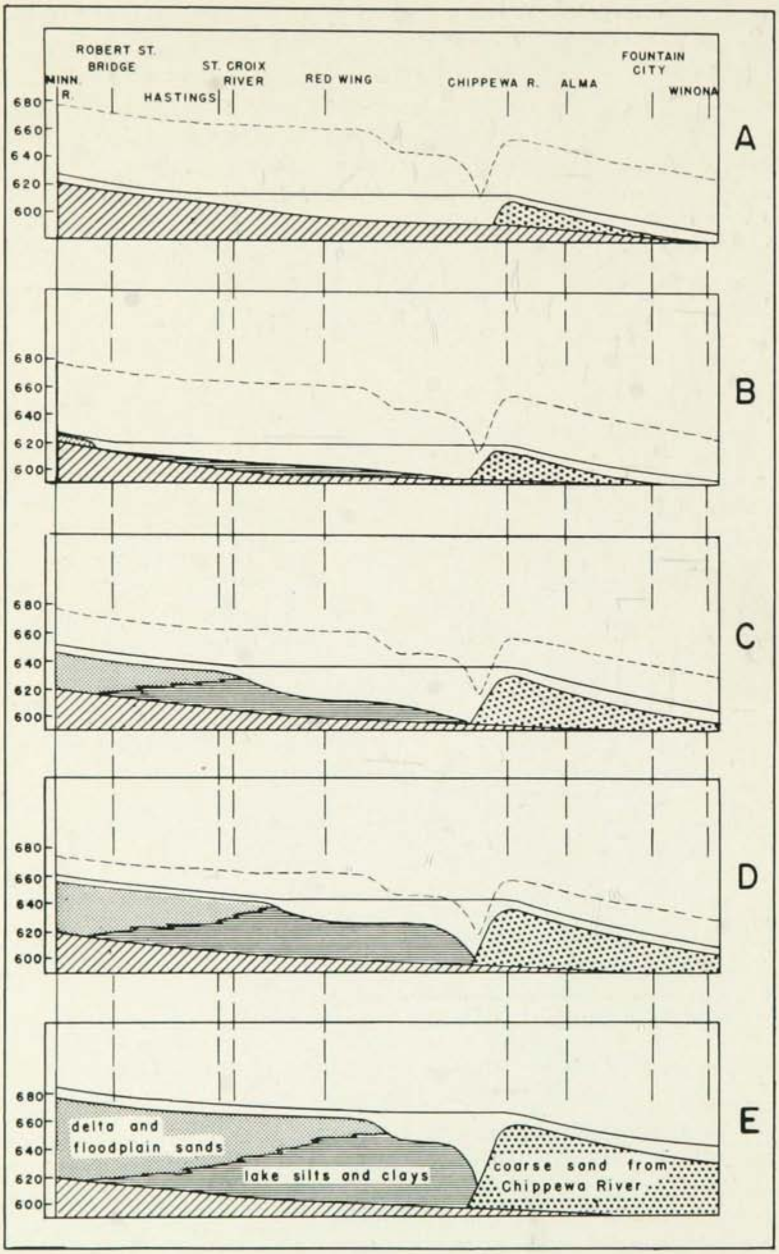

FIGURE 20. — A series of diagrams showing the sequence of events which produced present conditions in the Mississippi Valley between St. Paul and Winona. The dashed line shows the modern river-bottom profile. (Data compiled from records of borings by U.S. Corps of Engineers, St. Paul Office.)

the fact that borings by the Army Engineers at four dam sites downstream from Lake Pepin over a distance of 40 miles do not disclose any silt or clay like that found in the Mississippi above Lake Pepin. This information further substantiates the inference that the clays and silts in the borings at Red Wing and Hastings are genetically related to the formation of the alluvial fan at the mouth of the Chippewa.

We have yet to consider the cause of aggradation in the lower Minnesota Valley. With the foregoing analysis of the Mississippi below its confluence with the Minnesota, two causes become apparent, both of which may have been responsible for a considerable amount of aggradation in the lower Minnesota and the subsequent formation of the lakes in that segment of the valley. The first is the loss in volume from Lake Agassiz. This in itself would have been sufficient to change the river from an eroding stream to an aggrading one, and the first phases of postglacial alluviation in the lower Minnesota were probably a direct result of this factor. The second cause, which certainly could have affected the lower reaches of the Minnesota, was the downstream rise in base level when the Chippewa fan was constructed. It has already been demonstrated how alluviation proceeded along the Mississippi upstream from the mouth of the Chippewa, and there is no reason why these effects could not have been felt along the lower 20 or 30 miles of the Minnesota. With a reduction in volume and a rise in base level, the Minnesota would tend to flood its valley more frequently than before, and natural levees would be the normal result of this more frequent flooding. Hence, the rectilinear lakes (type 12) would develop behind the natural levees.

A summary of late-glacial and postglacial events for the segment of the Minnesota-Mississippi River System in question is as follows:

1. Discharge of Lake Duluth through the St. Croix Valley and discharge of Lake Agassiz through the Minnesota Valley, with the erosion of a deep channel in the Minnesota-Mississippi Valley.

2. Reduction in volume in Glacial River Warren and Glacial River St. Croix, permitting the formation of the Chippewa alluvial fan. Waters

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(A) Initial stage — loss of volume in the Mississippi River because the change of outlet of Glacial Lake Agassiz permitted the growth of an alluvial fan at the mouth of the Chippewa River.

(B) The continued growth of the Chippewa fan causes early Lake Pepin to extend upstream to Robert Street Bridge in St. Paul. A delta forms at the head of this lake, while silt and clay are deposited in the deeper, quiet waters of early Lake Pepin.

(C) The Chippewa fan grows larger and higher, while the delta at the head of the lake advances downstream to the mouth of the St. Croix, burying the previously deposited silts and clays and blocking the lower end of the St. Croix Valley, thus forming Lake St. Croix.

(D) The continued growth of the Chippewa fan raises the level of Lake Pepin, while the advance of the delta continues to cover previously deposited lake silts and clays.

(E) Present condition of sediments in the valley as shown by borings.

ponded upstream on the Mississippi to a point near the Robert Street bridge in St. Paul. The lower reaches of the St. Croix were also ponded at this time.

3. Alluviation of the lower Minnesota River in response to a decrease in the volume of River Warren or to a rise in the base level downstream at the mouth of the Chippewa.

4. Advance of the delta at the head of early Lake Pepin to a point below the mouth of the St. Croix, Lake St. Croix thus being formed.

5. Continued advance of the delta to its present position at Red Wing, resulting in the burial of Lake Pepin clays and silts by delta and floodplain sands.

CLASS B. BASINS PRODUCED BY STREAM EROSION AND STREAM DEPOSITION

Type 17. Meander scrolls

During the lateral and downstream migration of the meanders of a stream flowing on its floodplain, erosion on the outer bank is accompanied by deposition on the inner bank. The joint operation of these two processes produces a series of smoothly curved ridges and intervening swales which may be occupied by standing water. These arcuate troughs are meander scrolls, and their relation to channel migration has long been recognized.[37] The most recent studies of meander scrolls have been made by Fisk, who applied the term "point bar" to meander scrolls and intervening ridges.[38]

He explains their formation as follows: "Gradual changes in stream alignment accompany bend migration during the formation of a meander loop. These changes not only vary the erosional activity of the river but bring about a continual shift in the site of bar formation. Most low stage point bars form close to the water surface with a downstream submerged ridge-like extension which separates a deadwater portion of the stream from the deep part of the channel nearer the opposite shore. The change in stream alignment which occurs during rising river stage floods the low water bar and has a tendency to set up a current back of the bar through the low stage deadwater area. High water deposition takes place on the bar area and a ridge-like mass of fine-grained alluvium is laid down upon the low stage bar which maintains the trend in its arcuate shape.

"Scouring in the path of the high stage flow generally forms a deep narrow channel back of the bar ridge, particularly near its downstream

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[37] W. M. Davis, "Meandering Valleys and Underfit Rivers," *Association of American Geographers Annals*, 3:9 (1913).

F. A. Melton, "An Empirical Classification of Floodplain Streams," *Geographical Review*, 26:596 (1936).

H. N. Fisk, *Geological Investigations of the Alluvial Valley of the Lower Mississippi River* (Mississippi River Commission, Corps of Engineers, Vicksburg, Mississippi, 1944), p. 20.

[38] H. N. Fisk, *Fine-Grained Alluvial Deposits and their Effects on Mississippi River Activity* (Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, 1947), p. 33.

FIGURE 21. — Arcuate troughs along the Mississippi River in Benton County, associated with channel migrations of the river; they are called meander scrolls (type-17 lakes).

end. This channel, during the following low stage, forms a slough back of the bar in which river water is backed up as another deadwater mass. The slough receives a partial filling of fine sediments, carried in suspension by the waters which become trapped in the area. As channel migration continues, sand accretion progresses and the slough may become completely blocked off from the river by bar growth. It then becomes a lake which gradually fills with sediment carried into it by floodwaters."

Lakes of this type are not very common in Minnesota, but a few examples have been recognized along the Mississippi about 75 miles upstream from Minneapolis near Little Rock Lake (Fig. 21). Other depressions of type 17 occur on the Minnesota River between Shakopee and Fort Snelling in Dakota, Hennepin, and Scott counties.

Type 18. Oxbow lakes

Oxbow lakes form when the upstream arm of a meander loop migrates downstream faster than the downstream arm. This process eventually results in the breaching of the narrow neck of land between the upstream and downstream segments of the meander loop, which then is abandoned because of the closing of its end by deposition of alluvium.

A recent study of channel meanders by means of models was carried out by the Mississippi River Commission.[39] In over fifty laboratory tests with meandering channels in uniform sediments, not a single neck cut-off was produced. The tendency was always for the meanders to shift down-

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[39] J. F. Friedkin, *A Laboratory Study of the Meandering of Alluvial Rivers* (Mississippi River Commission, Corps of Engineers, Vicksburg, Mississippi, 1945).

stream, the upper arm migrating at the same rate as the lower one. Chutes developed across the convex point of the meander loop, but no neck cut-offs formed. The conclusion was as follows: "With all bends in a meandering river migrating down the valley at the same rate, a cut-off cannot possibly develop. . . . It is, therefore, indicated that it is the local difference in erodibility of the bank materials in natural rivers which causes narrow necks to form and cut-offs to develop."[40]

Oxbow lakes are known in Minnesota on the Red River of the North, the Minnesota River, and the Mississippi River. Besides being present on these major streams, oxbows are known to exist in association with several of the smaller streams in the state.

Probably the best examples in the state are found in Aitkin County where the Mississippi flows over the bed of Glacial Lake Aitkin. These oxbow lakes and meander loops are well known on the Aitkin quadrangle.[41] Since the time the survey for this map was made in 1914, cut-offs have caused the formation of several oxbows. In fact, a comparison of maps of the late 1890's with aerial photographs made in 1939 shows that the segment of the river shown on Figure 22 has been shortened by 25 per cent.

Close examination of Figure 22 shows that there has been little migration of the meander loops. Except for the major oxbow cut-offs, evidence of a previous history of channel migration is strikingly absent. This fact is attested to by the lack of point bars and meander scrolls, features which should be abundantly present if the meander loops evolved from a former course that was less curved than the present. One is led to the conclusion that the *original* course of the Mississippi River, where it flows across the bed of Lake Aitkin, was a meandering one. The concept of a *consequent meandering* course is not at variance with geological principles if one considers the conditions under which this particular course of the river was established. In this area the early postglacial Mississippi inherited the nearly flat gradient of Glacial Lake Aitkin, a gradient that was so slight that the velocity of the water was not strong enough to remove minor differences in the lake sediments. The river was diverted, therefore, by local minor obstructions it encountered as it established its course on the bed of Glacial Lake Aitkin. By the time the course became somewhat fixed, it was already as sinuous as the one shown on Figure 22. Once established, the early channel migrated very little because of the resistance of the lake silts and clays to bank caving, a process necessary for lateral migration of a stream.

A meandering course with many oxbow cut-offs is usually ascribed to rivers in "old age," the inference being that the stream originally had a much straighter course in "youth" and eventually evolved into a meandering stream. There is no doubt that such a change does take

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[40] *Ibid.*, p. 16.

[41] U.S. Geological Survey topographic map.

FIGURE 22. — Oxbow lakes (type-18 lakes) along the Mississippi River in Aitkin County, developed on the floor of Glacial Lake Aitkin. (U.S. Department of Agriculture photograph, September 1939.)

place in most rivers, but from the analysis made of the Mississippi in Aitkin County, we see that a stream does not necessarily need to have a straight course before meanders and, subsequently, oxbow lakes can develop.

Category 3. Lake Basins Due to the Modification of Larger Basins

CLASS A. BASINS THAT ARE REMNANTS OF PROGLACIAL LAKES WHICH WERE DRAINED IN LATE-GLACIAL TIME

Type 19. Remnants of proglacial lakes

Meltwaters issuing from the margin of a retreating glacier become ponded if the newly uncovered land slopes toward the ice front. Lakes developed under such circumstances are called *proglacial* lakes and are temporary features because they are rapidly drained when the glacier eventually retreats. One of the vestiges of a former proglacial lake is the persistence of shallow depressions on its floor (type-19 lakes).

The largest area in Minnesota formerly covered by a proglacial lake is the northwestern part of the state, where several counties lie entirely within the boundary of Glacial Lake Agassiz. The early drainage was southward through Glacial River Warren, but with further retreat of the ice toward the north, Glacial Lake Agassiz discharged through lower outlets into Hudson Bay.

Today, the largest single body of water within the boundaries of the state, Upper Red Lake and Lower Red Lake, which has a total area of 408 square miles, appears to consist of two shallow depressions on the floor of ancient Glacial Lake Agassiz. The exact reason for their position is not known, but they may be related to the topography of the till underlying the lake sediments.

CLASS B. LAKE BASINS PRODUCED BY SHORE PROCESSES

Type 20. Isolation of a small bay by the construction of a natural barrier across its mouth

Various processes in operation within a lake tend to produce a smooth shore line. These processes will be considered in detail in a later chapter, but for the purpose of this classification, the effect rather than the cause of the process is considered. One common effect of the shore-smoothing process is the isolation of a small bay or indentation due to the construction of a natural barrier or bar at its mouth. Such bays become separate basins which are generally short-lived because of rapid filling with clastic, vegetal, and chemical sediments.

Figure 9 shows an example of this type of lake. Mud Lake was once a bay on the east shore of Gull Lake but has since been isolated by a bar constructed between the two. Several hundred other examples could be cited, but the Mud Lake-Gull Lake situation exhibits the essential feature of this type of lake, namely, that the isolated segment is much smaller than the main body of water from which it was separated.

Type 21. Segmentation of one large basin into two or more separate basins of nearly equal size

A single body of water may become separated into two or more basins by the joining of points on the opposite sides of a lake. The manner of growth of these points is discussed in a later chapter.

An example of "twin lake" development is clearly seen in Figure 23, where Marion Lake in Ottertail County has become bifurcated because of the extension of a point from the south shore nearly across the lake to where it joins, during low water stages, with a less pronounced point on the north shore.

Type 22. Basins formed behind cuspate bars

A characteristic of a cuspate bar is the shallow depression that lies between it and the shore. Such a depression may persist for some time as a small lake before it becomes filled with vegetation and sediment.

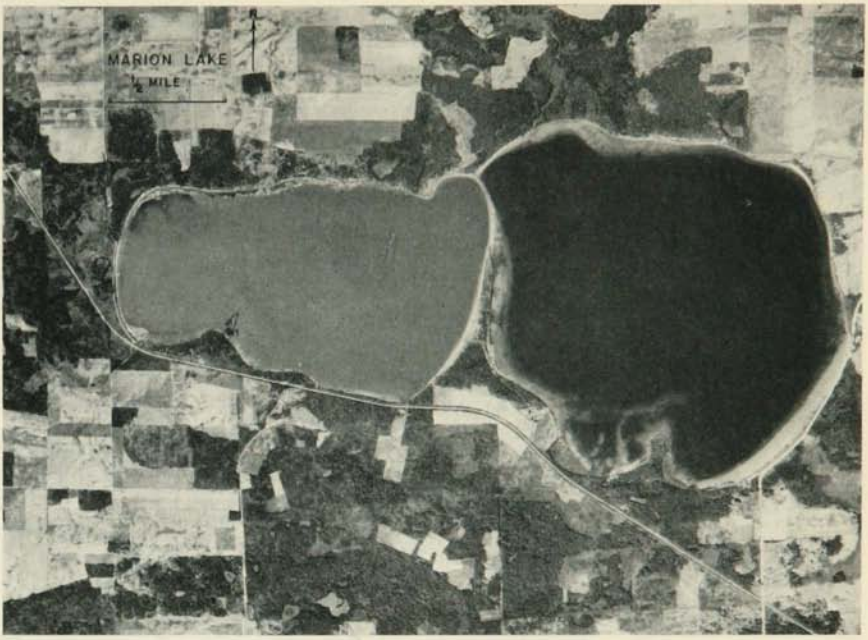

FIGURE 23. — Segmentation of Marion Lake in Otter Tail County by the growth of a point from the south shore of the lake. (U.S. Department of Agriculture photograph, June 1939.)

One of the largest of cuspate-bar depressions is Gould Lake (Fig. 24) in Cass County. Once part of Leech Lake, Gould Lake was formed behind two curved bars, one in Agency Bay, the other in Trading Post Bay. The old shore line of Leech Lake before Gould Lake was formed is conspicuous near the west shore of Gould Lake on Figure 24.

Category 4. Lake Basins Due to Organic Agencies

CLASS A. BASINS PRODUCED BY ANIMAL ACTIVITY

Type 23. Beaver-dam lakes

The building of dams by beavers may cause the inundation of several acres of land if the dams are constructed in areas of low relief.

An exceptionally large beaver dam was noted by Soper in Itasca State Park in southeastern Clearwater County.[42] There a lake 25 or 30 acres in area and from 6 to 8 feet deep was formed by the dam. Other examples of beaver-dam lakes can be found in St. Croix State Park in Pine County, where a beaver dam on Bear Creek has impounded the waters of that stream. Other lakes of this origin are known in Cook County and other northern counties in the state.

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[42] E. K. Soper, *The Peat Deposits of Minnesota* (Minnesota Geological Survey Bulletin 16, 1919), p. 43.

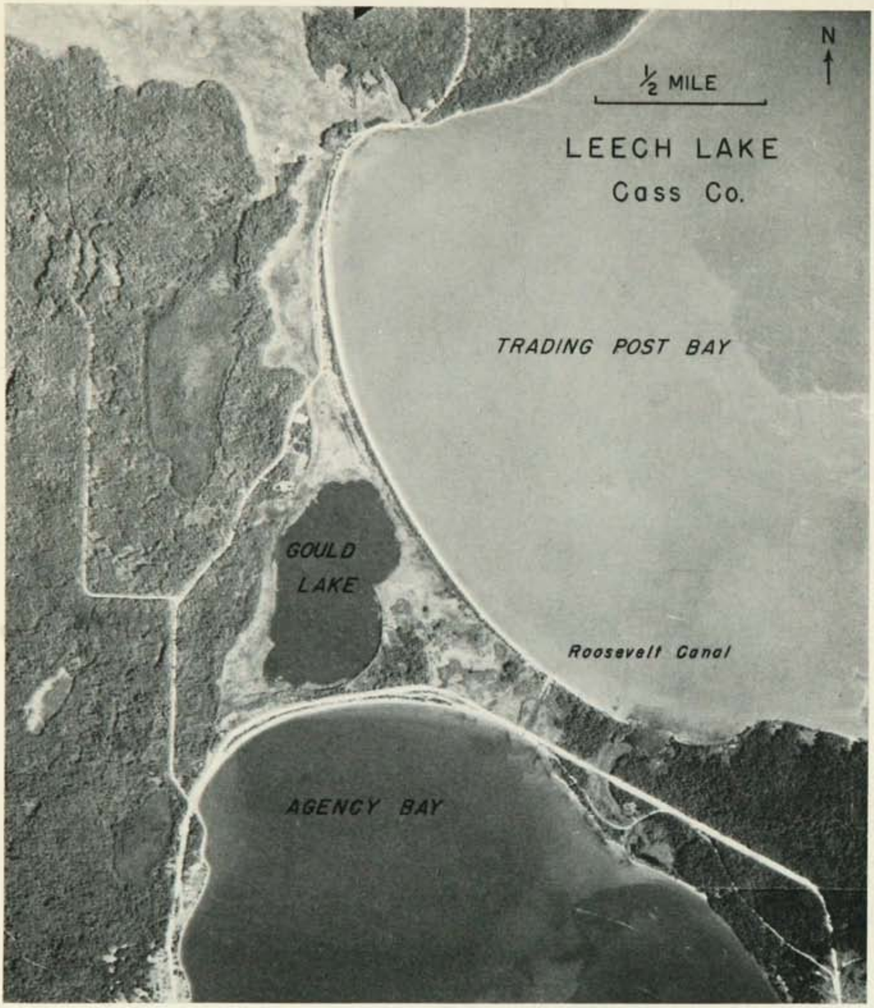

FIGURE 24. — Gould Lake (type 22), formed by the growth of a cuspate bar which is now attached to an island. (U.S. Department of Agriculture photograph, August 1939.)

Type 24. Lakes formed by artificial dams

Man as a geologic agent cannot be overlooked in a genetic classification of lakes. The impounding of water by artificial lakes deserves a place in this classification.

The South Fork of the Zumbro River in Wabasha and Olmstead counties of southern Minnesota has been dammed for water-power purposes. The reservoir, Lake Zumbro, has a shape that is obviously determined by the form of the river-cut valley to which it is confined and may be readily identified on the Rochester Quadrangle just west of United States Highway 63.[43]

Type 25. Lakes formed by mining and quarrying operations

Quarrying and open-pit mining operations involve the removal of large volumes of bedrock below the general level of the ground water table. The production of such bedrock basins will result in permanent lakes when the quarries and mining pits are abandoned and allowed to become filled by the seepage of ground water.

Examples of these lakes may be seen in the region around St. Cloud in Stearns and Benton counties, where several abandoned granite quarries are partially filled with water. Other potential lake basins are numerous in the iron mining districts of Crow Wing, Itasca, and St. Louis counties, where open-pit mining operations have produced several basins in bedrock. Many of these pits have already filled with water, whereas others are kept dry by pumping.

Category 5. Lake Basins, Potential or Real, Formed by Geologic Processes of Minor Importance in Minnesota

CLASS A. BASINS PRODUCED BY WIND PROCESSES

Type 26. Blowouts

The process of wind deflation produces closed basins that are usually shallow and quite small in areal extent. Although the writer knows of no blowouts in Minnesota that now contain any appreciable amount of water, some of them may have been lakes in the past because they now contain shallow deposits of peat.[44] The possibility does exist that some of them may become lakes and ponds in the future.

In his study of sand dunes in Minnesota, Cooper describes a few blowouts.[45] West of the town of Brainerd he described dry depressions as "holes excavated by the wind." An exceptionally large blowout was described by the same author in association with the dunes of Bunker Prairie in Anoka County. The blowout is located in the SE¼ of Sec. 35, T. 32 N., R. 24 W., just west of the Great Northern Railroad track.

CLASS B. BASINS PRODUCED BY THE ACTION OF GROUND WATER

Type 27. Sinkholes

Ground-water activity in carbonate rocks produces cavernous openings of varying sizes. The collapse of the roof of a cave which is near the surface may produce closed depressions known as *sinkholes*, and these eventually may become filled with water.

There are no known large lakes in Minnesota of sinkhole origin, but

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[43] U.S. Geological Survey topographic map.

[44] W. S. Cooper, *The History of the Upper Mississippi River in Late Wisconsin and Postglacial Time* (Minnesota Geological Survey Bulletin 26, 1935).

[45] *Ibid.*, p. 91.

many dry sinks are known in the southeastern part of the state. The sinks occur in dolomite and limestone of the Galena formation (Ordovician) which caps many of the bluffs in Fillmore and adjoining counties.[46] The writer has not investigated the area in which the sinkholes occur, but their presence is reported by George A. Thiel, Department of Geology, University of Minnesota, and other workers in southeastern Minnesota.

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[46] G. A. Thiel, *The Geology and Underground Waters of Southern Minnesota* (Minnesota Geological Survey Bulletin 31, 1944), p. 74.

IV. LAKE MODIFICATION

From the moment a lake is formed until the time when the last water has evaporated or drained from its bed, various geologic processes are actively engaged in modifying the original shape and configuration of the lake basin. The rate at which these processes accomplish their work varies with the dimensions of the lake, the climatic conditions, and the type of material forming the shores of the lake. The ultimate fate of all lakes is extinction, but under the prevailing climatic and geologic conditions, several of the lakes in Minnesota will outlive their contemporaries by many thousands of years. For instance, the bedrock lakes in northeastern Minnesota will have undergone only slight modification long after the lakes of south-central Minnesota have become extinct.

Lake extinction may be classified into two types: (1) *Permanent extinction* involves the destruction of the lake basin itself so that the basin no longer has closure and therefore cannot hold water. (2) *Temporary extinction* is characterized by a loss of water only, without the destruction of the basin. So long as the basin does not become filled or breached, it is still a potential lake, because the water content is determined largely by either the regional or the perched ground-water levels, which in turn are controlled by fluctuations in the climatic and geologic environment.

The changes which a lake may undergo before it reaches a stage of temporary or permanent extinction can be attributed to one or a combination of several processes of lake modification. The causes as well as the effects of such processes will be the consideration of this chapter, and examples of some of the changes will be cited. The following is an outline of these processes as they will be taken up:

A. Wave and current action on the shores
B. Ice action on the shores
    1. Ice push (ice shove)
    2. Ice jams
C. Loss of water in the basin
    1. Downcutting of outlet
    2. Evaporation and transpiration
    3. Lowering of the water table
D. Deposition of sediment in the basin
    1. Clastic sediment
    2. Chemical sediment
    3. Organic sediment

WAVES AND CURRENTS

Waves. Friction of the wind on the surface of a lake causes waves to develop. Their size is a function of three factors: (1) the velocity of the wind, (2) the length of time it continues to blow from a single direction, and (3) the length of the stretch of water over which it blows, called the *reach* or *fetch.* A fourth factor, depth of water, must be considered in lakes with a maximum depth of only a few feet. Shallow water has the general effect of decreasing the wave length (distance from crest to crest) and increasing the height (difference in elevation between crest and adjacent trough).

Waves perform erosion on the shore line of a lake because this is where the wave energy is dissipated. Steep shores situated at the end of a long fetch are especially susceptible to attack of the waves. Erosion by waves is dependent not only on the size of the waves but also on the steepness of the shore and the material against which the waves are impelled. Sandy shores are easily cut away, but shores of clayey material or bedrock are not so easily eroded.

The maximum depth of water at which a surface wave will still keep the water particles in motion is limited to about one half the distance from one wave crest to another.[1] This depth of water is known as the *wave base,* an important factor in the determination of the profile of the near-shore, underwater surface. Thus, waves approaching a shore at 5-foot intervals will "feel" bottom at about 2½ feet. Sand particles lying at a depth of water less than the wave base will be set in suspension and may be moved around by the motion of the wave. Since wave lengths vary from one storm to the next, it follows that the wave base is also subject to this variation, and therefore the depth at which waves affect the bottom during one storm may differ from the depth at which waves "feel" bottom in another storm. It is understandable, then, why the underwater profiles in a lake with sandy shores may undergo considerable change during the course of a single year.

Currents. Douglas W. Johnson defined many types of currents in connection with the modification of existing marine shore lines.[2] Fortunately, insofar as lake currents are concerned, the majority of the marine currents either do not exist or are so insignificant that they can be ignored in most studies dealing with processes of lake modification.

By far the most important current operating on the shore of a moderate-sized lake is the *wave current.* The wave current is produced by the combined effect of the *swash,* which is the water driven up the beach slope when a wave strikes the shore, and the *backwash,* or the water which moves down the shore slope after being carried landward by a wave. When a wave strikes the shore at an oblique angle, a net

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[1] J. M. Caldwell, "An Elementary Discussion of Tides, Currents, and Wave Action in Beach Erosion," *Beach Erosion Board Bulletin,* vol. 2, no. 4 (1948), p. 8.

[2] Douglas W. Johnson, *Shore Processes and Shoreline Development* (New York: John Wiley & Sons, 1919), p. 88.

longshore transport of material results. Johnson calls this phenomenon *beach drifting* and explains it thus: ". . . the swash of the waves advances obliquely up the slope, continuing the direction of advance of the wave; but the backwash, being under the control of gravity, tends to return directly down the steepest slope."[3] Figure 25 shows how the combined influence of the swash and backwash will roll particles along the beach in a series of parabolic curves.

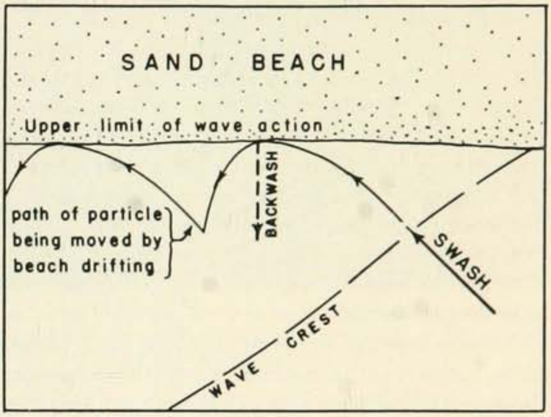

FIGURE 25. — A diagram showing the process of beach drifting, which involves the combined effect of swash and backwash to move sand particles along the beach.

Because waves and currents are so closely related, the separate effects of each cannot always be isolated. For this reason they are considered together.

The *wave-cut cliff* forms where the initial shore of a lake is subjected to the direct attack of the waves. The height of the cliff depends on the original topography of the shore area, and the steepness of the cliff is a function of the material in which the cliff is cut. An original shore line composed of a vertical bedrock escarpment which descends below lake level to a depth *greater* than the wave base will not be affected much, even by waves of storm size. The waves approaching the vertical shore do not "break" in the same manner as waves breaking against a sloping shore because of the absence of shallow water immediately offshore from the cliff front. The retrogression of the cliff because of wave action of this type is extremely slow.

A cliff cut in boulder clay (till) may have its base marked with a residual concentrate of cobbles and boulders, material that is too large to be moved by the strongest waves (Fig. 26). The base of the wave-cut escarpment may stand at a considerable distance from the mean water line because most of the work is done by the highest storm waves. Yearly fluctuations in lake level also influence the position of the cliff base.

The surface formed by wave planation between the mean lake level and the base of the cliff is called the *wave-cut* terrace. If it is cut in boul-

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[3] *Ibid.*, p. 94.

der clay (till) it can be distinguished from the adjacent lakeward depositional terrace by the presence of residual coarse concentrates left as the wave-cut cliff receded (Fig. 26). If the wave-cut terrace forms in outwash or other well-sorted, unconsolidated material, its lakeward margin may not be apparent because it merges imperceptibly into the subaqueous terrace which is parallel to it (Fig. 27).

Debris made available by the formation of a wave-cut cliff and a wave-cut terrace is distributed along the shore by the process of beach drifting. Some of the material is deposited in the form of an underwater terrace which may extend around the entire shore of a lake. The outer margin of the underwater terrace is marked by a rapid change in slope and is the so-called "drop-off" in popular terminology. The underwater terrace is referred to by geologists as the *wave-built* terrace, but since such terraces may be continuous around the entire lake shore and cannot always be ascribed to direct action by the waves, the term *subaqueous terrace* is preferred by the writer.[4] The width of the terrace may vary considerably depending on the size and amount of material available for its construction and on the competency of beach drift to transport the material.

Where an original lake shore is very irregular and marked by several bays, arms, and indentations, the subaqueous terrace is extended across the mouths of such irregularities and eventually isolates them from the main body of water. The tendency, then, is for the lake to become more regular in outline as the subaqueous terrace develops. This tendency is more pronounced in lakes that lie in sandy material than in those formed in clay or bedrock, but eventually even the latter will be changed in form by the development of the subaqueous terrace.

In Minnesota, lakes can be cited in which all stages of development of the subaqueous terrace are present. Small bays that are now in the process of being isolated as well as those cut off long ago and filled with sediment can be seen at many places.

On Pelican Lake, north of Brainerd in Crow Wing County, isolated bays are especially well shown. Figure 28 illustrates the typical way in which a lake in outwash is modified by growth of the subaqueous terrace. The small pond on the southeast shore of Pelican Lake was obviously part of the original lake basin, but is now completely cut off from the main body of water. The depression behind the bar is nearly filled with vegetation and contains little if any open water. On the opposite side of the lake, the isolation of a bay of similar size has not yet gone to completion, but the expansion of the underwater terrace across its mouth necessitates the dredging of a channel from the bay to the main body of water in order to facilitate passage by small fishing boats harbored in the bay. Note how the subaqueous terrace varies in width all

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[4] O. F. Evans, "Mass Transportation of Sediments on Subaqueous Terraces," *Journal of Geology*, 47:325–334 (1939).

FIGURE 26. — Residual boulders on a wave-cut terrace, northeast shore of Lake Bemidji, Beltrami County. The break in the slope at the right of the man marks the contact between the wave-cut terrace and a wave-cut cliff.

FIGURE 27. — A wave-cut terrace formed in outwash on Ottertail Lake in Otter Tail County. The lakeward margin of the terrace merges imperceptibly into the subaqueous terrace near the water's edge.

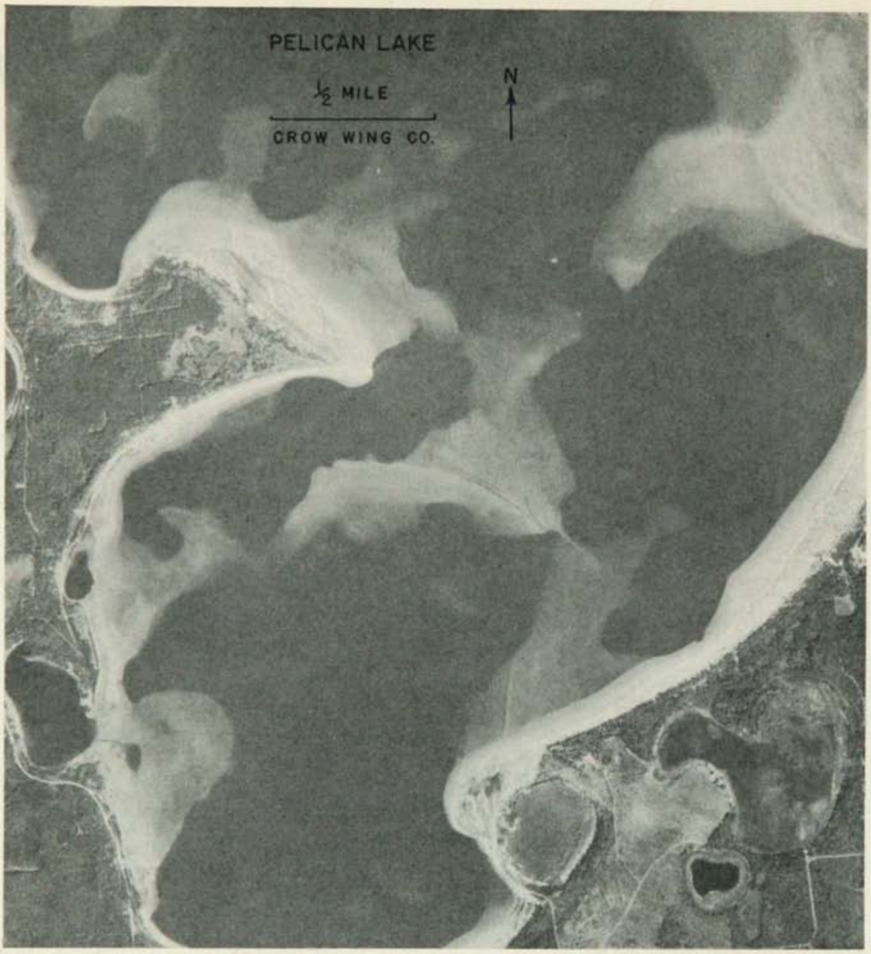

FIGURE 28. — Isolated bays formed by growth of the subaqueous terrace. (U.S. Department of Agriculture photograph, September 1939.)

around the shore. Without doubt the process of beach drift has been actively engaged in modifying the shore of Pelican Lake.

Buck Lake, a former bay of Cass Lake in Beltrami County, furnishes us with another fine example of a bay cut off from the main lake by the development of the subaqueous terrace (Fig. 29). The old shore line of Cass Lake is readily visible on the west side of Buck Lake, and the pond west of Buck Lake is also part of the original Cass Lake basin.

A detailed study of prevailing winds on Cass Lake might bring to light certain facts which bear on the problems of the formation of underwater features such as are seen in Cass Lake. Minor dunelike ridges and depressions on the subaqueous terraces and on other submerged shallow

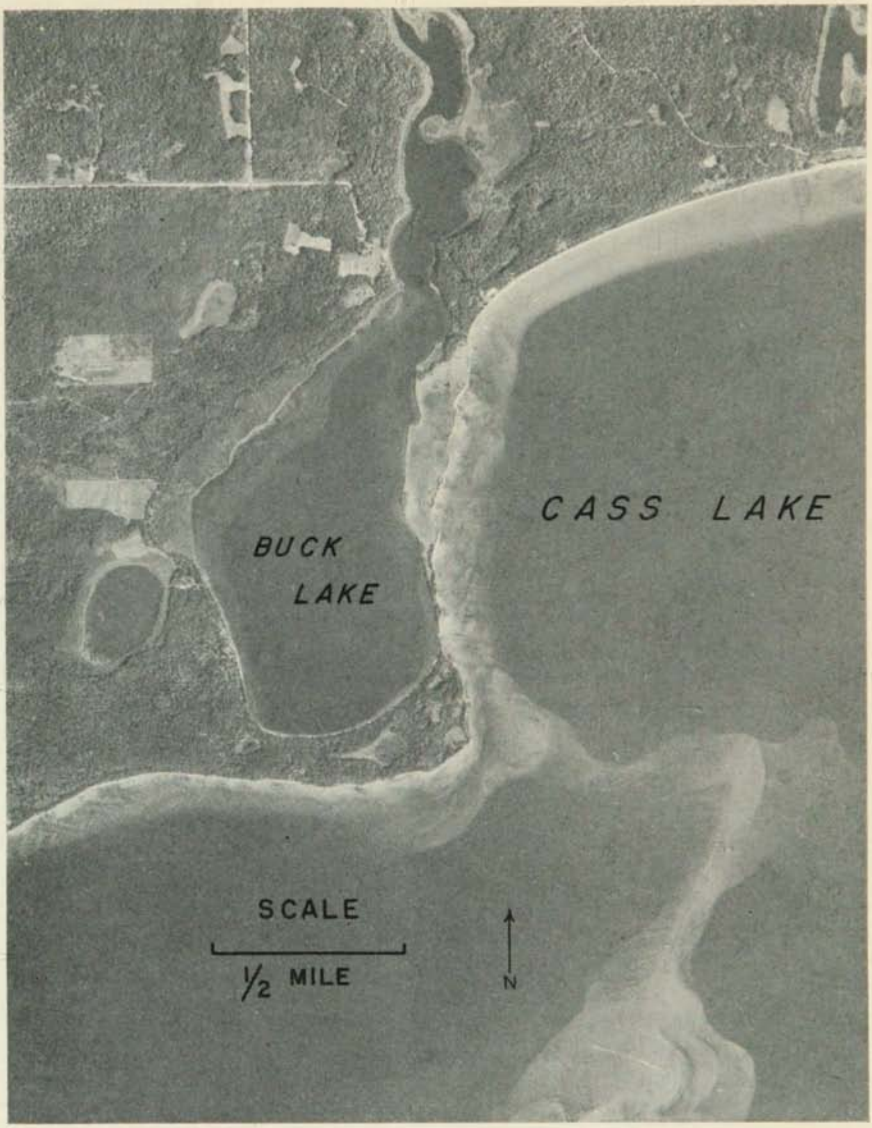

FIGURE 29. — Buck Lake, a former bay of Cass Lake in Beltrami County, was formed by the growth of a subaqueous terrace across its east side. (U.S. Department of Agriculture photograph, September 1940.)

areas surely must be related to the direction of prevailing winds (Fig. 29). The origin of such features would constitute a very enlightening line of research.

The process of beach drifting also explains the formation of cuspate bars, or "points" as they are sometimes called in the more common

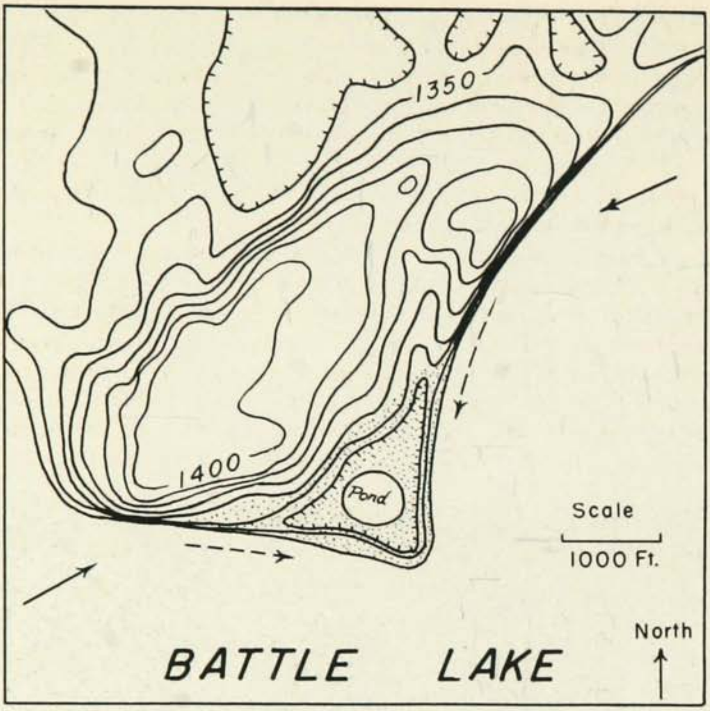

FIGURE 30. — A map showing the development of a cuspate bar on the north shore of Battle Lake in Otter Tail County. The solid arrows indicate the direction of the wave attack against the wave-cut cliffs. The dashed arrows show the direction of the beach drift. The contour interval is 10 feet. The stippling indicates the cuspate bar.

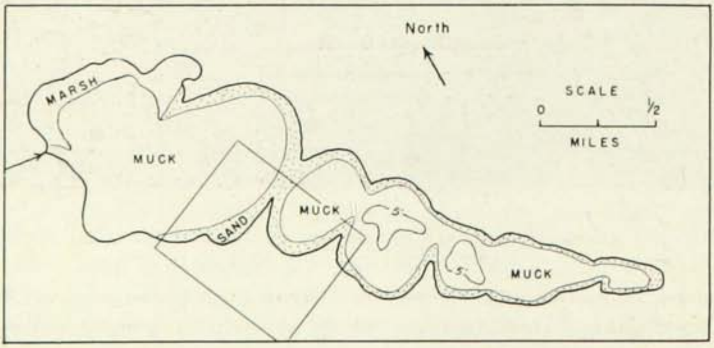

FIGURE 31. — "Counterpoints" developed on the southeastern part of Heron Lake in Jackson County. (After Minnesota Department of Conservation. The rectangle encloses the area shown in Figure 32.)

terminology. This feature is well illustrated on the north shore of Battle Lake in Otter Tail County (Fig. 30). The source of the material from which the bar was built are the two wave-cut cliffs, one facing southeast and the other facing south. Debris supplied by wave action against these two cliffs was transported by beach drifting from two directions, a process which climaxed in the formation of the cuspate bar. A characteristic type-22 lake is present between the landward side of the bars and the old shore line.

Cuspate bars may be constructed directly opposite each other on a lake, and continued growth will result in a bar which extends completely across the lake, from one cuspate bar to the other. The original lake thus becomes segmented into two basins. Segmentation of this type is now in progress on Heron Lake in Jackson County. The growth of points and counterpoints on opposing shores will ultimately reduce the lake to a series of oval ponds (Fig. 31). An aerial photograph of two such points is shown in Figure 32. Similar features in lagoons along the Massachusetts coast have been described, and their origin and growth ascribed to beach drifting.[5] It was suggested in this same paper that the reason the points formed opposite one another was an underwater transport of

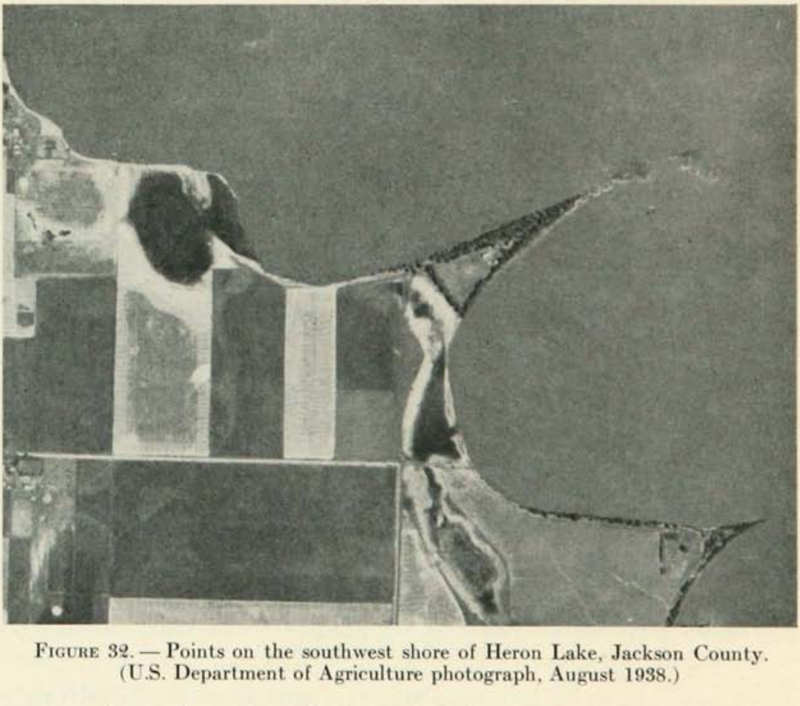

FIGURE 32. — Points on the southwest shore of Heron Lake, Jackson County. (U.S. Department of Agriculture photograph, August 1938.)

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[5] E. J. Raisz, "Rounded Lakes and Lagoons of the Coastal Plains of Massachusetts," *Journal of Geology*, 42:839–848 (1934).

sand from the tip of one point to the opposite shore where the growth of the "counter point" would be initiated. On Heron Lake the underwater extension of the largest point reaches across the lake and merges with the counter point, but whether the growth of the point on either shore was initiated because of the underwater transport of sediment from the opposite shore cannot be stated with any degree of certainty.

On Marion Lake in Otter Tail County (Fig. 23) segmentation is nearly complete. The northern half of the point on the south shore is constructional and has an underwater extension all the way across the lake to the north shore. This extension is exposed in times of low water, but during high water periods the extension is submerged, although it still forms a definite barrier that divides the lake into two distinct parts. At the junction of the extension with the north shore, a counterpoint is now being formed as a direct consequence of the point on the south shore. The submerged part of the initial point is marked by a line of white caps in Figure 33.

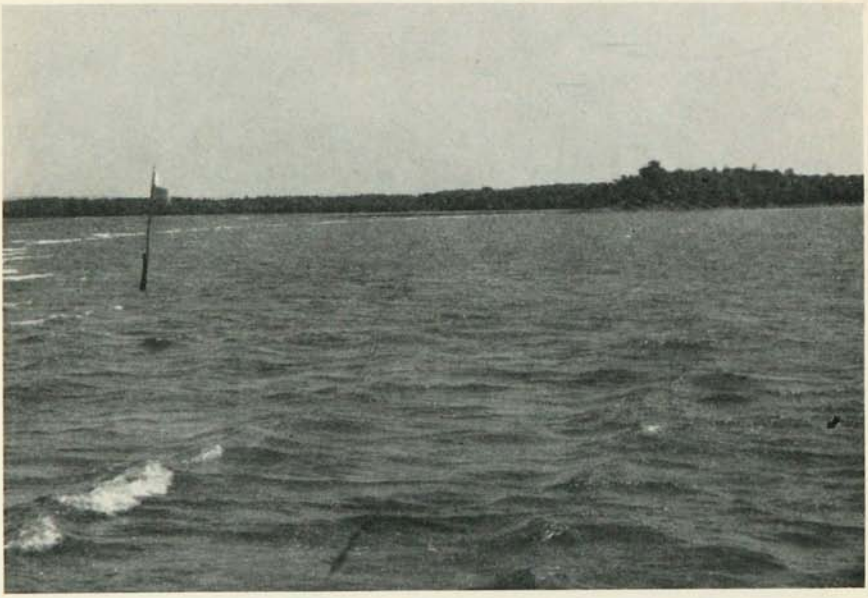

FIGURE 33. — Looking south across Marion Lake in Otter Tail County. A submerged bar extends entirely across the lake and is marked by a line of white caps. The flag indicates the small-boat channel.

Much remains to be learned about the process of beach drifting and the subaqueous terraces in lakes, and until the time when experimental or observational evidence provides the answers to many basic questions related to sediment transport along beaches, the origin of many of the features will remain in doubt. One approach to the problem might be the determination of the relation of the subaqueous terrace profile to the size of the storm waves and periods of calm. Other relations might be found between the profile of the subaqueous terrace and the depth of water at its outer edge, or between the profile and size gradation of the particles of which the terrace is built.

Conclusions concerning the effects of waves and currents in lakes. (1) Waves produce wave-cut cliffs and wave-cut terraces and make available an appreciable amount of material which can be transported by beach drift. (2) Beach drift is the process whereby sediment is transported along the shore, and it may be responsible for the formation of: (a) bars across the mouths of bays or indentations (baymouth bars), (b) cuspate bars or points, (c) other accretionary features along lake shores and in shallow water areas in general. (3) The subaqueous terrace is an important factor in the modification of lake basins, but more basic studies are needed to understand its formation and the development of features associated with it.

ICE ACTION

Ice push. In regions where lakes freeze over during the winter months, the relation of the ice layer to the shore must be considered. Buckley established the principles of the action of lake ice on shores, and a summary of his general conclusions is pertinent here.[6]

After the initial ice cover forms on a lake, the thickness increases slowly and may reach several feet in extremely cold winters. Water expands when it freezes, but, once frozen, the ice reacts to temperature changes like any other solid; that is, it contracts when its temperature is lowered and expands when the temperature is raised. Lake ice attaches itself to the shore and may even freeze to the bottom of a very shallow area. A rapid fall in air temperature causes the ice on the lake to contract. Since it cannot pull away from the shore area to which it is firmly frozen, it develops tension cracks in the main ice cover. Water rises into these cracks from below and freezes, thus increasing the total mass of the ice cover. A subsequent rise in air temperature will cause the ice to expand again, and the area of the ice will be greater than it was before contraction. This increase in area of the ice cover will result in compressive forces along the shore, or, in other words, the ice exerts a "push" on the shore. If the shore material is unconsolidated and the slope of the shore is not exceptionally steep, the ice will push the material into an *ice rampart,* a ridge of debris lying more or less parallel to the shore line. The size of an ice rampart depends on the number of times the temperature has fluctuated sufficiently to produce a new push while the lake remained at the same level.

Ice ramparts are not formed in this manner on all lakes that freeze. If the shore material is firmly consolidated or if the shore is a steep cliff, then the resistance of the shore is greater than the resistance of the ice

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[6] E. R. Buckley, "Ice Ramparts," *Wisconsin Academy of Science Transactions,* 13:141–162 (1900).

itself, and the ice will buckle offshore and will form "pressure ridges" which may extend across the entire lake. Furthermore, the ice on a lake must be strong enough to transmit the stress induced in it by expansion.[7] Neither porous, or rotten, ice, formed as a result of spring thawing, nor thin ice of the early winter is competent to transmit a thrust or "push" on the shore, even if a rapid rise of temperature takes place. A thick layer of snow on the ice also reduces the magnitude of the ice push because it acts as an insulator and thus prevents the temperature change of the atmosphere from being transferred to the ice.

The size of the lake also seems to be a limiting factor in the development of an ice push that will produce ice ramparts. The lake area cannot be too large or too small if ice ramparts are to develop by ice push. The thrust against the shore is carried by the ice, which acts as a girder or beam in transmitting the stress. The ice layer on a large lake will tend to buckle upon expansion, regardless of the topography of the shore, because the rigidity of the ice as a girder decreases with an increase in the diameter of the lake (Fig. 34).

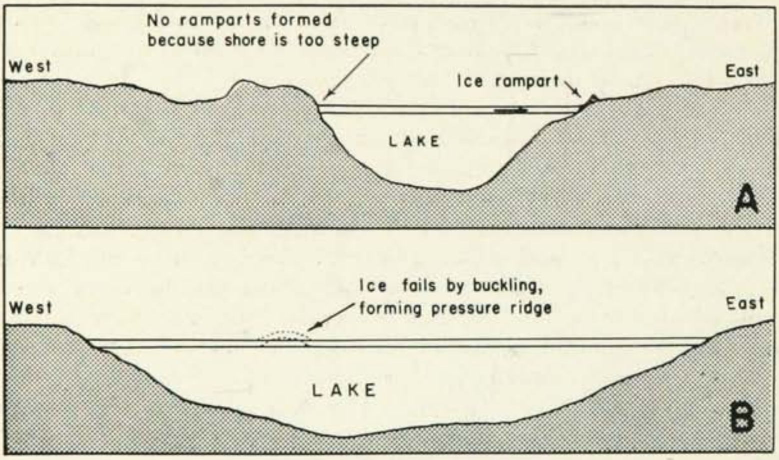

FIGURE 34. — (A) A moderate-sized lake (in unconsolidated material) in which the ice cover is rigid enough to transmit the stress (heavy arrow) induced by expansion after a cold spell. No ramparts are formed on the west shore because the shore is too steep. The less steep east shore is ideal for ice push.

(B) A large lake in which no ice ramparts form by ice push because the ice layer cannot transmit the stress induced by expansion and thus fails by buckling.

No quantitative data are known that will allow one to make an accurate statement on the maximum and minimum size of a lake in relation to the effectiveness of ice push. Strictly from a theoretical point of view, there ought to be a lower and an upper limit of lake size (diameter) — limits below which ice push would not operate because of slight expan-

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[7] W. H. Hobbs, "Requisite Conditions for the Formation of Ice Ramparts," *Journal of Geology*, 19:158 (1919).

sion and above which it would not operate because of the tendency of a large ice layer to buckle when expanding. Whether or not such limits do exist is a matter to be decided by field observation, and the state of Minnesota would provide an excellent proving ground for the theory proposed above.

Ice jams. Ice ramparts may be formed in another way. Examples of a second manner of ice-rampart formation have been described for Michigan lakes.[8] Usually the ice cover on a lake thaws more rapidly around the shore than elsewhere in the lake because of the more rapid transfer of heat from land to ice. Eventually a lane of open water forms around the shore so that the entire layer of ice is completely free from any shore connection. If a strong wind develops while the ice is in this condition, the whole mass of ice will be moved toward the lee shore with a tremendous force. This is called an *ice jam*. The force exerted against some shores by ice jamming is sufficiently strong to cause the movement of shore material, and thereby produce ice ramparts. Even when the ice layer is broken into slabs that become "shingled" along the lee shore, the force exerted is sufficient to form ice ramparts. Ramparts produced in this manner do not differ appreciably from those formed by ice push, but on a very large lake where ice push cannot operate, ice ramparts are likely to have been formed by ice jamming.

The effects of ice action. Ice ramparts or ice-push terraces may consist of a heterogeneous mixture of clastic material with a wide range in particle size, or they may be built of sand and gravel with a small range in the size of the constituent particles, in which case they are subject to rapid modification by storm waves during the spring, summer, and fall seasons and may not persist from one year to the next. Ramparts containing boulders become more or less permanent shore features and remain as conspicuous forms long after the lake has become extinct. Occasionally ice ramparts contain a large amount of organic material intermixed with clastic particles.

Ice ramparts may develop at the mouth of a shallow bay or the indentation of a lake and isolate the bay from the main body of water. An example of a lake where such a condition exists can be seen at the east end of Rose Lake in Otter Tail County. There a small pond called Pug Lake was originally a bay of Rose Lake, but an ice rampart was constructed across the mouth of the bay and now contains trees and other vegetation on its surface (Fig. 35).

Griggs cited examples of lakes in Becker and Otter Tail counties that had been divided into segments by the growth of ice ramparts across shallow parts of the lakes.[9] It is probable that the shallows were primary parts of the lakes, but the ice may have been the final agent in the raising of the ridges above the water level.

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[8] I. D. Scott, *Inland Lakes of Michigan* (Michigan Geological and Biological Survey, Publication 30, Geological Series 25, 1921), p. 59.

[9] R. F. Griggs, "Divided Lakes in Western Minnesota," *American Journal of Science*, 4th Series, 27:383–392 (1909).

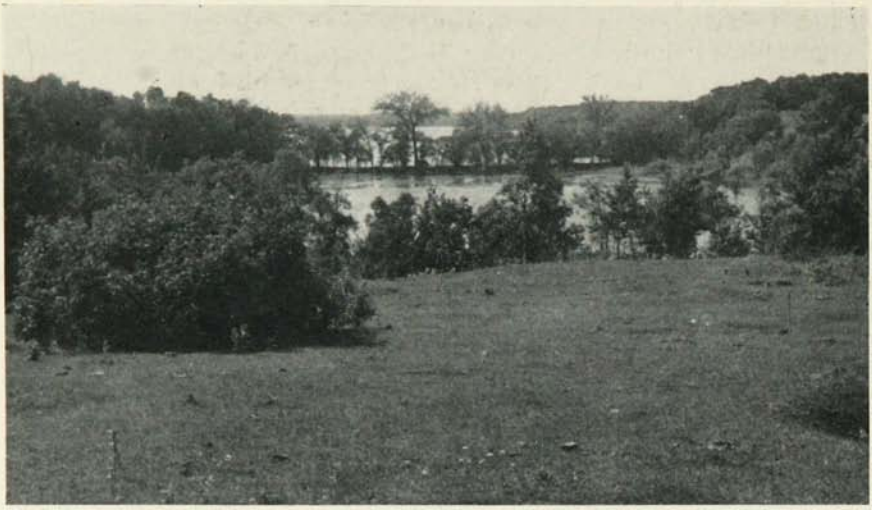

FIGURE 35. — Pug Lake (in the foreground) was originally a bay of Rose Lake, Otter Tail County, but the former is now isolated from the latter owing to the development of an ice rampart which is now stabilized by vegetation.

Ancient ice ramparts are recognized by their steep-sided, ridgelike form and by their position with respect to the shore line of a former lake level. Ramparts formed from sand are more likely to be destroyed by wave action, but one was observed on the east shore of Agency Bay on Leech Lake (Fig. 36). A whole series of stabilized ramparts composed largely of sand were observed on the north shore of Mille Lacs Lake between Wealthwood and Malmo in Aitkin County. The sand ridges occupy successively higher levels above the present lake, indicating that they are related to higher lake levels of the past. The crests of the ridges are undulating rather than level, proving that the ridges were formed by ice action rather than by waves.

Besides producing ice ramparts, lake ice has been known to be very destructive to lake-shore property built close to the shore line. Buildings lying in the path of a shoreward-moving ice jam are liable to damage and even complete destruction. Usually one should examine the shore area for evidence of ice action before erecting any small buildings along the shore. Occasionally an old stabilized rampart may parallel the lake shore at a level several feet above the lake surface, and there is no better place to build a cabin or boat house because the old ice rampart is a feature related to an earlier chapter in the lake's history. For this reason, one need have no fear for the structure located on an ancient rampart insofar as ice push from the modern lake is concerned. Once in a while an ice jam may be forced up on these old ramparts to a height of 20 or 30 feet, but this happens only in rare instances, and buildings atop

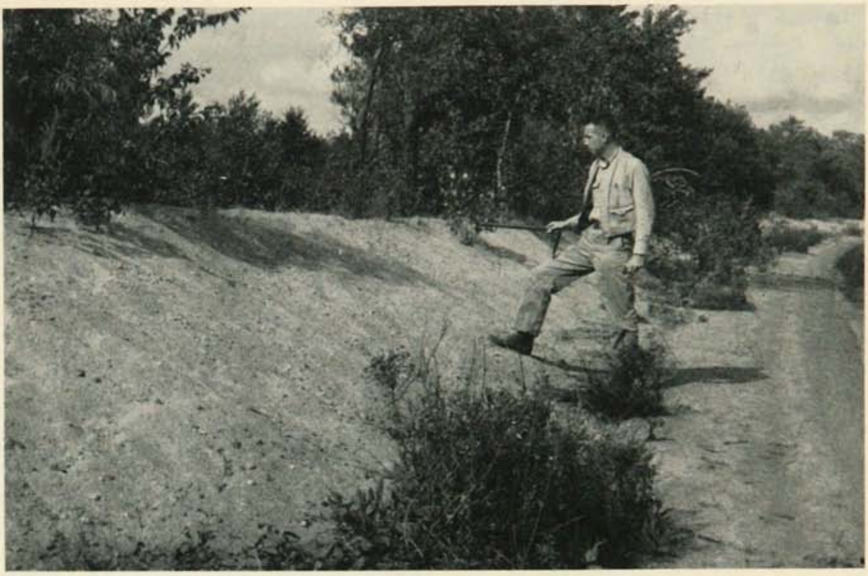

FIGURE 36. — Ice ramparts formed from sand and gravel on the east shore of Agency Bay, Leech Lake in Cass County.

ancient ramparts are comparatively safe from both ice push and ice jamming.

LOSS OF WATER

If the loss of water in a lake exceeds the gain, the most obvious effect is a reduction in lake area and decrease in depth. Every lake loses some of its water each year in one way or the other, but usually the loss is offset by new water added from streams and springs and from direct precipitation into the lake. However, lake levels may fluctuate from year to year, and even from season to season, unless they are closely controlled by dams at the outlets. Many examples of lakes which have been altered in depth and outline because of loss of water in various ways could be cited. Several are described in the paragraphs that follow.

Downcutting of lake outlet. A lake may drain by downward erosion of its outlet, permanent extinction resulting. This process may be relatively slow in operation if the outlet must cut through bedrock or cohesive clay. Clastic particles carried by a stream are the chief tools used in abrading the stream channel, but most outlet streams are relatively free of these tools because water flowing through the outlet originates in the lake basin where much, if not all, of the sediment drops to the bottom. Therefore, the process of downward cutting by outlet waters is usually not so effective as normal stream erosion.

An example of a permanent lowering of a lake level by downward erosion of the outlet is Wall Lake in Otter Tail County. This lake has been lowered by 20 feet, owing to the downward erosion at the outlet (Fig. 37). The old shore line is distinctly visible as is the old lake bed which was formerly under water.

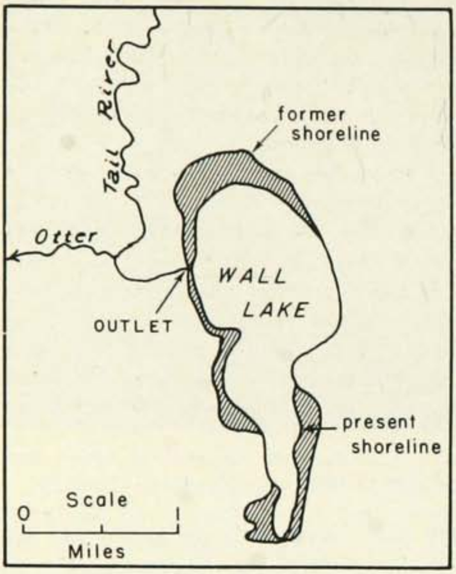

FIGURE 37. — A sketch map of Wall Lake in Otter Tail County showing the relation of the former shore line to the modern one. The shaded area represents the net loss in lake area because of the downcutting of the outlet on the west side.

In rare instances a lake may suffer a radical loss in water by the rapid cutting of its outlet in a very short period of time. A single example of such an event took place in 1931 near Ely, Minnesota, in St. Louis County.[10] Bass Lake and Low Lake occupy a single elongated rock basin, but until 1931 they were separated by a ridge of glacial gravel which served as a dam between them. Bass Lake drained into Low Lake over an outlet at the east end of the former; the two lake levels differed in elevation by 60 feet. A sluiceway was constructed between the two lakes for lumbering operations, and subsequent leakage developed seepage channels in the gravel dam, resulting in the failure of the natural partition between the two lakes. In less than ten hours Bass Lake was lowered 55 feet, and the torrential outflow of water from Bass to Low Lake cut a gorge 250 feet wide. Bass Lake was reduced in area by 35 to 40 per cent because of this unusual event. Although such rapid lowering of a lake level is due to a set of unique conditions and not likely to happen very often, the incident is striking in comparison with the normally slow process of water loss by downcutting at the outlet.

The process of downcutting by an outlet stream may be further impeded if a chain of lakes is connected by a single stream, for the base

[10] G. A. Thiel, "Giant Current Ripples in Coarse Gravel," *Journal of Geology*, 40:454 (1932).

level for the outlet of a given lake is the surface of the next lower lake in the chain. Therefore, downcutting at the outlets for each lake in the chain progresses from the lowest to the highest lakes.

Evaporation and transpiration. Loss of water by excessive evaporation or transpiration usually produces only temporary extinction. Transpiration is the process by which water vapor escapes from a living plant into the atmosphere. It is a process of more importance in swamps than in open bodies of water. The extent to which these processes exceed the addition of new lake water will determine the amount of lowering of the lake level, provided other factors are constant.

Lowering of the water table. The water level in a lake may be part of the general water table, or it may be related to a perched water table. In either case a temporary or permanent lowering of the water table will be reflected in the level of a lake with which it is connected. Temporary lowering occurs during a succession of dry years when precipitation is less than the amount of water returned to the atmosphere by evaporation and transpiration. A general lowering of the water table can also be caused by downward erosion of streams. Lakes marginal to such downward-eroding streams, but not necessarily connected to them by surface channels, will suffer a loss of water because of the contemporaneous lowering of the water table adjacent to the streams.

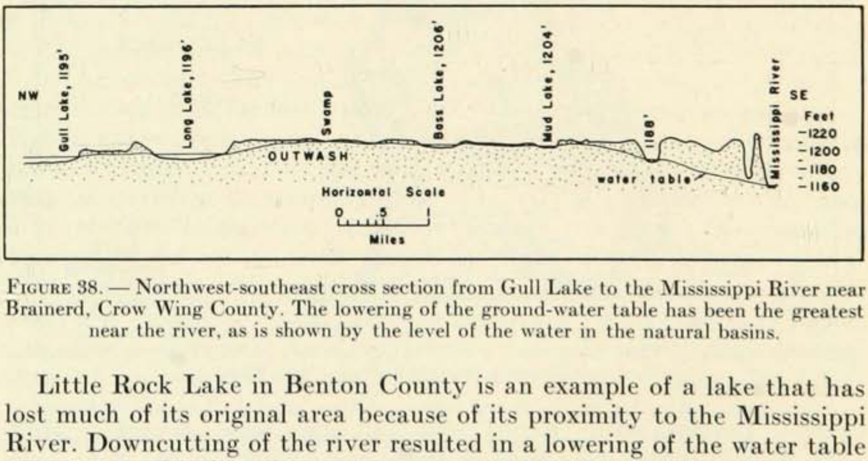

FIGURE 38. — Northwest-southeast cross section from Gull Lake to the Mississippi River near Brainerd, Crow Wing County. The lowering of the ground-water table has been the greatest near the river, as is shown by the level of the water in the natural basins.

Little Rock Lake in Benton County is an example of a lake that has lost much of its original area because of its proximity to the Mississippi River. Downcutting of the river resulted in a lowering of the water table adjacent to the river, hence, a lowering of lake levels within that area. Farther north along the Mississippi River, near Brainerd in Crow Wing County, a similar lowering of the water table accounts for the presence of dry kettle holes near the river.[11] A cross section at right angles to the river is shown in Figure 38, and it demonstrates how the gradient of the ground-water table steepens as the river is approached. This is a direct consequence of the postglacial entrenching of the Mississippi

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[11] W. S. Cooper, *The History of the Upper Mississippi River in Late Wisconsin and Postglacial Time* (Minnesota Geological Survey Bulletin 26, 1935), p. 102.

River. Thus the kettles nearest the river are dry, while those farther back have lost less water.

Water loss in a lake is not necessarily explained simply as the result of a single process, such as downcutting of the outlet or a lowering of the water table. Not infrequently a combination of these processes is involved, and the relative importance of one over the other is not easily determined. Mille Lacs Lake, for instance, has lost much of its original area, but to what extent the downcutting of its outlet or the general lowering of the water table has been responsible for the decrease in the area of the lake is unknown. Figure 39 shows the former extent of the lake when its level was 10 to 15 feet higher. At that time Round, Borden, Almond, Smith, Kenny, and Holt lakes were all part of Mille Lacs. Several islands composed of knobs and hillocks in the Mille Lacs moraine persisted above the level of the lake, and the western shore line was very irregular, a situation much in contrast to the modern west shore line.

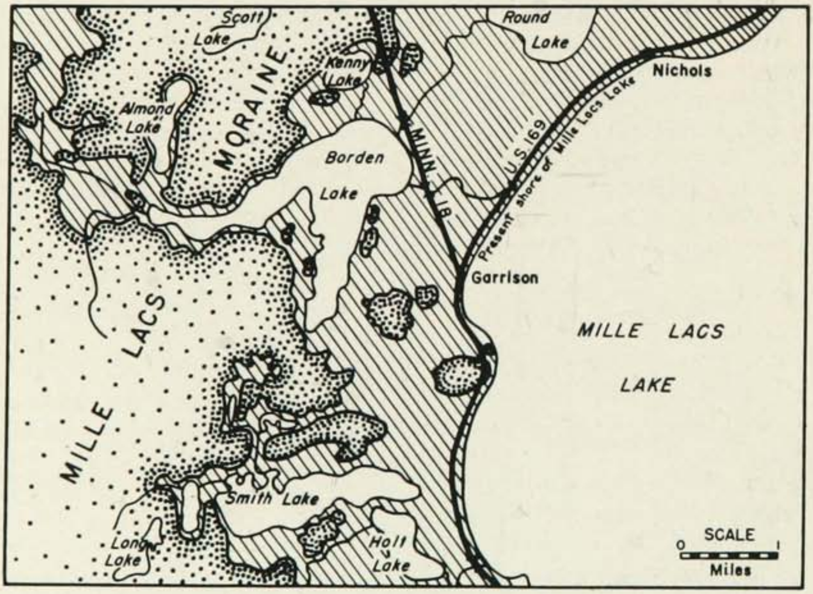

FIGURE 39. — A map showing the former extent of Mille Lacs Lake when its level was 15–20 feet higher than the present level. The shaded area indicates dry land today that was formerly covered by early Mille Lacs.

Lake level fluctuations over short periods of time, as from five to ten years, leave their marks on the lake shores. Recent low levels may be recognized by the presence of submerged vegetation on the former subaqueous terrace. Trees and dead brush along the shallow water areas of a lake are evidence of a recent rise in the lake. Kiester Lake in Martin

County illustrates this point. In 1938 that lake was completely dry, but in 1949 Kiester Lake contained over 5 feet of water. Drought in the early 1930's caused many hundreds of lakes in Minnesota to dry up, but they have since been rejuvenated by the normal precipitation of the succeeding years.

In a study of Prior Lake in Scott County, S. A. Frellson, state hydrologist, showed a definite relation between low water levels in the lake and a decline in precipitation during the drought period of 1931 to 1935 plus a marked increase in summer temperatures.[12] Lake Minnetonka in Hennepin County also declined in water level during the same period.

Citizens who own lake-shore property are much concerned about the maintenance of proper lake levels, and understandably so because low lake levels reduce the value of lake-shore property, owing to the unsightly encroachment of swamp vegetation in what once was a clear bathing beach or fishing bay. Several attempts have been made in various instances to maintain lake levels by dams at outlets or by artificial recharge from wells. A movement was even under way in the 1930's to restore Lake Minnetonka by diversion of the Crow River into the lake, a costly project that was never carried out. The lake was restored to some extent by a natural increase in rainfall, but is still controlled somewhat by pumping.

Prospective resort owners and other people anticipating ownership of property with lake frontage would be wise to give careful consideration to the question of lake levels, either high or low, and their relation to the future value and use of the lake shore. In this respect the following quotation from Frellson's report on Prior Lake is extremely appropos: "Lakes *without outlets* are subject to a greater variation in levels than those with outlets, since during times of heavy inflow the incoming water must be stored in its entirety, while otherwise part would be disposed of by outflow. Lakes *with outlets,* which rise quickly, have a greater opportunity for outflow and hence less variation in level, while lakes with rapid inflow, without outlets, must rise suddenly and to a greater height than a lake of similar size and character with an outlet."[13] Lakes with dams at the outlet would react in a similar manner to those having no outlet, as long as there was no flow of water over the dam.

Mention should also be made of the tendency for shallow bays to be the first parts of a lake affected by a loss in water. Whereas such bays might have shores well suited to the development of lake shore property, the cottage or resort builder or buyer should be aware that these bays are subject to rapid encroachment by vegetation when the level of the main lake falls in response to a few years of drought. Hundreds of property owners with lake frontage on one of the several bays of Lake Minnetonka experienced a great decrease in property value during low

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[12] S. A. Frellson, *Report on Restoration of Prior Lake* (Department of Conservation, Division of Drainage and Waters, State of Minnesota, 1940).

[13] *Ibid.*, p. 16.

levels in the 1930's when their quiet bays were reduced to mosquito-infested swamps.

DEPOSITION OF SEDIMENT

The accumulation of sediment of all types, clastic, chemical, and organic, tends to reduce the volume of the lake basin. A detailed consideration of lake sedimentation is beyond the scope of this study, but a brief summary of the different types of sediment and the varieties of some of the minor sediments is in order.

Clastic sediment. Clastic sediments are derived from erosion of the lake shore by waves and also from streams carrying sediment into the lake basin. A small amount of clastic material may become incorporated in the bottom sediments of a lake from atmospheric dust, but this is probably a minor source in most Minnesota lakes.

Clastic sediments range in size from colloids to boulders, and all sizes may be found in a single lake. The coarser fraction of the total clastic deposit in a lake is generally restricted to that part of the basin covered by the beach and subaqueous terrace, although the sand bars that exist in many lakes are not necessarily confined to the near-shore areas. For example, Pelican Lake in Crow Wing County (Fig. 28) and Cass Lake in Cass and Beltrami counties (Fig. 29) show a wide distribution of sandy, submerged areas that are not directly connected to the shore areas.

The finer silt and clay fraction of the total lake sediment settles out only when the motion of the water does not keep it in suspension, a condition which is more likely to prevail in the deeper parts of the lake basin. An ideal distribution of sediments in a single lake would show the sand on the subaqueous terrace in the shallow near-shore areas, and a gradation to silt, clay, and colloidal organic matter toward the deeper water. Such an ideal distribution is very nearly reached in the sedimentation pattern of Upper Red Lake in northern Beltrami County (Fig. 40).

The distribution of sediments in Upper Red Lake is probably the exception rather than the rule because most of the lakes in Minnesota have a bottom configuration that is less nearly symmetrical than the Red lakes. Islands and irregular outlines of the lakes greatly modify the pattern of sediment distribution. For example, Lake Mille Lacs shows a considerable variation in the grain size of sediment at the same depth of water (Fig. 41). This variation may be ascribed partly to the fact that boulder areas are part of the original lake bottom, and partly to the fact that the islands disrupt the control of sedimentation by the depth of water. In spite of local variation, however, it is significant that the clay and organic material (muck) are concentrated in the deep central part of the lake.

In bedrock lakes, clastic sediment is confined to the mouths of inlets where some sediment is available for local distribution by beach drifting. A subaqueous terrace may then grow from the point of the influx

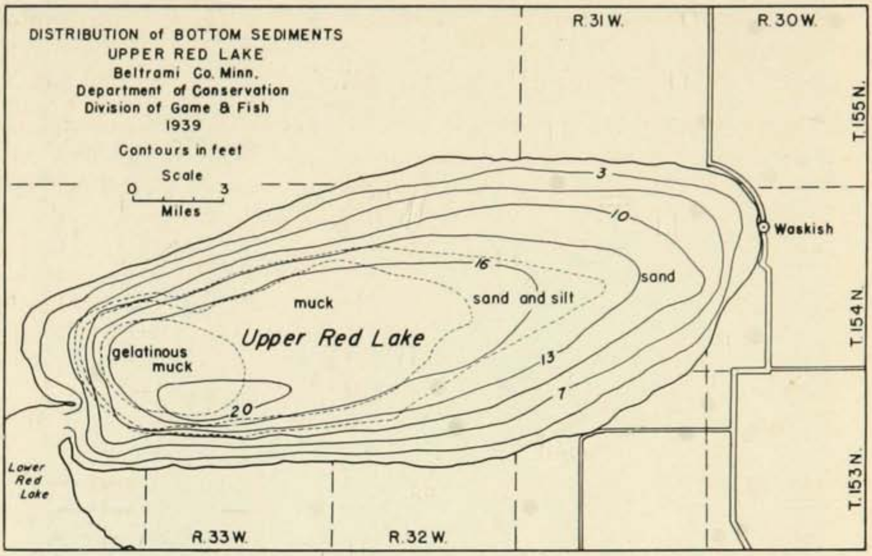

FIGURE 40. — A map of Upper Red Lake, Beltrami County. (After Minnesota Department of Conservation.)

of new sediment around the shore on either side of the inlet. An example of this process can be observed in Gunflint Lake on the Canadian Border in Cook County. Streams enter the lake at the east and west ends, carrying sand that is distributed by wave action along the shore. Sandy beaches and subaqueous terraces have resulted in both cases (Fig. 42). If the supply of sediment is too great for distribution by beach drifting, a delta is formed at the mouth of the stream.

Chemical sediment. One of the chief chemical deposits in lakes is marl, a soft, earthy material composed largely of calcium carbonate. The deposition of calcium carbonate depends on the geological setting of the lake. Moyle divided the lakes of Minnesota into four groups, each characterized by a certain carbonate hardness.[14] Calcium carbonate is more likely to be precipitated in the hard-water lakes than in the soft-water lakes. Moyle's classification is as follows:

Group 1. Lakes in Pre-Cambrian rocks of Cook, Lake, and St. Louis counties
Group 2. Lakes in morainic topography of central, northern, and western Minnesota
Group 3. Shallow lakes of gently rolling moraines south and west of the Minnesota River
Group 4. Lakes lying in the basin of Glacial Lake Agassiz

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[14] J. B. Moyle and N. Hotchkiss, *The Aquatic and Marsh Vegetation of Minnesota and its Value to Waterfowl* (Minnesota Department of Conservation Technical Bulletin 3, 1945), p. 7.

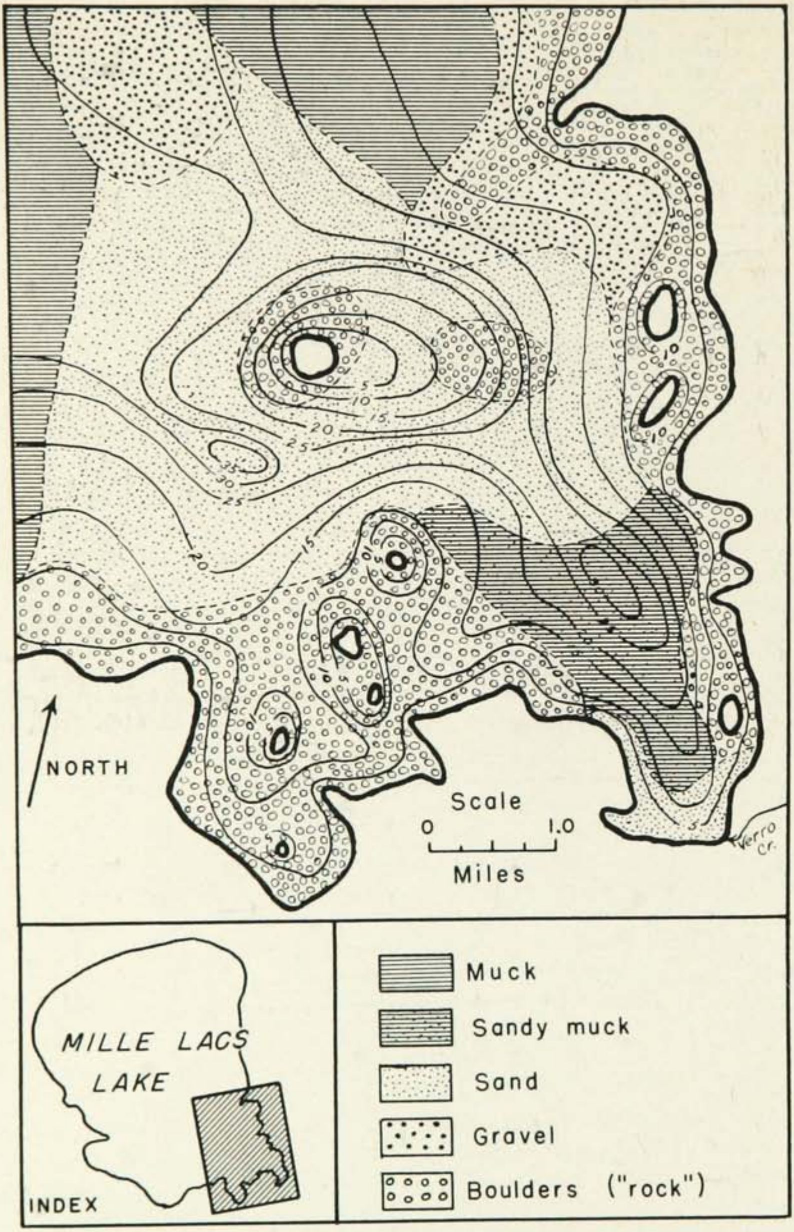

FIGURE 41. — A map of part of Mille Lacs Lake showing the distribution of bottom sediments. The shore is shown in heavy black line. The lake-bottom contour interval is 5 feet. (After Minnesota Department of Conservation.)

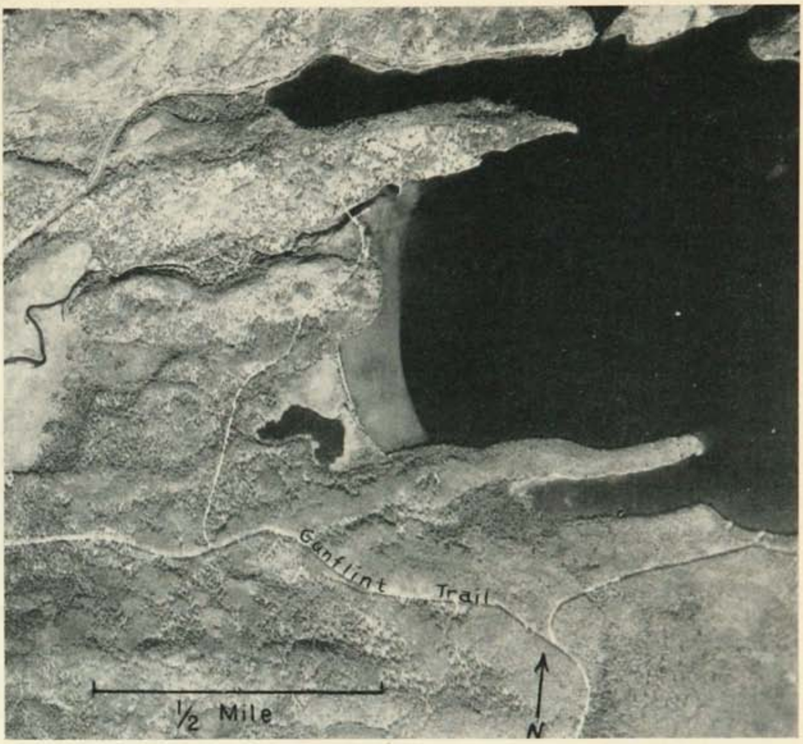

FIGURE 42. — A subaqueous terrace developed on the west end of Gunflint Lake, Cook County. Sand was supplied by the inflowing stream from the west. (U.S. Forest Service photograph.)

Group 1 is characterized by a carbonate content of less than 40 ppm[15] and a pH value from 6.8 to 7.4.[16] Lakes in group 2 have a carbonate content of 40 to 200 ppm and a pH value of 8.0 to 8.8. Lakes in groups 3 and 4 have a carbonate concentration as high as 225 ppm and a pH as high as 9.2.

From this information it follows that the precipitation of calcium carbonate is not a serious matter in lakes of group 1, but in lakes belonging to the other groups, the deposition of calcium carbonate is to be expected.

Thiel's study of the marls of Minnesota showed the greatest concentration to be in lakes within the Cary drift.[17] The Mankato drift is much more calcareous than the Cary, but Thiel concluded that the Cary drift

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[15] The letters *ppm* stand for *parts per million*.

[16] The term *pH* refers to the acidity or alkalinity of the water. High concentrations of calcium carbonate ($CaCO_3$) contribute to the water's alkalinity or "hardness," and such water will have a pH above 7. A pH value above 7, therefore, is an index of the hardness of the water.

[17] G. A. Thiel and C. A. Stauffer, *The Limestones and Marls of Minnesota* (Minnesota Geological Survey Bulletin 23, pt. 2, 1933).

was more permeable and thus allowed a greater percolation of ground water to carry more calcium carbonate to the lakes. The distribution of Cary drift falls within the limits of Moyle's group 2.

Minor chemical precipitates in lakes do not contribute much to the total volume of sediment on the lake bottom, but some deposits of lesser importance insofar as quantity of sediment is concerned are interesting from the standpoint of occurrence and origin.

An excellent opportunity to examine some of the minor chemical constituents of lake sediments presented itself during the summer of 1949 in Crow Wing County. There Rabbit Lake was partially drained by a mining company in order to reach a high grade iron ore body that lay beneath the lake. On the exposed floor of Rabbit Lake there were the usual clay, muck, and sand accumulations. On some "high points" in the lake bed — that is, places covered by water only a few feet deep when the lake level was normal — a mantle of pebbles, cobbles, and boulders was observed (Fig. 43). These stones of various sizes and different lithologic types were covered with a "wormy" encrustation of a gray-black material (Fig. 44). A mineralogical determination of this material showed that it was composed of a mixture of manganese oxide and calcium carbonate. The origin of the calcium carbonate was probably the drift which contained the lake basin, but the manganese was more likely derived from water percolating through the underlying bedrock, which is rich in manganese-bearing iron formation. Or perhaps the drift contained material locally derived from the same bedrock, and water percolating through the drift dissolved the manganese.

The precipitation of the manganese may have been brought about by algae in the lake, but the peculiar form, the "wormy" pattern, is still unexplained. The occurrence of manganese in association with fresh-water lake deposits is not an uncommon feature, and the fact that it can be precipitated by organic agencies was demonstrated by Thiel,[18] but the mode of occurrence of the manganese encrustations in Rabbit Lake is apparently an unusual one.

Organic sediment. The remains of both plants and animals may become incorporated in lake sediments. Planktonic plants and animals accumulate on the lake bottom in the form of a black organic mixture known as *sludge.*[19] The sludge may or may not have calcium carbonate mixed with it and is generally inhabited by a countless number of bacteria. A mixture of sludge and mud is common to shallow lakes and swamps, and is commonly called *muck.* This black ooze has a composition that is variable between wide limits. Not infrequently branches, leaves, and entire logs become incorporated in this muck and add considerably to its volume.

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[18] G. A. Thiel, "Manganese Precipitated by Micro-organisms," *Economic Geology*, 20:301–310 (1925).

[19] W. H. Twenhofel, "Sediments of Fresh-Water Lakes," *American Association of Petroleum Geologists Bulletin*, 25:826–849 (1941).

FIGURE 43. — Cobbles and boulders on the former bottom of Rabbit Lake, Crow Wing County.

FIGURE 44. — Close-up view of "wormy" encrustations, composed of manganese carbonate and manganese oxide, in Rabbit Lake, Crow Wing County.

Peat, a fibrous tangle of plant remains, is an important constituent of shallow lake sediments. It may contain varying amounts of clastic debris and lime, but some peat is made up almost entirely of woody material. An exposed section of peat deposited in a lake bed may show gradational changes from bottom to top, and these changes clearly reflect the changing environment of peat deposition.

Such a changing environment develops as follows. As a lake grows smaller in area because of any one or a combination of the processes of lake modification, vegetation progressively encroaches on the lake margin. The successive rims of different kinds of plants that surround the lake are known collectively as a *succession*.[20] The succession represents a series of plants trying to invade a new habitat. The first plants to survive the new environment are the *pioneers*, and they must have adaptations which will permit them to survive under extreme conditions. The effect of pioneer vegetation on a new area such as a lake is to improve the general conditions for plant growth such that plants requiring less moisture than the pioneers can eventually invade an area that was originally too wet for their survival. A succession of this type is known as a *hydrarch succession*.[21] As each successive zone of the hydrarch invades the next zone in a lakeward direction, the dead remains of the various zones form a stratified record of the succession. The end result is a layered sequence of plant remains with the pioneers at the bottom and the modern assemblage at the top. Each will contain a characteristic suite of plant species which give rise to the formation of different kinds of peat, the fibrous at the bottom and a gradation to the woody peat on the top.[22]

The hydrarch succession is important in the matter of permanent lake extinction because it represents the final phase in the fillings of the lake basin. The rate at which the succession progresses toward the permanent floral population for a given climatic zone is dependent to some extent on other factors associated with the lake. For example, a temporary rise or fall in the lake level will retard or accelerate the rate of advance of the succession, but the end product is always lake extinction. It should be noted that stratified peat deposits in old lake basins have provided a basis for chronologies related to climatic fluctuations since the retreat of the last continental glacier both in Europe and North America. The chief element in establishing postglacial chronologies from peat beds is the examination of pollen grains buried during the accumulation of the organic detritus.

A *bog succession* differs from a normal hydrarch succession in that

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[20] H. J. Oosting, *The Study of Plant Communities* (San Francisco: W. H. Freeman and Company, 1948), p. 214.

[21] W. S. Cooper, "The Climax Forest of Isle Royale, Lake Superior and Its Development," *Botanical Gazette, 55*:1–44 (1913).

[22] For further details on Minnesota peat deposits the reader is referred to an excellent discussion of the various kinds of plants involved in the formation of peat in Bulletin 16 of the Minnesota Geological Survey (1919), pp. 63–74.

the later stage of the bog sequence is characterized by the bridging over of open water by the development of a floating sedge mat which grows lakeward from the periphery of the bog.[23] The mat, composed of various sedges, is extended outward each year as new shoots grow from the rhizome tips. When the floating mat covers an open body of water, it is known as *quaking bog*, and when it gets to be about 2 feet thick it can support the weight of a man. The pioneer sedge mat is succeeded by swamp trees such as black spruce, tamarack, and white cedar, which in turn are followed by the final stage of the succession, the swamp hardwoods.

FIGURE 45. — A shallow lake in the Minnesota River Valley between Chaska and Mendota, in the process of being filled with vegetation.

The effect of the growth of vegetation around the margin of a lake is generally twofold. Besides actually decreasing the area of the lake when the vegetal cover is extended out into the lake, the vegetation increases the loss of water by transpiration. Bog successions have still another effect: when the floating sedge mat completely covers a lake it prevents any further accumulation of inorganic clastic material in the basin.

Examples of vegetal fillings in Minnesota lakes could be cited by the hundreds, but two typical cases will suffice to show the general conditions prevailing during the last stages of a lake's life span. The lakes along the Minnesota River between Chaska and Fort Snelling are very shallow and are being modified by vegetal filling. The advance of the

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[23] J. E. Weaver and F. E. Clements, *Plant Ecology* (New York: McGraw-Hill Book Company, 1938), p. 76.

hydrarch is checked each spring, however, when the lakes become flooded during the high stages of the Minnesota River. In spite of this, several of the lakes in the valley have been nearly filled with vegetal accumulations. Figure 45 shows the condition of one of these shallow lakes in July 1949. The area of open water is rapidly declining.

Another good example of a typical bog succession in Minnesota can be seen in Figure 46, where lakes in various stages of filling are visible. The sedge mat in the upper lake in Figure 46 is not yet complete, but the lake in the southeast corner is completely mantled by a vegetal mat. Sometimes part of the mat near the shore of a lake becomes separated from the main mass by a strong wind and is blown across the lake. Such

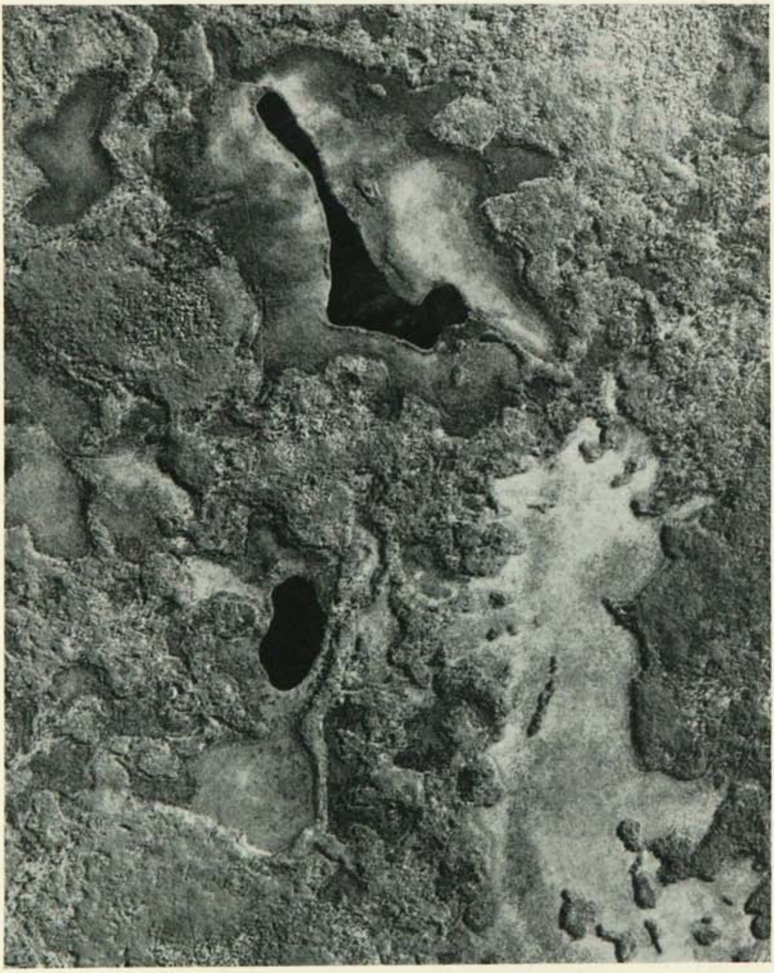

FIGURE 46. — A bog succession in Aitkin County. (U.S. Department of Agriculture photograph, September 1939.)

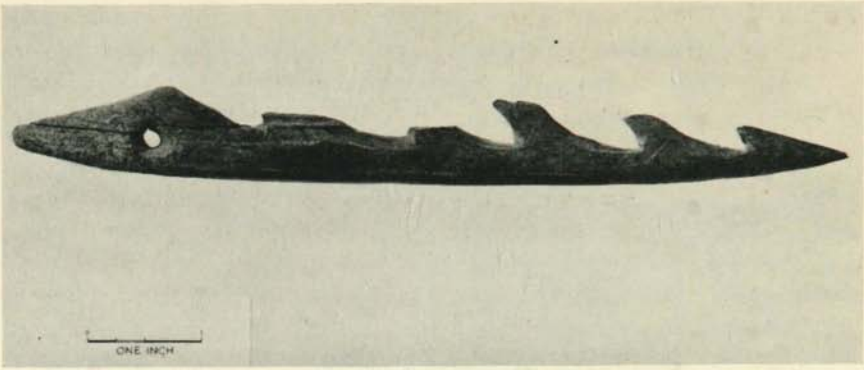

FIGURE 47. — Harpoon head found on the floor of Rabbit Lake, Crow Wing County. Lakes frequently yield such articles indicative of prehistoric inhabitations. (Photograph through the courtesy of the Smithsonian Institution.)

"floating islands" even contain small trees and can support the weight of a man, although many floating bogs are extremely weak and should not be trusted to carry much weight. More than one unwary hunter has lost his life by drowning because he broke through a floating bog that was being used as a duck blind.

Lake sediments often contain the bones and skeletal remains of animals and are therefore good hunting grounds for paleontologists, especially those interested in the distribution of animals along the retreating margin of the continental glaciers of the Ice Age. Artifacts, products of human workmanship, are uncovered from time to time in association with lake deposits. A harpoon head from Rabbit Lake in Crow Wing County was found by an employee of the Minnesota Department of Conservation, Division of Lands and Minerals, and presented to the Smithsonian Institute by Mr. Fred W. Uhler of the Ironton office of that organization (Fig. 47). The harpoon was probably used by primitive natives in Minnesota that had migrated into the region after the Ice Age.

CONCLUSIONS

A lake is a dynamic feature with a definite life span, although the life expectancy of all lakes in Minnesota is by no means the same or even of the same order of magnitude. However, the life span of all fresh-water lakes is usually short in terms of geologic time. Some bedrock lakes in which little sedimentation is taking place will outlive their contemporaries in the drift-covered regions by many thousands of years.

Because a lake basin receives sediment from the time it is formed until it becomes dry, it faithfully records the changing environment that prevailed during its existence. We can look, therefore, to extinct lakes for our climatological and environmental record of the recent past and need only to interpret the layers of sediment to reconstruct the passing parade of events during the life of the lake.

V. LAKE DISTRIBUTION

This chapter is devoted to a description of the various parts of the state of Minnesota in which certain types of lakes predominate. Since it has been shown in Chapter III that in general each of the lakes in the classification has a distinct relation to the type of material exposed at the surface, it is convenient to divide the state into areas or sections, each of which is characterized by a predominant type of surface material and topography.

The boundaries of 17 sections are shown in Figure 48, a map of the lake distribution in Minnesota, based chiefly on the 1932 map of surficial deposits by Leverett and Sardeson.[1] It is much generalized, and although a section may be dominated by one particular type of deposit, it may also contain minor deposits of other material. For instance, sections 12 and 13 are characterized by ground moraine, but some end moraine and some outwash do occur within their boundaries.

The first part of this chapter will deal with a description of the various sections, each of which bears a name of geographic or geologic significance. The second part is a tabulation of examples of lakes of each type in the classification presented in Chapter III, and the location of each lake with respect to the lake distribution map and with respect to county. Only about 1,000 lakes are included in the tabulation, about 10 per cent of the total lakes in the state, but it is believed that the larger and most important lakes are included, and that a representative group of lakes from each area is contained in the list. The tabulation is based partly on field examination and partly on the interpretation of aerial photographs in conjunction with Leverett's map of 1932. Lake names were taken from the 1936 county road maps published by the Minnesota Department of Highways.

1. ST. CLOUD OUTWASH

The St. Cloud section of outwash parallels the Mississippi River from St. Cloud in Stearns County to Elk River in Sherburne County. It includes the southwestern part of Sherburne County, the extreme northern and northwestern part of Wright County, and the eastern and southeastern parts of Stearns County. The predominant lakes are ice-block basins in an outwash plain (type 5) and ice-block basins in till and outwash (type 8).

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[1] Frank Leverett and F. W. Sardeson, *Quaternary Geology of Minnesota and Parts of Adjacent States* (U.S. Geological Survey Professional Paper 161, 1932), plates 1 and 2.

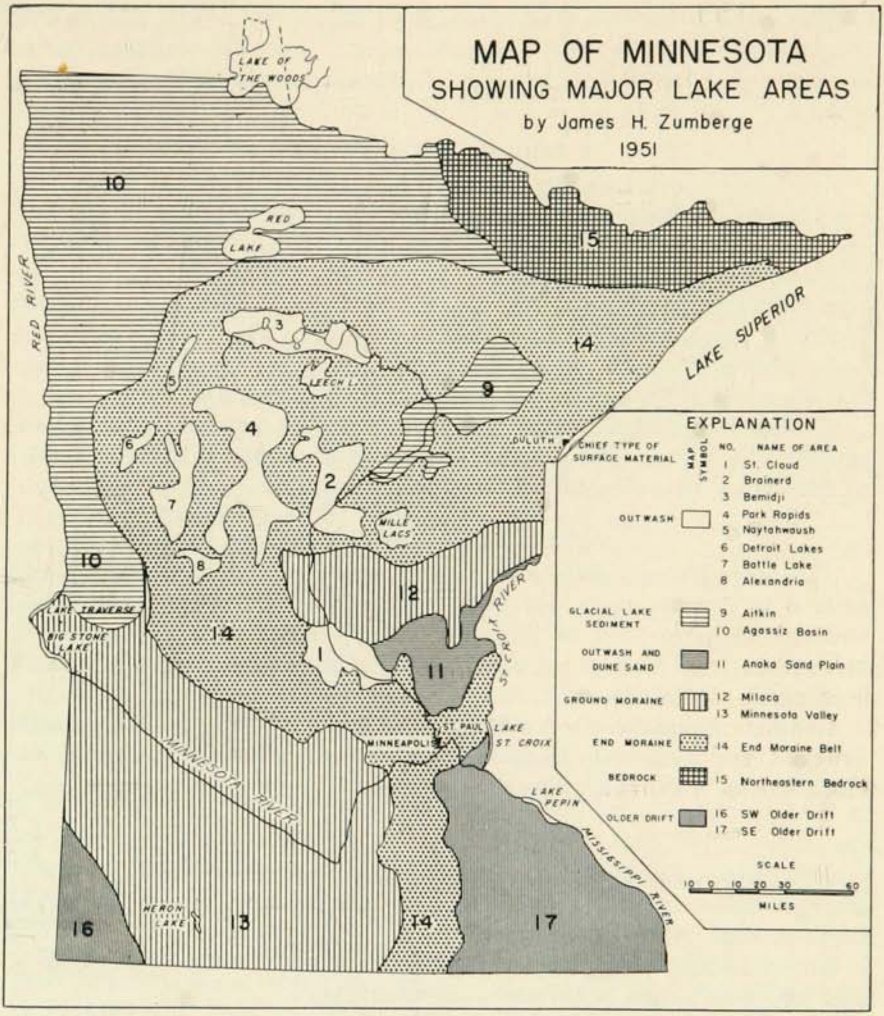

FIGURE 48

2. BRAINERD OUTWASH

The Brainerd section lies almost entirely within the boundary of Crow Wing County but overlaps into Cass County west and north of the former. The predominant lakes are ice-block basins in outwash lying in a preglacial valley (type 3), ice-block basins in an outwash plain (type 5), and ice-block basins in till and outwash (type 8).

3. BEMIDJI OUTWASH

The Bemidji section extends from northern Clearwater County as a strip 65 miles long and 20 miles wide, eastward to west-central Itasca

County. It also includes part of southern Beltrami County and part of north-central Cass County. The predominant lakes are ice-block basins in an outwash plain (type 5) and ice-block basins in till and outwash (type 8).

4. PARK RAPIDS OUTWASH

Extending south from Park Rapids in southern Hubbard County to a point east of Wadena in south-central Wadena County, a distance of over 40 miles, the Park Rapids section is the largest continuous deposit of outwash in northern Minnesota. In south-central Wadena County the area splits into two prongs: one prong extends southwestward to Parkers Prairie in southeastern Otter Tail County, and the other extends to Long Prairie in central Todd County. From Park Rapids another arm extends northwestward into east-central Becker County.

The predominant lakes are ice-block basins in outwash lying in preglacial valleys (type 3), ice-block basins in an outwash plain (type 5), and ice-block basins in till and outwash (type 8).

5. NAYTAHWAUSH OUTWASH

The Naytahwaush section of outwash is only about 16 miles long and from 2 to 6 miles wide. Its long axis lies in a north-south direction, and the northern limit of the section is at the town of Naytahwaush in southeastern Mahnomen County; but the largest part of the area is in north-central Becker County.

Characteristic lakes are ice-block basins in outwash lying in preglacial valleys (type 3), ice-block basins in an outwash plain (type 5), and ice-block basins in till and outwash (type 8).

6. DETROIT LAKES OUTWASH

The Detroit Lakes section is a small area extending from the town of Detroit Lakes in southwestern Becker County to Pelican Rapids in north-central Otter Tail County.

The dominant lakes are ice-block basins in an outwash plain (type 5) and ice-block basins in till and outwash (type 8).

7. BATTLE LAKE OUTWASH

The Battle Lake section extends from southern Becker County southward for over 50 miles almost to the southern edge of Otter Tail County. It ranges in width from 5 to 18 miles and is best described as a well developed pitted outwash plain.

The predominant lakes are ice-block basins in outwash lying in preglacial valleys (type 3), ice-block basins in an outwash plain (type 5), and ice-block basins in till and outwash (type 8).

8. ALEXANDRIA OUTWASH

Lying wholly in north-central and northeastern Douglas County, the

Alexandria section of pitted outwash is about 25 miles long and from 3 to 12 miles wide.

Characteristic lakes are ice-block basins in outwash lying in preglacial valleys (type 3), ice-block basins in an outwash plain (type 5), and ice-block basins in till and outwash (type 8).

9. AITKIN GLACIAL-LAKE BED

Although the Aitkin Glacial-Lake Bed section is named for Glacial Lake Aitkin, which occupied most of the northern half of Aitkin County, it includes also the area covered by Glacial Lake St. Louis (Glacial Lake Upham) in southwestern St. Louis County (Fig. 3). Together these two glacial-lake beds comprise a belt trending northeast-southwest, from 10 to 30 miles wide and about 80 miles long. The tract is largely swampy and contains few well-defined lakes. The surface material consists primarily of clay, silt, and sand deposited in the glacial lakes during their existence in the early retreatal stages of the Superior lobe and the St. Louis sublobe. The exact limits of both Glacial Lake Aitkin and Glacial Lake St. Louis are somewhat vague since they probably did not exist long enough to develop well-defined shore lines. The area formerly covered by them is roughly delineated on the basis of the distribution of the sediments deposited in them and not on distinct shore features.[2]

The only prominent lakes in this area are oxbow lakes (type 18), which are developed in old meanders of the Mississippi River in Aitkin County. The many square miles of swamp in this area are probably all that is left of lakes that are remnants of proglacial lakes, type 19.

10. AGASSIZ GLACIAL-LAKE BED

Glacial Lake Agassiz once occupied all of the Red River Valley and much of northwestern and north-central Minnesota (Fig. 3). In spite of the fact that this area was once covered by a single lake which extended northward into Manitoba, 500 miles north of Winnipeg, it is one of the large areas in the state characterized by a scarcity of lakes. Save for a few large remnants of Glacial Lake Agassiz and several oxbow lakes associated with the Red River, which forms the western boundary of the state from Traverse County to Kittson County, the area is practically devoid of lakes. The reason for this lies in the fact that sediment deposited in Glacial Lake Agassiz filled most of the small depressions that might have existed in the original lake bottom. Subsequent drainage of the lake through the Minnesota River Valley left the lake bottom as a nearly flat, featureless plain except for the few places where standing water persisted in depressions that were not filled with sediment. Notable lakes of this class (type 19) are the Red lakes in Beltrami County, Thief and Mud lakes in Marshall County, Lake of the Woods in Lake of the Woods County, and Nett Lake in Koochiching County.

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[2] Leverett and Sardeson, *Quaternary Geology of Minnesota and Parts of Adjacent States*, p. 54.

11. ANOKA SAND PLAIN

The chief surface material of the Anoka Sand Plain is outwash, but it is somewhat different from other areas of outwash in that the sands are generally finer and have locally been reworked by wind. The term Anoka Sand Plain as used in this bulletin includes not only the area designated by Cooper[3] as the Anoka Sand Plain but also a narrow strip of alluvium along the St. Croix River in northern Chisago and southeastern Pine counties.

The dominant lakes of this area are ice-block basins in outwash lying in preglacial valleys (type 3) and ice-block basins in an outwash plain (type 5). A few basins formed by wind action may exist, but they are not known to contain any standing water.

12. MILACA GROUND MORAINE

The Milaca Ground Moraine section lies in east-central Minnesota and extends eastward from the inner border of the massive St. Croix moraine in eastern Todd County to the Minnesota-Wisconsin border in eastern Pine County, a distance of over 115 miles. The maximum north-south width of the belt is 40 miles in the western half and 25 miles in the eastern half. A prong 8 miles wide extends down into the Anoka Sand Plain for a distance of about 20 miles in northwestern Chisago and east-central Isanti counties. The main area is bordered on the north by the outer margin of the Mille Lacs moraine in northern Mille Lacs and northern Kanabec counties.

This area is characterized essentially by ground moraine save for a small belt of outwash on the east side of the Mississippi River in southwestern Morrison County and northwestern Benton County. There are few lakes, compared with areas to the north, south, and east of the Milaca section. The lakes that do exist were all formed by continental glaciation (Category 1) except for a few along the Mississippi River in Benton County, the meander scars associated with the channel migrations of the Mississippi River (type-17 lakes).

13. MINNESOTA VALLEY

The Minnesota Valley section embraces a large part of south-central and southwestern Minnesota. The chief surface material is ground moraine deposited by the last glacier that invaded the state, the Des Moines lobe. Several end moraines cross the area from northwest to southeast and some local deposits of outwash are present, but the dominating topography is the swell and swale type associated with ground moraine.

Shallow lakes formed by the irregular deposition of till (type 1) are the most common in this area, but other lakes formed by continental glaciation are also present. Of these, the most important are the so-called "chains of lakes" in Martin County. There are four distinct lake chains

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[3] W. S. Cooper, *The History of the Upper Mississippi River in Late Wisconsin and Postglacial Time* (Minnesota Geological Survey Bulletin 26, 1935), plate 2.

in this county, and the longest is 23 miles and contains 18 lakes. All of these lakes are ice-block basins in till lying in preglacial valleys (type 4).

Along the Minnesota River valley are three large lakes (Traverse, Big Stone, and Lac qui Parle) which were formed by tributaries damming a master stream (type-14 lakes). All of these lakes occupy the channel through which water from Glacial Lake Agassiz once flowed. When this southern channel was abandoned for an outlet north to Hudson Bay, drastic changes took place; the great loss in the volume of water in the Minnesota River prevented immediate transport of the debris carried into it by tributaries, and the valley became segmented by tributary fans. The Little Minnesota River, one of the western tributaries, deposited an alluvial fan in the Minnesota River at Browns Valley. This alluvial fan was built so high that it not only caused the formation of Lake Traverse upstream from the fan, but also caused a reversal of drainage in this segment so that Lake Traverse drains north to the Red River. Browns Valley is thus on the divide between the drainage to Hudson Bay and the drainage to the Gulf of Mexico. The Browns Valley alluvial fan is well shown on the Peever topographic map of the United States Geological Survey.

In general, lakes are becoming fewer in number in the Minnesota Valley section because they were shallow originally and have undergone rapid modification due to the deposition of sediment in them.

14. END-MORAINE BELT

The End-Moraine Belt is characterized by a topography which is considerably more rugged than any of the previously described sections. This is due to the concentrated deposition of drift at the ice edge during extended pauses in the general retreat of the ice front. At each pause a ridge of hills was built along the ice margin, and ice blocks that became stagnated and detached from the main ice mass were buried under debris that was heaped into the moraines. Later, when the main glacier retreated back to a new position, the buried ice blocks melted and left depressions now occupied by water. These ice-block basins in till (type 7), or ice-block basins in outwash (type 5) if the moraine contains much outwash, make up the bulk of the lakes in the huge end-moraine belt. As a matter of fact, they form an estimated 80–85 per cent of the lakes in Minnesota.

Small areas of ground moraine and outwash plains occur in the end-moraine belt, but they are minor features when compared to the rest of the area. Near Lake Superior the drift is thin and even absent in some places, so that the bedrock is locally exposed at the surface. In the central part of the state, massive end moraines have given rise to a rugged topography in which there are literally thousands of lakes.

Two of the largest lakes in Minnesota fall within the boundaries of Section 14. They are Lake Mille Lacs in Mille Lacs and Aitkin counties and Leech Lake in Cass County. Both are good examples of lakes formed by moraine dams (type 2).

The many lakes of the Twin Cities region also lie in this area. Lake Minnetonka, an integrated or connected group of ice-block basins (type 7), is the largest in this region; other examples of various lake types in or near Minneapolis and St. Paul can be found by referring to the tabulation at the end of this chapter.

15. NORTHEASTERN BEDROCK

The Northeastern Bedrock section occupies the northeastern part of the state in Cook, Lake, and St. Louis counties. Lakes in this section are primarily the result of glacial erosion, although some are partially the result of glacial deposition. Characteristic lakes include bedrock basins localized by preglacial valleys (type 9), bedrock basins with no relation to preglacial valleys (type 10), and bedrock basins partially dammed by drift (type 11). Several examples of all three types are tabulated at the end of this chapter.

16. SOUTHWESTERN OLDER DRIFT

The Southwestern Older Drift section in the extreme southwestern corner of the state is of importance only because it contains no lakes. The reason for this lies in the fact that the surface has been exposed to erosion long enough to allow the streams to drain all of the lakes that undoubtedly once existed.

17. SOUTHEASTERN OLDER DRIFT

Like the section just described, the Southeastern Older Drift section is characterized by a topography devoid of lakes save for those along the bottom lands of the Mississippi River. These include lakes formed by the uneven aggradation of a floodplain (type 13), lakes formed by the damming of the master stream by a tributary (type 14), lakes formed by the damming of a tributary by the master stream (type 15), and delta lakes (type 16). All of the examples of lakes of each of these types were selected from this area and are described in Chapter III of this bulletin.

Many limestone sinkholes occur in Fillmore County, but none is known to contain a permanent lake.

EXAMPLES OF LAKE TYPES

Name	Section	County
TYPE 1. Lakes Formed by the Irregular Deposition of Till		
Addie	13	McLeod
Allie	13	Renville
Altnow	13	Sibley
Andrew	14	Kandiyohi
Ann	12	Kanabec
Ann	13	Wright
Ash	14	Grant
Aspinwall	14	Mahnomen
Bachelor	13	Brown
Badger	13	Murray
Bakers	13	McLeod
Ballantyne	13	Blue Earth
Barrows	13	Grant
Bass	13	Faribault
Bassett	14	St. Louis
Beaulieu	14	Mahnomen
Belle	13	Meeker
Big	14	St. Louis
Big Birch	14	Todd
Big Kandiyohi	13	Kandiyohi
Big Rice	14	Cass
Big Rice	14	St. Louis
Boulder	14	St. Louis
Buffalo	13	Waseca
Cadotte	14	St. Louis
Cedar (near Sauk Center)	14	Stearns
Church	14	Mahnomen
Clarks	13	Scott
Coombs	13	Meeker
Comstock	14	St. Louis
Cottonwood	13	Grant
Cottonwood	13	Lincoln
Crystal	13	Stevens
Current	13	Murray
Dead Goon	13	Lincoln
Devils	12	Kanabec
Doughty	13	Grant
Duck	13	Blue Earth
Eagle	13	Blue Earth
East Graham	13	Nobles
East Toqua	13	Big Stone
Elbow	14	St. Louis
Elizabeth	13	Kandiyohi
Emily	13	Le Sueur
Emma	13	Wright
Fish	12	Kanabec
Fox	14	Rice
Freeborn	13	Freeborn
French	14	Rice
Full of Fish	12	Kanabec
George	14	Stearns
German	13	Le Sueur
TYPE 1, continued		
Gorder	13	Stevens
Gorman	13	Le Sueur
Graham	13	Grant
Granite	14	Wright
Greenwood	14	Lake
Heron	13	Jackson
High Island	13	Sibley
Hoeffkens	13	Carver
Irish	13	Watonwan
Iron	13	Murray
Jefferson	13	Le Sueur
Jones	13	Grant
Kansas	13	Watonwan
Kings	13	McLeod
Kings	13	Meeker
Kings	14	Stearns
Knife	14	Stearns
Lewis	12	Kanabec
Lillian	13	Kandiyohi
Lime	13	Murray
Lincoln	14	Pope
Linwood	14	St. Louis
Little Spirit	13	Jackson
Long (near Aurora)	14	St. Louis
Long	13	Stevens
Long	13	Watonwan
Long Tom	13	Big Stone
Loon	13	Jackson
Lower Twin	14	Freeborn
Lure	13	Blue Earth
McCormick	14	Stearns
Madison	13	Blue Earth
Maple	14	Polk
Maple	14	Todd
Maria	13	Murray
Markham	14	St. Louis
Mary	13	Wright
Mennetago	13	Kandiyohi
Middle	13	Nicollet
Minnesota	13	Faribault
Mud	14	Pope
Mud	13	Sibley
Mud	14	St. Louis
Nelson	13	Grant
Nichol	14	St. Louis
Niemakl	13	Grant
Oliver	13	Swift
Olson	13	Stevens
Osakis	14	Todd
Oscar	13	Murray
Oscar	14	Otter Tail
Otter	14	St. Louis

Name	Section	County
TYPE 1, continued		
Page	13	Stevens
Patchem	13	Grant
Pelican	14	Wright
Pickerel	14	Freeborn
Pine	14	St. Louis
Pippin	13	Le Sueur
Pomroy	12	Kanabec
Preston	13	Renville
Pullman	13	Grant
Pupopsky	14	Beltrami
Rice (near Delavan)	13	Faribault
Rice	14	Steele
Rock	13	Lyon
Round	13	Grant
Round	13	Jackson
Sand	14	Lake
Sand	14	Stearns
Sarah	13	Murray
School	13	Brown
School	13	Watonwan
Scotch	13	Le Sueur
Shakopee	13	Wright
Shaver	13	Grant
Silver	13	McLeod
Silver	14	St. Louis
Silver	13	Sibley
Silver	13	Waseca
Spellman	13	Yellow Medicine
Stony	14	Grant
Stinking	14	Becker
Sulem	13	Watonwan
Swan	13	McLeod
Swan	13	Nicollet
Swanson	13	Big Stone
Thompson	13	Meeker
Tiger	13	Carver
Timber	13	Nicollet
Titlaw	13	Sibley
Union	14	Rice
Upper Rice	14	Clearwater
Upper Twin	14	Freeborn
Vanose	14	Mahnomen
Volney	13	Le Sueur
Wagonga	13	Kandiyohi
Walnut	13	Faribault
Washington	13	Le Sueur
Washington	13	Sibley
West Graham	13	Nobles
West Toqua	13	Big Stone
Whitefish	14	Lake
Wigwam	14	Lake
Wild Rice	14	St. Louis
William	14	Todd
Willow	13	Chippewa
Willow	13	Redwood
Wilson	14	Lake

Name	Section	County
TYPE 1, continued		
Wita	13	Blue Earth
Wood	13	Lyon
Wood	13	Watonwan
Wood	13	Yellow Medicine
Yager	13	Wright
Yankton	13	Lyon
Young America	13	Carver
Zanders	13	Brown
TYPE 2. Lakes Formed by Moraine Dams		
Leech	14	Cass
Mille Lacs	14	Mille Lacs–Aitkin
Shetek	13	Murray
TYPE 3. Ice-Block Basins in Outwash Lying in Preglacial Valleys		
Amelia	14	Pope
Augusta	13	Cottonwood
Baldwin	11	Anoka
Barrett	13	Grant
Boat	11	Anoka
Browns	14	Stearns
Burr	13	Grant
Cannon	14	Rice
Carlos	8	Douglas
Centerville	11	Anoka
Coon	11	Anoka
Cowdry	8	Douglas
Darling	8	Douglas
Donalds	7	Otter Tail
East Leaf	7	Otter Tail
Eden	14	Stearns
Elizabeth	11	Isanti
Eller	14	Pope
Ethel	7	Otter Tail
Fawn	11	Anoka
Fifth Crow Wing	4	Hubbard
Forsham	11	Anoka
Frances	14	Le Sueur
Francis	11	Isanti
Geb Watch	11	Anoka
George Watch	11	Anoka
Golden	11	Anoka
Gourd	7	Otter Tail
Grass	7	Otter Tail
Ham	11	Anoka
Hanson	7	Otter Tail
Hoffman	11	Isanti
Horseshoe	11	Isanti
Itasca	14	Clearwater
Johnson	13	Grant

TYPE 3, continued

Name	Section	County
Latotka	8	Douglas
Leven	14	Pope
Lightning	14	Grant
Linwood	11	Anoka
Long	4	Hubbard
Long	11	Isanti
Lower Long (SE of Brainerd)	2	Crow Wing
Lower Sakatah	14	Rice
Martin	11	Anoka
Mill Pond	14	Grant
Netta	11	Anoka
North Pomme de Terre	13	Stevens
Ohlsrud	13	Grant
Peltier	11	Anoka
Pickle	7	Otter Tail
Pokegama	14	Itasca
Pomme de Terre	14	Grant
Portage	7	Otter Tail
Randeau	11	Anoka
Rays	14	Le Sueur
Rice (near Linwood)	11	Anoka
Rice (near Centerville)	11	Anoka
Seventh Crow Wing	4	Hubbard
Sixth Crow Wing	4	Hubbard
South Pomme de Terre	13	Stevens
Stony Brook	14	Grant
Straight	4	Becker
Tamarack	11	Anoka
Tamarack	11	Isanti
Tamarack	11	Otter Tail
Tennyson	11	Isanti
Tetonka	14	Le Sueur
Turtle	14	Ramsey
Tustin	14	Le Sueur
Twin	5	Mahnomen
Typo	11	Isanti
Upper Long (SE of Brainerd)	2	Crow Wing
Upper Sakatah	14	Le Sueur
Villard	14	Pope
Watermute	13	Stevens
West Leaf	7	Otter Tail
Wilson	13	Grant

TYPE 4. Ice-Block Basins in Till Lying in Preglacial Valleys

Name	Section	County
Albert Lea	14	Freeborn
Amber	13	Martin
Bass	14	Otter Tail
Benton	13	Lincoln
Big Pine	12	Pine
Big Swan	14	Todd
Big Twin	13	Martin
Blue	14	Isanti
Bright	13	Martin
Budd	13	Martin
Buffalo	13	Martin
Calhoun	14	Hennepin
Campell	13	McLeod
Canright	13	Martin
Cedar	14	Hennepin
Cedar	13	Martin
Charlotte	13	Martin
Chatauqua	14	Otter Tail
Clayton	13	Martin
Clear	13	Martin
Cole	14	Carlton
Cross	12	Pine
Crystal	13	Blue Earth
Dane	14	Otter Tail
Eagle	14	Carlton
East Chain	13	Martin
Eighth Crow Wing	14	Hubbard
Eleventh Crow Wing	14	Hubbard
Elk	13	Grant
Elbow	14	Otter Tail
Elbow	12	Pine
Elysian	13	Waseca
Emily	14	Pope
Fish (NW chain)	13	Martin
Fish (central chain)	13	Martin
Fiske	14	Otter Tail
Fountain	14	Freeborn
Gervais	14	Ramsey
Grass	12	Pine
Great Sweitzer	14	Hubbard
Griffin	13	Swift
Grindstone	12	Pine
Hall	13	Martin
Hanska	13	Brown
Harriet	14	Hennepin
Henry	13	Swift
Hiawatha	14	Hennepin
High	13	Martin
Imogene	13	Martin
Indian	12	Pine
Inlet	13	Martin
Iowa	13	Martin
Island	14	Carlton

TYPE 4, continued

Name	Section	County
Jolly Ann	14	Otter Tail
Jorgens	14	Todd
Keiler	14	Ramsey
Kiester	13	Martin
Lady	14	Todd
Lake of the Isles	14	Hennepin
Lake of the Valley	14	Otter Tail
Lilly	13	Blue Earth
Little Sauk	14	Todd
Long (near Grove City)	14	Meeker
Long (near Underwood)	14	Otter Tail
Long (near Vegas)	14	Otter Tail
Loon	13	Blue Earth
Loring	14	Hennepin
Lower Elk	13	Grant
Martin	13	Martin
Mills	13	Blue Earth
Mud	13	Martin
Murphy	13	Martin
Ninth Crow Wing	14	Hubbard
Nokomis	14	Hennepin
North	13	Martin
North Silver	13	Martin
North Turtle	14	Otter Tail
Ocheda	13	Nobles
Okamanpeedem	13	Martin
Olaf	14	Otter Tail
Otter	13	McLeod
Owasso	14	Ramsey
Perch	13	Martin
Phalen	14	Ramsey
Pierce	13	Martin
Pimushe	14	Otter Tail
Pleasant	14	Ramsey
Powderhorn	14	Hennepin
Prior	14	Scott
Rapidan	13	Martin
Rose	13	Martin
Sager	13	Martin
Sarah	14	Hennepin
Sauk	14	Todd
Shaokatan	13	Lincoln
Sisseton	13	Martin
Spring	14	Scott
Spring	13	Grant
String	13	Cottonwood
Susan	13	Martin
Swan	14	Otter Tail
Tamarack	14	Carlton
Tenth Crow Wing	14	Hubbard
Twin	14	Todd
Upper Lightening	14	Otter Tail
Upper Pine	12	Pine
Vadnais	14	Ramsey
West Port	14	Pope
Wilmer	13	Kandiyohi
Wilmert	13	Martin

TYPE 5. Ice-Block Basins in an Outwash Plain

Name	Section	County
Abbey	6	Becker
Agnes	8	Douglas
Andrusia	13	Beltrami
Annalaide	4	Otter Tail
Annie Battle	7	Otter Tail
Antler	14	Itasca
Bass	1	Wright
Bear	14	Freeborn
Becker	14	Stearns
Belmont	7	Otter Tail
Bemidji	3	Beltrami
Big	14	Stearns
Big	3	Beltrami
Big	1	Sherburne
Big Portage	2	Cass
Big Rat	5	Becker
Big Rush	4	Becker
Birch	11	Sherburne
Bladder	4	Hubbard
Blanche	7	Otter Tail
Blueberry	4	Wadena
Briggs	1	Sherburne
Buchanan	7	Otter Tail
Burnt Shanty	14	Itasca
Caroline	1	Stearns
Cass	3	Beltrami
Clear	1	Sherburne
Clearwater	1	Wright
Clitherall	7	Otter Tail
Crane	7	Otter Tail
Crow	14	Stearns
Cullen	2	Crow Wing
Deer	7	Otter Tail
Detroit	7	Otter Tail
Diamond	14	Hennepin
Eagle	7	Otter Tail
Eagle	1	Sherburne
East Battle	7	Otter Tail
Edwards	2	Crow Wing
Elk (S. of Briggs Lake)	1	Sherburne
Elk (E. of Rice Lake)	11	Sherburne
Ellingson	7	Otter Tail
Elmo	14	Washington
Eunice	6	Becker

TYPE 5, continued

Name	Section	County
Finn	4	Wadena
First Crow Wing	4	Hubbard
Fish	11	Anoka
Fish	6	Otter Tail
Fourth Crow Wing	4	Hubbard
Gebo	7	Becker
Geneva	8	Douglas
George	11	Anoka
German	11	Isanti
Gilman	13	Brown
Goodner	1	Stearns
Goose	14	Lake
Grace	3	Beltrami
Grand	1	Stearns
Grass	2	Crow Wing
Great Northern	14	Stearns
Green	11	Isanti
Ham	4	Hubbard
Highland	14	Itasca
Horseshoe	4	Otter Tail
Howe	7	Becker
Hubert	2	Crow Wing
Ida	6	Becker
Island	2	Cass
Jack Haw	5	Becker
Jim Crow	4	Wadena
Julia	1	Sherburne
Laura	1	Stearns
L'Homme Dieu	8	Douglas
Little Pine	7	Otter Tail
Little Rock	12	Benton
Long (near Merrifield)	2	Crow Wing
Long (near Ottertail)	7	Otter Tail
Long	1	Sherburne
Louise	8	Douglas
Louissa	1	Stearns
Lower Hay	2	Crow Wing
Lower Mission	2	Crow Wing
Mellissa	6	Becker
Mitchell	1	Sherburne
Molly Stark	7	Otter Tail
Mud	7	Becker
Murphy	7	Otter Tail
Palmer	14	Hennepin
Palmer	3	Hubbard
Pearl	14	Hennepin
Pearl	1	Stearns
Pelican	2	Crow Wing
Pelican	6	Otter Tail
Pickerel	7	Otter Tail
Pickerel	1	Sherburne
Pierz	12	Morrison
Pine	7	Otter Tail
Pleasant (near Rockville)	1	Stearns
Pleasant (near Annandale)	1	Wright
Ponta	2	Cass
Rice	12	Morrison
Rice	11	Sherburne
Round	11	Anoka
Round	2	Crow Wing
Round	7	Otter Tail
Round	14	Pope
Rush	7	Otter Tail
Rush	1	Sherburne
Sandbar	2	Crow Wing
Sanburn	2	Cass
Sandy	14	Aitkin
Sallie	6	Becker
St. Clair	6	Becker
Schneiders	14	Stearns
Second Crow Wing	4	Hubbard
Seven Beavers	14	St. Louis
Silver (N. of town of Battle Lake)	7	Otter Tail
Siverson	7	Otter Tail
Skunk	12	Morrison
South Maple	4	Otter Tail
South Partridge	14	St. Louis
Spectacle	11	Isanti
Spilsers	7	Otter Tail
Stocker	4	Wadena
Stocking	4	Wadena
Stone	8	Douglas
Stony	4	Hubbard
Strawberry	5	Becker
Swenoda	14	Pope
Swenson	3	Beltrami
Tamarac	6	Otter Tail
Third Crow Wing	4	Hubbard
Toad	7	Becker
Twin (near Robbinsdale)	14	Hennepin
Twin	4	Wadena
Twin	7	Otter Tail
Upper Hay	2	Crow Wing
Upper Mission	2	Crow Wing
Walker	7	Otter Tail
West Battle	7	Otter Tail
Whitefish	2	Crow Wing
Winona	8	Douglas
Wood	14	Hennepin
Wolf	3	Beltrami
Wolf	4	Hubbard

TYPE 6. Esker Troughs *

Name	Section	County
Coon	14	Itasca
Hill	14	Crow Wing
Pine	14	Crow Wing
Sandwick	14	Itasca

* This list is not representative of the distribution of these lakes in Minnesota. Completion of this tabulation is contingent on a study of esker distribution in the state.

TYPE 7. Ice-Block Basins in Till †

Name	Section	County
Baby	14	Cass
Bald Eagle	14	Ramsey
Balsam	14	Itasca
Bartlett	14	Koochiching
Bass (near Crystal)	14	Hennepin
Bass	14	Itasca
Battle	14	Koochiching
Bay	14	Crow
Bear	14	McLeod
Beaver	14	Steele
Belle	14	McLeod
Beltrami	14	Beltrami
Beers	14	Otter Tail
Benson	14	St. Louis
Berg	14	St. Louis
Big	14	Carlton
Big Carnelian	14	Washington
Big Constance	14	Koochiching
Big Deep	14	Cass
Big Fish	14	Stearns
Big Marine	14	Washington
Big Sand	14	Hubbard
Big Swan	14	Meeker
Big Watab	14	Stearns
Blackduck	14	Beltrami
Blackwell	14	Douglas
Blooms	14	Chisago
Bluewater	14	Itasca
Bowstring	14	Itasca
Boy	14	Cass
Borden	14	Crow Wing
Brandon	14	Douglas
Bryant	14	Hennepin
Buffalo	14	Becker
Buffalo	14	Wright
Bush	14	Hennepin
Byron	14	McLeod
Cameron	14	St. Louis

† The reader is cautioned that not all of the lakes listed as type 7 were examined in the field. Some were classified by use of aerial photographs in conjunction with Leverett's 1932 map of surficial deposits. It is now known that much of the area mapped by him as end moraine composed essentially of till is actually outwash of ice-contact origin. Therefore, it is likely that many of the lakes here classified as ice-block basins in till are in reality ice-block basins in outwash.

TYPE 7, continued

Name	Section	County
Camp	14	Swift
Caribou	14	St. Louis
Cataract	14	Otter Tail
Caron	14	Rice
Cedar	14	Rice
Cedar	14	Scott
Cedar	14	Wright
Child	14	Cass
Chippewa	14	Douglas
Chisago	14	Chisago
Christina	14	Douglas
Circle	14	Rice
Clear	14	Meeker
Clear	14	Waseca
Clear (near Dalton)	14	Otter Tail
Clearwater	14	Crow Wing
Cleary	14	Scott
Cody	14	Rice
Cokato	14	Wright
Comfort	14	Chisago
Como	14	Ramsey
Cotton	14	Becker
Cormorant	14	Grant
Crescent	14	St. Louis
Crooked	14	Douglas
Crooks	14	Crow Wing
Cross	14	Carlton
Cross	14	Polk
Crystal	14	Otter Tail
Cut-Foot-Sioux	14	Itasca
Deer (near Grand Rapids)	14	Itasca
DeMontreville	14	St. Louis
Devils	14	Otter Tail
Dewey	14	St. Louis
Diamond	14	Kandiyohi
Dinham	14	St. Louis
Dora	14	Itasca
Dora	14	Le Sueur
Dumbell	14	Lake
Eagle	14	Hennepin
Eagle	14	Kandiyohi
Echo	14	Douglas
Egg	14	Becker
Elbow	14	Cook
Fallon	14	Meeker
Fish	14	Hennepin
Fish	12	Morrison
Fish	14	Otter Tail
Fish Hook	14	Hubbard
Five	14	Otter Tail
Flat	14	Becker
Florida	14	Kandiyohi
Forest	14	Washington
Forget-Me-Not	14	Becker
Four Mile	14	Cook
Franklin	14	Koochiching
Franklin	14	Otter Tail
Freeborn	14	Douglas

Name	Section	County
TYPE 7, continued		
French	14	Wright
Games	14	Kandiyohi
Geis	14	Scott
Gilbert	14	Douglas
Gilchrist	14	Pope
Goose	14	Carver
Goose	14	Waseca
Grand	14	St. Louis
Grants	14	Douglas
Green	14	Chisago
Green	14	Kandiyohi
Greenleaf	14	Meeker
Grove	14	Otter Tail
Gull	14	Beltrami
Halverson	14	Otter Tail
Hassel	13	Swift
Haydens	14	Hennepin
Height of Land	14	Becker
Hill	14	Aitkin
Hokk	14	McLeod
Hook	14	Otter Tail
Horseshoe	14	Le Sueur
Howard	14	Wright
Independence	14	Hennepin
Inquadon	14	Cass
Island	14	Becker
Island	14	Hubbard
Island (near Northome)	14	Itasca
Island	14	Pine
Island	14	St. Louis
Jennie	14	Meeker
Jim	14	Otter Tail
Johanna	14	Pope
Johanna	14	Ramsey
Johannes	14	Otter Tail
Johnson	14	Otter Tail
Josephine	14	Ramsey
Kego	14	Crow Wing
King	14	Itasca
Kittleson	14	Polk
Koronis	14	Stearns
Latoka	14	Douglas
Lawrence	14	Itasca
Leander	14	St. Louis
Leek	14	Otter Tail
Lida	14	Otter Tail
Little Boy	14	Cass
Little Carnelian	14	Washington
Little Cormorant	14	Becker
Little Oak	14	Pine
Little Round	14	Becker
Lobster	14	Douglas
Long (near Elizabeth)	14	Otter Tail

Name	Section	County
TYPE 7, continued		
Long (near Richmond)	14	Stearns
Longyear	14	St. Louis
Loon	14	Otter Tail
Lower Sand	14	Lake
McCarron	14	Ramsey
Mantrap	14	Hubbard
Many Point	14	Becker
Marion	13	McLeod
Mary	14	Douglas
May	14	Crow Wing
Mazaska	14	Rice
Medicine	14	Hennepin
Mills	14	Douglas
Mina	14	Douglas
Mineral	14	Otter Tail
Minnetonka	14	Hennepin
Minnewashta	14	Carver
Minnie	14	Meeker
Moore	14	Swift
Moose	14	Itasca
Nest	14	Kandiyohi
North Partridge	14	St. Louis
Norway	14	Otter Tail
Oak	14	Pine
Oak	14	Polk
O'Dowd	14	Scott
Okabeno	13	Nobles
Onamia	14	Mille Lacs
Orchard	14	Dakota
Otter	14	Otter Tail
Otter	14	Ramsey
Oscar	14	Douglas
Peguaywan	14	St. Louis
Pelican	14	Grant
Perch	14	Carlton
Perch	14	St. Louis
Phelps	14	Rice
Pickerel	14	Anoka
Pike	14	St. Louis
Pine	14	Clearwater
Pleasant	14	Cass
Pleasant	14	Scott
Pleasant	14	Otter Tail
Pocquette (Lost)	14	Koochiching
Pokegama	12	Pine
Portage	14	Crow Wing
Potato	14	Hubbard
Prairie	14	St. Louis
Pulaski	14	Wright
Rabbit	14	Crow Wing
Rachel	14	Douglas
Rebecca	14	Hennepin
Red Rock	14	Douglas
Reno	14	Pope
Rice (near Montgomery)	14	Le Sueur

TYPE 7, continued

Name	Section	County
Rice	14	Stearns
Rice	14	Waseca
Roberd	14	Rice
Rock	14	Becker
Rock	14	Cass
Rogers	14	Dakota
Round	14	Itasca
Round	14	Ramsey
Rush	14	Meeker
Ruth	14	Crow Wing
Sabre	14	Le Sueur
Sanborn	14	Le Sueur
Sand	14	Itasca
Sand	14	Pine
Sand	14	St. Louis
Sandberg	14	Otter Tail
Sand Hill	14	Polk
Sasse	14	Le Sueur
Scalp	14	Otter Tail
Schubert	14	St. Louis
Sewell	14	Otter Tail
Shakopee	13	Chippewa
Shakopee	14	Mille Lacs
Shoal	14	Itasca
Sig	14	Otter Tail
Side	14	St. Louis
Silver	14	Ramsey
Sioux	14	Meeker
Siseebakwet	14	Itasca
Slate	14	Lake
Spider	14	Itasca
Spirit	14	Otter Tail
Spoon	14	Ramsey
Sprague	14	Rice
Spunk	14	Stearns
Square	14	Washington
Square	14	Washington
Squaw	14	Itasca
Stahlis	14	McLeod
Star	14	Meeker
Star	14	Otter Tail
State Line	14	Freeborn
Stony	14	Cass
Stowes	14	Douglas
Sturgeon	14	St. Louis
Sunfish	14	Dakota
Sunset	14	Washington
Suttin	14	Scott
Swan	14	Itasca
Swede	14	Carver
Sybil	14	Otter Tail
Tamarack	14	Becker
Ten Mile	14	Cass
Terrapin	14	Washington
Three Islands	14	Beltrami
Thunder	14	Cass
Todd	14	McLeod
Towhey	14	Cook
Town Line	14	Cass
Trout (near Bovey)	14	Itasca

TYPE 7, continued

Name	Section	County
Turtle	14	Beltrami
Turtle	14	Polk
Two Rivers	14	Stearns
Union	14	Polk
Upper Sand	14	Lake
Wabedo	14	Cass
Waconia	14	Carver
Washington	14	Meeker
Waverly	14	Wright
Webb	14	Cass
West Lost	14	Otter Tail
White Bear	14	Ramsey
White Earth	14	Becker
White Pine	14	Cook
William	14	Douglas
Wolf	14	Becker
Woman	14	Cass
Young America	13	Carver
Zumbra	14	Carver

TYPE 8. Ice-Block Basins in Till and Outwash

Name	Section	County
Ada	2	Cass
Ball Club	3	Itasca
Big Basswood	4	Becker
Brookway	2	Cass
Cormorant	6	Becker
Cottonwood	13	Cottonwood
Crystal	14	Hennepin
East Fox	2	Crow Wing
Elbow	4	Hubbard
Emily	14	Crow Wing
Five Point	2	Cass
Gegoka	14	Lake
Geneva	14	Freeborn
Graham	14	Otter Tail
Grove	14	Pope
Gull	2	Cass
Gull	2	Crow Wing
Gunn	14	Itasca
Hand	2	Cass
Hanging Horn	14	Carlton
Hattie	2	Cass
Ida	8	Douglas
Jessie	14	Itasca
Jewett	14	Otter Tail
John	1	Wright
Laura	14	Cass
Lind	2	Cass
Little Moose	14	Lake
Little Winnibigoshish	3	Itasca

TYPE 8, continued

Name	Section	County
Lizzie	6	Otter Tail
Long	6	Becker
McCloud	14	Pope
Manuella	14	Meeker
Maud	6	Becker
Miltona	8	Douglas
Minnewaska	14	Pope
Mitchell	14	Crow Wing
Pickerel	2	Cass
Pine Mountain	2	Cass
Roosevelt	2	Crow Wing
Rush	2	Cass
Serpent	1	Crow Wing
Shell	4	Becker
Smith	14	Douglas
Stalker	14	Otter Tail
Stella	14	Kandiyohi
Sturgeon	14	Pine
Sugar	1	Wright
Sylvia	14	Wright
Tamarack (near Underwood)	14	Otter Tail
Talcot	13	Cottonwood
Twin	14	Wright
Wabana	14	Itasca
Warren	13	Cottonwood
Winnibigoshish	3	Cass
Wimar	14	Otter Tail

TYPE 9. Bedrock Basins Localized by Preglacial Valleys

Name	Section	County
Alder	15	Cook
Birch	15	Cook
Caribou	15	Cook
Clearwater	15	Cook
Crocodile	15	Cook
Daniels	15	Cook
Duncan	15	Cook
Dunn	15	Cook
East Bearskin	15	Cook
Flower	15	Cook
Hungry Jack	15	Cook
Iron	15	Cook
Kekekabic	15	Lake
Knife	15	Lake
Loon	15	Cook
Moose	15	Lake
Ogishkemuncie	15	Lake

TYPE 9, continued

Name	Section	County
Pine	15	Cook
Poplar	15	Cook
Portage	15	Cook
Rose	15	Cook
South	15	Cook
West Bearskin	15	Cook
Winchell	15	Cook

TYPE 10. Bedrock Basins Not Related to Preglacial Valleys

Name	Section	County
Bat	15	Cook
Burntside	15	St. Louis
Gabimichigami	15	Cook
Greenwood	15	Cook
Kabetogama	15	St. Louis
LaCroix	15	St. Louis
Namakan	15	St. Louis
Saganaga	15	Cook
Sea Gull	15	Cook
Snowbank	15	Lake
Teal	15	Cook
Trout	15	St. Louis
Tuscarora	15	Cook

TYPE 11. Bedrock Basins Partially Dammed by Drift

Name	Section	County
Barker	14	Cook
Brule	15	Cook
Cascade	14	Cook
Caribou	14	Cook
Clara	14	Cook
Devil	14	Cook
Gunflint	15	Cook
Little Cascade	15	Cook
Pelican	15	St. Louis
Pine	14	Cook
Tait	14	Cook
Trout	14	Cook
Two Island	14	Cook
Vermilion	14	St. Louis

TYPE 12. Lakes Related to Natural Levees *

Name	Section	County
Blue	14	Scott
Fisher	14	Scott
Rice	14	Scott
River	14	Scott

* Type 12 also includes other, unnamed lakes along the Minnesota River bottom between Carver and the confluence of the Minnesota with the Mississippi.

TYPE 13. Lakes Produced by the Uneven Aggradation of a Floodplain

NOTE. Since many of these lakes are short-lived, they generally bear no name, but they may be observed along the bottom lands of the Mississippi River between Pike Island and southeastern Houston County.

TYPE 14. Lakes Formed by a Tributary Damming the Master Stream

Name	Section	County
Big Stone	13	Big Stone
Lac qui Parle	13	Lac qui Parle
Pepin	17	Goodhue–Wabasha
Traverse	13	Traverse

TYPE 15. Lakes Formed by the Master Stream Damming a Tributary

NOTE. The only known example of a lake of this type is Lake St. Croix, in Washington County, Section 17.

TYPE 16. Lakes Formed during the Construction of a Delta

NOTE. Only one named example, Sturgeon Lake in Goodhue County, exists in Minnesota. Others may be observed on the Lake Pepin delta near Red Wing on both sides of the Minnesota-Wisconsin boundary.

TYPE 17. Lakes Formed by a Shift in Channel Alignment of a Stream

NOTE. These lakes are extremely short-lived and have only been observed along the Mississippi River in Benton County and along the Minnesota River in Section 13.

TYPE 18. Oxbow Lakes

NOTE. None of these lakes is known by any official name, but they may be observed along the following rivers: the Mississippi in Aitkin County, the Minnesota upstream from New Ulm, the Red from Breckenridge in Wilkin County to the Canadian border in northwestern Kittson County, and Two Rivers in Kittson County.

TYPE 19. Lakes That Are Remnants of Proglacial Lakes

Name	Section	County
Gun	9	Aitkin
Lake of the Woods	10	Lake of the Woods
Lower Red	10	Beltrami
Mud	10	Marshall
Nett	10	Koochiching

TYPE 19, continued

Name	Section	County
Rice (near Walters)	13	Faribault
Thief	10	Marshall
Upper Red	10	Beltrami

TYPE 20. Lakes Formed by the Isolation of a Small Bay on a Larger Lake

Name	Section	County
Buck	3	Beltrami
Duck	6	Otter Tail
Mud	2	Crow Wing
Pug	14	Otter Tail
Schram	3	Beltrami
Sugar	14	Itasca

TYPE 21. Lakes Formed by the Segmentation of a Larger Lake into Two or More Separate Basins

Name	Section	County
McDonald	14	Otter Tail
Marion	14	Otter Tail
Ten Mile	14	Otter Tail

TYPE 22. Lakes Formed behind Cuspate Bars

NOTE. Because these lakes are small and intermittent, most of them are not named. Several examples exist on large lakes in which cuspate bars have been formed. One excellent example is a small pond on the north shore of Battle Lake in Otter Tail County. Another is Gould Lake in Cass County.

TYPE 23. Beaver-Dam Lakes

NOTE. A few examples of this type of lake exist in St. Croix State Park in Pine County. Several others prevail in the northern part of the state, although these have not been studied in detail.

TYPE 24. Lakes Formed by Artificial Dams

NOTE. Lake Zumbro in Wabasha and Olmstead counties is one of the best examples of this type of lake. Another good example can be observed on the Otter Tail River southwest of Fergus Falls in Otter Tail County.

TYPE 25. Lakes Formed by Mining and Quarrying Operations

NOTE. The best examples of this type of lake may be seen in the St. Cloud area, where abandoned granite quarries have become filled with water. Some lakes occur at the sites of large gravel pits and are widely distributed over the state. The largest of these artificially made basins occur on the iron ranges in northern Minnesota.

GLOSSARY

ablation moraine. Loose debris accumulated on the surface of a glacier, and eventually on the ground, owing to downward melting of the ice surface.

alluvium. Stream deposited sediment.

backwash. The movement of water down the slope of a beach.

base level. The elevation which controls the level to which a stream can erode or build up its bed. Sea level is a *general base level* while a lake or a hard layer of rock over which the stream flows is a *local base level.*

beach drift. The process whereby particles on a beach are moved parallel to the shore under the combined effect of the *swash* and *backwash.*

bedrock. Any solid rock mass either right at the surface or underlying such surface deposits as drift.

carbonate rocks. Sedimentary rocks composed of minerals with a high carbonate content. Examples are limestone (calcium carbonate) and dolomite (calcium magnesium carbonate).

clastic sediment. Sediment formed from fragments of other rocks. Sand is a clastic sediment.

colloid. An organic or inorganic substance in a very fine state of dispersion.

continental glacier (ice sheet). A slowly moving mass of ice covering areas of continental size. Modern examples exist on Greenland and Antarctica.

cuesta. An asymmetrical ridge formed by a gently tilted layer of resistant rock.

cuspate bar. A deposit formed along the shore of a lake having the plan shape of a triangle, the base of which parallels and is attached to the shore. A shallow depression near the center of the triangle is common.

chute. A channel occupying the floodplain area near the inside of a meander, and formed during flood stage of the river.

deflation. The process whereby wind removes loose surface material.

diabase sill. A tabular mass of dark crystalline rock intruded while molten between two pre-existing rock layers.

drift. Any deposit in the glaciated area originating as a result of continental glaciation, including both stratified and unstratified deposits.

end moraine. Debris heaped in the form of a belt of hills at the margin of a glacier. *Terminal moraines* are end moraines that mark the maximum extent of the ice during a major advance. End moraines that mark the margin of the ice after a slight readvance during the general shrinking of the ice sheet are called *recessional moraines.*

esker. A ridge of gravel deposited by a subglacial stream flowing in an ice tunnel.

floodplain. The flat surface marginal to a stream which is flooded during the high stages of the stream.

gabbro. A dark-colored, coarse, crystalline rock.

glacial quarrying. The process whereby a glacier removes large blocks of bedrock, possibly through the process of melting and refreezing of water in joints.

granite. A light-colored crystalline rock containing quartz and feldspar.

Great Ice Age. See Pleistocene.

ground water. Water below the surface of the ground which completely fills the voids of the bedrock and drift.

ground-water level (water table). The level below which the bedrock or drift is saturated with water. Usually a subdued replica of the surface topography.

ground moraine. Debris deposited underneath the glacier directly by the ice.

hydrology. An earth science dealing with the occurrence and movement of water upon and beneath the land areas of the earth.

ice-contact deposit. Material deposited by meltwater streams near or at the margin of a glacier. The side of the deposit nearest the glacier rests against the ice which, when melted, allows the deposit to slump, an *ice-contact slope* thus being formed.

ice rampart. A ridge of debris on land lying roughly parallel to the shore line formed by ice push or ice jamming.

joints. Planes of parting in a rock mass. Commonly vertical.

kettle. Any closed depression in drift. May or may not contain water.

kettle rim. A rim of outwash or boulders around a kettle that formed from the melting of a partially buried ice-mass in drift.

knob and kettle. Characteristic topography of end moraines, consisting of a belt of irregular hills and depressions.

limnology. The study of both the physical and biological conditions of freshwater bodies.

marl. A soft, earthy material composed largely of calcium carbonate.

meander. A curved or crescent-shaped segment of a river.

mica schist. A foliated rock in which the chief mineral is mica.

moraine. Unconsolidated debris deposited chiefly by glacial ice. *See also* end moraine, ground moraine, and ablation moraine.

morainic system. A wide belt of closely spaced end moraines.

natural levee. A ridge of stream-deposited material formed during flood stage and lying parallel to the river banks, separating the stream channel from the floodplain proper.

outwash. Sorted and stratified material laid down by glacial meltwater streams. Commonly composed of sand and gravel.

perched ground-water table. The upper level of a zone of ground water which lies above the general water table owing to an impervious barrier that prevents downward movement of the water.

plankton. Floating or weakly swimming animal and plant life, usually inhabiting the surface zone of a body of water.

Pleistocene (Great Ice Age). A recent geological epoch of about one million years' duration, during which time continental glaciers waxed and waned in North America, Eurasia, and Patagonia.

proglacial lake. A body of water lying adjacent to a glacier. The ice front itself forms a segment of the shore.

subaqueous terrace. The underwater depositional terrace roughly parallel to the lake shore, extending from the water's edge to the edge of the "drop off."

swash. The movement of water up the slope of a beach.

swell and swale. The characteristic topography of uneroded ground moraine.

till. Unstratified and unsorted glacial drift deposited directly by the glacier.

transpiration. The process by which water vapor escapes from a living plant to the atmosphere.

wave current. The movement of lake water resulting from waves striking a shallow near-shore area.

wave-cut cliff. An escarpment formed by wave erosion on a steeply dipping shore.

wave-cut terrace. A wave-planed surface between the base of a *wave-cut cliff* and the water's edge.

wave front. A line marking the crest of a single wave as it approaches the shore of a lake.

wave height. The difference in elevation from trough to crest of a single wave.

wave length. The distance from crest to crest or trough to trough between any two consecutive waves.

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