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Origin and Developmental History of Minnesota Lakes

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ABSTRACT—Most lakes in Minnesota owe their origin directly or indirectly to glacial deposition or erosion 10,000 to 20,000 years ago. The lakes' shapes have since been modified by waves and currents near the shores and by the deposition of sediment off-shore—principally the sediment produced by growth of algae and other organisms. This sediment is a receptacle for pollen grains blown into the lake from the surrounding vegetation, and the stratigraphic succession of pollen grains records the postglacial vegetational and thus climatic history of the area. The sediment also preserves the fossils of microorganisms that reveal by their chemical composition the record of past changes in salinity, which in turn is related to water levels and thus to climate. Knowledge of the natural prehistoric processes in lakes and landscapes as recorded in lake sediments provide a perspective for evaluating the effects of modern land use and pollution on the chemical and biological processes in lakes, and it may assist in plans for improving their water quality and management.

Introduction

Any map that emphasizes the distribution of surface waters of the United States shows immediately three major areas with abundant lakes — the limestone sink holes of Florida, the structural basins of the Southwest, and the glaciated landscapes of the northern part of the country. Minnesota lies in the heart of the area that was covered by the last ice sheet about 10,000 to 20,000 years ago. This is recent enough that most of the depressions left by the ice sheet are still occupied by lakes or wetlands. By contrast, in areas glaciated at earlier times (such as the northern edges of Kansas and Nebraska and the southeast and southwest corners of Minnesota and adjacent Iowa), the original lakes have been filled with sediment or have been drained by erosion of the outlets. This review (1) summarizes the geological origins and modifications of those Minnesota lakes that are directly or indirectly related to the last glaciation; (2) discusses the paleoenvironmental reconstructions that can be made from analysis of lake sediments, and (3) comments on the effects of human disturbance of lakes and lake catchments.

Formation of Glacial Lakes

The lakes in Minnesota are distributed in distinct bands, which reflect the glacial history (Figure 1). The broad arcuate band east of the Red River and the Minnesota River marks the location of the Alexandria moraine complex, formed by ice from the northeast and later overridden by ice from the west. A smaller and less distinct band extends westward from the St. Croix River area and thence northward west of a parallel to the Mississippi River; this marks the St. Croix moraine, formed by a different ice lobe spreading from the Lake Superior basin (1). Terminal moraines are formed when an ice lobe maintains a stationary position for many hundreds or even thousands of years during a period of stable climate, as the continued ice flow piles up rock debris eroded from the substratum and deposited at the terminus when the ice melts. Each lake depression represents a so-called ice block, or more accurately a section of the glacier ice that contained relatively little rock debris, in contrast to the adjacent sections of debris-loaded ice that produced the hills surrounding the depressions (Figure 2). Lake Minnetonka west of Minneapolis, for example, is a complex of morainic depressions joined together by a high groundwater table.

Many lakes are located on sandplains where patches of debris-free ice ("ice blocks") were buried by glacial meltwater sediments (outwash) and even forests (2). Some of the largest lakes in the state are of this nature, e.g. Lake Winnibigoshish, Leech Lake, and the cluster of large lakes on the broad sandplains north of Brainerd (Figure 1).

With climatic warming the terminus of the active ice retreated from the ice-cored or "dead-ice" moraine. As the buried ice gradually melted out — and this phase may have lasted additional thousands of years — hummocky topography resulted, as unstable slopes over the melting ice caused shifting of the rock debris. Initial lakes within the moraine were partially filled with sediment washed in by superglacial streams, and when the ice walls melted and the lakes were drained, the sediment remained as a flat plateau surrounded by steep slopes leading down to a dead-ice landscape — an example of topographic reversal. The airfield east of White Bear Lake is located on such an ice-walled lake plain.

Other types of glacial lakes are common in Minnesota. Lake Mille Lacs in the center of the state is located behind (east of) a prominent arcuate moraine (Figure 1). Many small lakes are not associated with distinct moraines, however, but rather just result from irregular deposition of glacial sediment back from the terminus. Strings of lakes can be found in "tunnel valleys", which were formed by high-velocity subglacial streams. When the ice thinned and the water velocity decreased, some of the stream sediment was locally deposited in the tunnel valley, providing a series of depressions between the deposits.

In addition to lakes associated with glacial deposition, others are related to glacial erosion. The Lake Superior basin

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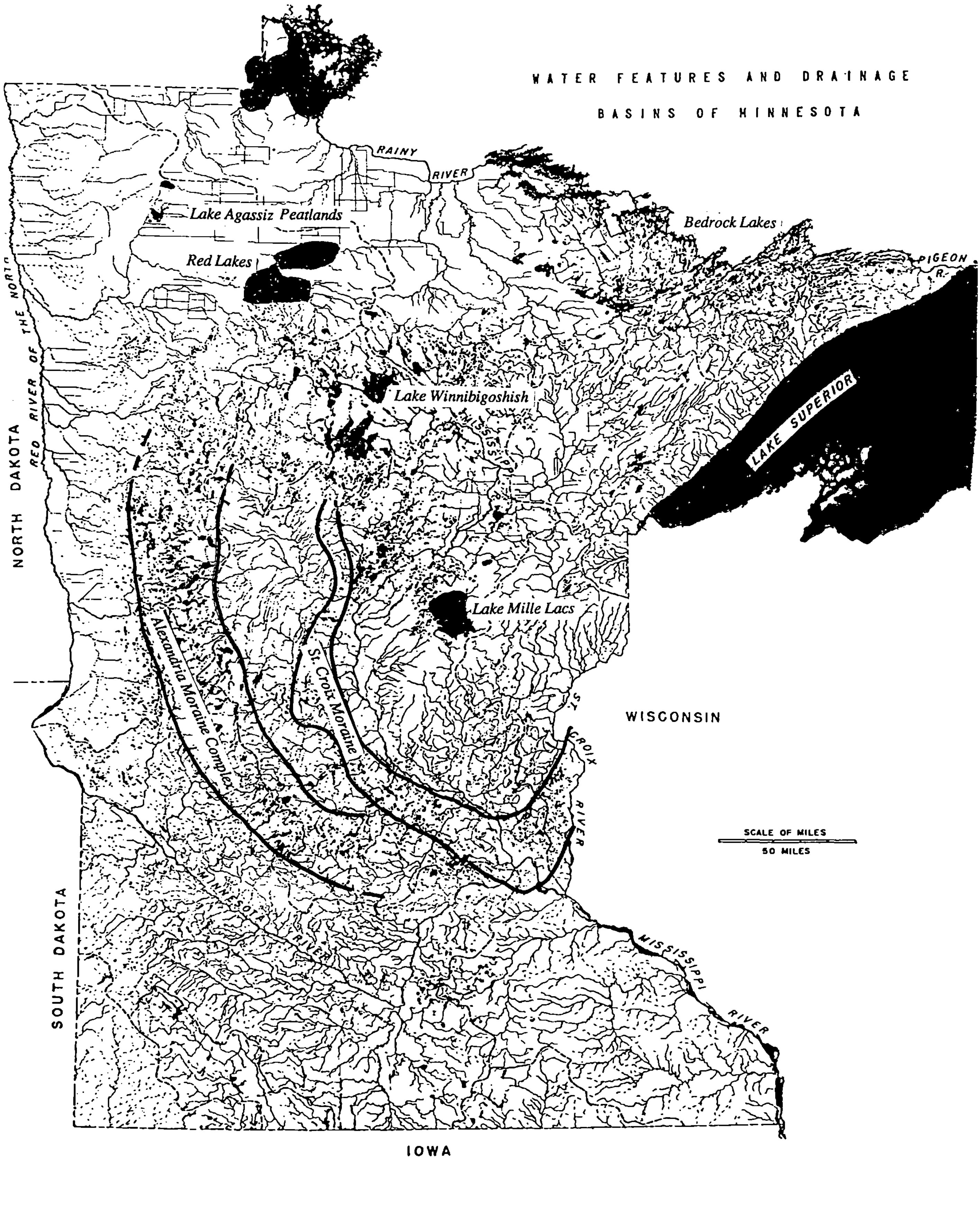

Figure 1. Map showing how the lakes of Minnesota are related to major glacial features.

The Distribution of Minnesota Fishes and Late Pleistocene Glaciation

JAMES C. UNDERHILL

Introduction

The fishes of Minnesota have been the focus of research for almost a century beginning with the pioneer ichthyologists Ulysses O. Cox (1, 2), Alfred Woolman (3) and with more recent contributions by Thaddeus Surber (4), Samuel Eddy (5) and many others (6, 7, 8, 9). At present the ichthyofauna totals 153 species belonging to 19 families, including 13 species which have been introduced (Table 1). The origin of and the migration routes followed by various species have been of interest for over a half century (10). Minnesota was covered by glacial ice up until at least late Wisconsinan time (11). Species that migrated into the state from the periglacial region could have been derived from three refugia; unglaciated Alaska, the Atlantic refugium, and/or the lower Mississippi River refugium. The routes followed in their dispersal were dependent on drainage connections that existed during late Pleistocene and early Holocene time.

Late Pleistocene and Holocene History

Minnesota is unusual in that its waters drain by three widely divergent courses; 57 percent via the Mississippi River to the Gulf of Mexico, 35 percent via the Red River, Rainy River and Lake of the Woods to Hudson Bay, and 8 percent to the Lake Superior basin to the Gulf of St. Lawrence.

The Mississippi drainage can be subdivided into five subbasins: (1) the upper Mississippi basin, from the headwaters at Lake Itasca to St. Anthony Falls at Minneapolis; (2) the lower Mississippi basin, southward to the Iowa boundary, including the Cedar River of southeastern Minnesota and the Des Moines River of southwestern Minnesota; (3) the St. Croix basin, from the headwaters of the Snake and Kettle River in Minnesota and the St.Croix River in northwestern Wisconsin, to the Mississippi River near Hastings, Minnesota; (4) the Minnesota basin, from the source of the Little Minnesota River, northeastern South Dakota and Big Stone Lake to the mouth of the Minnesota River at Fort Snelling, and (5) the Missouri basin, 1348 km² in Minnesota, comprising a few small streams in southwestern Minnesota which drain through Iowa and South Dakota to the Missouri River.

The upper Mississippi River rises in Lake Itasca in southern Clearwater County. It flows northeasterly and then in an almost complete circle to the mouth of the Crow Wing River; at this point it is only 121 km from its source, but the distance by river is almost 563 km. From the mouth of the Crow Wing River, the Mississippi flows southeastward to Minneapolis; St. Anthony Falls at Minneapolis is here considered the lower boundary of the upper Mississippi River basin.

The lower Mississippi River flows southward below St. Anthony Falls and is joined by the Minnesota River at Fort Snelling and the St. Croix River near Hastings, Minnesota. The Cedar River, an important tributary to the Mississippi River in Iowa, drains 3120 km² in Freeborn, Mower, and parts of Faribault, Fillmore, Dodge, and Steele counties in southeastern Minnesota. The Des Moines River, another important tributary to the Mississippi River in Iowa, drains 3940 km² in seven counties in southwestern Minnesota.

The Hudson Bay drainage comprises the Rainy River system, which connects Rainy Lake and Lake of the Woods, and the succession of lakes about Rainy River, the Boundary Waters, which drain northward in Manitoba through English-Winnipeg river system to the south end of Lake Winnipeg. The area drained in Minnesota is about 29,267 km².

The Red River, while draining into Lake Winnipeg and Hudson Bay, is considered a separate basin. It has its headwaters in Jim Creek, a tributary to Lake Traverse in Roberts County, northeastern South Dakota, and flows northward for a distance of 314 km to the International Boundary. From the boundary, it flows northward approximately 240 km to Lake Winnipeg, Manitoba, Canada. The entire basin lies within the Glacial Lake Agassiz basin. It drains a total of 88,100 km² in Minnesota.

The St. Louis River is the largest tributary to Lake Superior draining 4,400 km² in Carleton, Lake, St. Louis, Aitken, and Itasca Counties. The Pigeon River, which forms a portion of the International Boundary, drains a total area of 1620 km² and is the second largest stream in the basin.

Glaciation has had a profound effect on Minnesota and its ichthyofauna; events in the late Pleistocene and Holocene have determined in large part the distribution of fishes within the drainage systems of the state. All of Minnesota was glaciated at some time and as recently as 14,000 years ago the Des Moines Lobe of Wisconsinan ice occupied all but the southwestern and southeastern corners of the state (11). Therefore all of the drainage systems, except the Mississippi River below St. Paul and melt water streams of the southwest, were covered by ice. Ice also filled the Lake Superior basin and the high ground to the north. The eastern margin of the Des Moines Lobe was controlled by a moraine of earlier date, but in the region of Minneapolis the ice overrode the retaining St. Croix moraine to form the Grantsburg Sublobe (12). The Grantsburg Sublobe, at its maximum, extended northeastward to Grantsburg, Wisconsin, across the bed of the present St. Croix River. This sublobe completely blocked the upper Mississippi channel and diverted its flow to the northeast around the tip of the ice. Water impounded by the ice formed a large shallow lake known as Lake Grantsburg.

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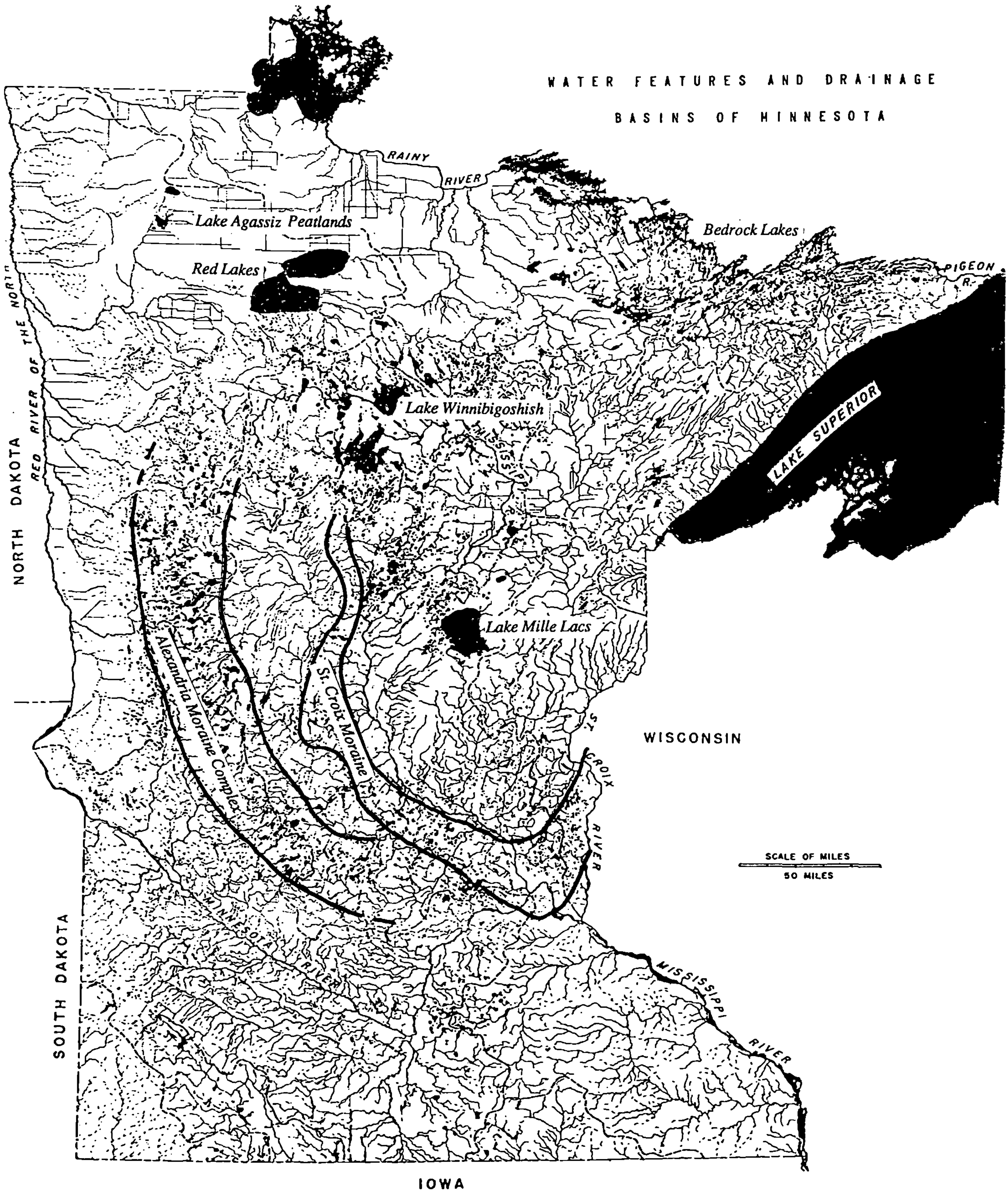

Figure 1. Map showing how the lakes of Minnesota are related to major glacial features.

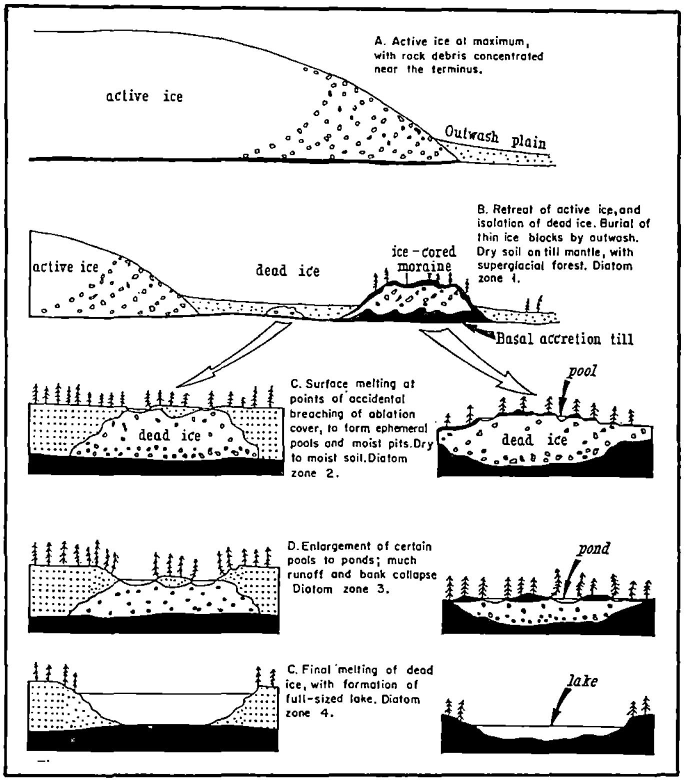

Figure 2. Diagrams showing how ice-block lakes are formed in moraines and outwash plains. The diatom zones mentioned record changing depth and limnological conditions in the superglacial pond and subsequent lake at the site of Kirchner Marsh in the St. Croix moraine south of St.Paul (2).

is a preglacial stream valley greatly overdeepened by repeated glaciation by a major ice lobe that removed perhaps 300 m of rock from the floor over the last million years or so. Smaller examples are the many interconnected lakes of the Boundary Waters Canoe Area in northeastern Minnesota, whose shapes reflect the differential resistance of the rock formations and thus their stratigraphy and structure (Figure 1).

The geological classification of the glacial lakes of Minnesota was established by Zumberge (3), whose scheme was adopted in the definitive treatise by Hutchinson (4) on the physical and chemical characteristics of lakes. Zumberge also described the few nonglacial lakes in Minnesota, the most prominent of which are long river lakes, which, however, are indirectly related to glaciation. Specifically, Lake Pepin was formed in the deep valley cut by the Glacial River Warren, which served as the outlet of Glacial Lake Agassiz. When this outlet was abandoned about 9500 years ago, the descendant Minnesota/Mississippi River could no longer transport the sand brought by the tributary Chippewa River, which deposited a dam across the deep valley to form Lake Pepin (5). Farther upstream Lac Qui Parle, Big Stone Lake, and Lake Traverse were formed in the same way. Lake St. Croix is a secondary result of this process, for the delta of the Mississippi River, at the head of the originally much longer Lake Pepin, deposited a bar across the mouth of the St. Croix River as the delta advanced downstream.

Lakeshore Modification

Once the glacial ice finally melted from the area around each lake basin, the depressions became filled with water, depending on the configuration of the groundwater table, for the lake surfaces are basically outcrops of the water table. On sandplains the lakes tend to have similar elevations, because of the high permeability of the sand and the flatness of the water table. But in moraines the lakes may have highly variable levels, for different patterns of groundwater flow are controlled by variable permeabilities of the morainic sediments.

Once the postglacial water levels in lakes were established, the geological processes of erosion and deposition began. The most conspicuous results of these processes were the modification of shorelines. Irregular headlands were eroded, and the resulting sediment was shifted laterally to form bars across embayments, some of which have been cut off to form separate lakes. The overall tendency was to smooth out the shorelines (Figure 3). The erosional work is done by waves which, when approaching the shore obliquely, carry sand and gravel along the shore to build beaches. At the same time the undertow of strong waves can carry the sediment offshore, sometimes into deep water in large lakes with strong waves.

Lake Sedimentation

Meanwhile the lake floor receives sediment from two principal sources. Entering streams may construct deltas of coarse sediment at the point of entrance. Excellent examples of such deltas can be seen in Lake St. Croix, which is segmented into a series of sub-basins by deltas deposited by streams especially from the Wisconsin side. In addition, organic production within the lake water generates the fine organic ooze that accumulates in the deeper parts of the lake, where water currents are minimal. An average Minnesota lake contains 9-12 m of such organic sediment in its deeper parts. The sediment in small, deep lakes located in regions of high forest may be annually laminated, because the sheltered setting prevents the circulation of oxygen-bearing water to the base, inhibiting the growth of bottom-dwelling organisms that otherwise homogenize the annual layers. Such layers (varves) are of great value in permitting a precise chronology of sedimentation to be determined, so that rates of change can be calculated, and even the seasonal changes in lake sedimentation and thus lake processes can be detected. In a study of three small lakes in Itasca State Park, the thickness of the varves varied in a systematic and consistent way, permitting correlation with the weather record of the past 150 years for Minnesota, and suggesting that a drop in lake levels during dry periods (such as the 1930s and 1950s) caused increased shore erosion and influx of mineral sediment to the lake (Figure 4). The dry periods were also times of increased frequency of forest fires, as recorded not only by fire scars on the rings of living trees but by the frequency of charcoal fragments in the varved lake sediments (6).

Landscape History

The postglacial deposition of sediments in Minnesota lakes generally started 13,000 to 10,000 years ago, depending on the location and the persistence of buried ice. The detailed history of the lakes since that time is best recorded by the microfossils and chemical constituents of the sediments, along with the mineral sediment derived from shore erosion or from inflowing streams. This history reveals patterns of environmental change that reflect regional climatic trends and their effects on vegetation, water levels, and lake processes.

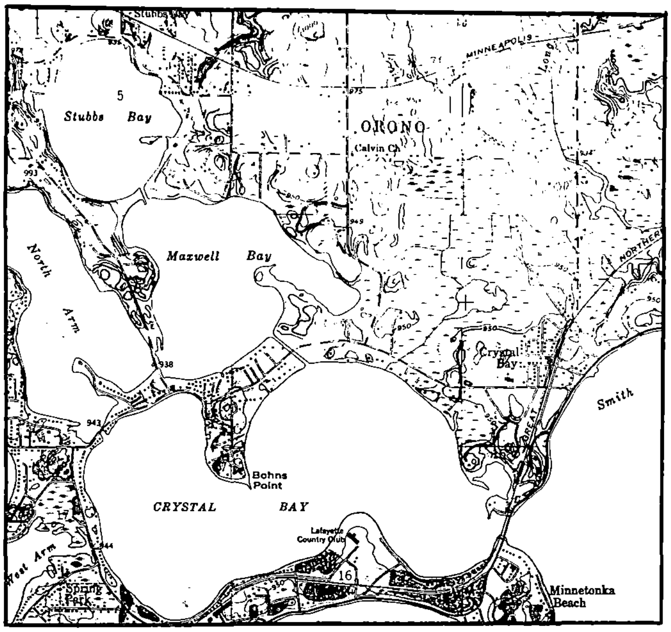

Figure 3. Smooth-sided bays of Lake Minnetonka, west of Minneapolis, closed off in part by the wetlands. Excelsior topographic map, U.S. Geol. Survey.

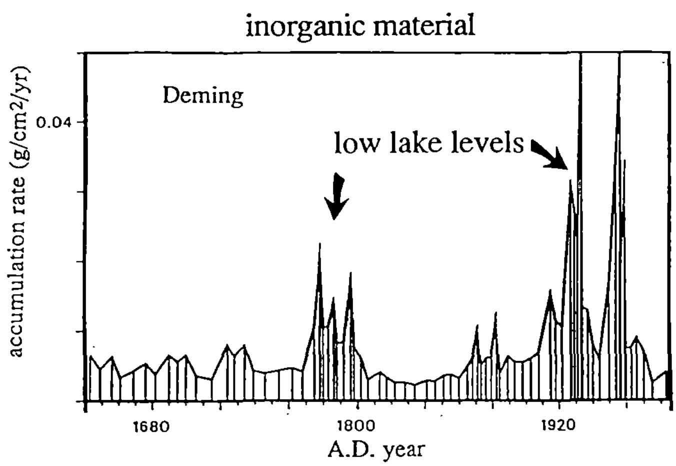

Figure 4. Thickness of annual laminations of lake sediment (varves) at Deming Lake in Itasca State Park (6) as a record of shore erosion at times of low lake level and thus of relatively dry climate (e.g. 1930s, 1880s, and 1790s).

Lake-level changes documented by historical observations illustrate how sensitive the lakes are to the basic climatic variables of precipitation and temperature (as it controls evaporation). The effects are particularly noticeable in closed-basin lakes, which have no outlets, and in lakes in the western part of Minnesota, where the balance between precipitation and evaporation is nearly even.

This history of lake level change can be followed in various ways. The mineral sediment in a lake is confined largely to shallow water, which is also the area of littoral emergent vegetation (reeds, waterlilies, etc.). When the lake level is depressed because of a change in water balance, the littoral zone moves out into the basin, and the mineral sediment and the macrofossils of the littoral vegetation (seeds, leaves, etc.) are deposited there. When the water level rises again these materials are buried by the deeper-water organic ooze. A core through the lake sediments may therefore reveal layers recording times of low lake levels, and the time can be determined by radiocarbon dating of the organic sediment.

The first study revealing such water-level changes was undertaken at Kirchner Marsh, located in the moraine south of St. Paul. The marsh had been a lake until about 1700 years ago, and a core of sediments 12 m long showed by pollen analysis that the early succession of regional vegetation from tundra to spruce forest to pine forest to oak/elm forest was followed about 8500 to 5000 years ago by prairie with oak groves (7). Analysis of the plant macrofossils in the sediment indicated several intervals, spaced a few hundred years apart, when the lake repeatedly dried up, allowing the colonization by weedy wet-ground annual plants. Frequent but temporary rises in the lake level prevented the succession to perennial plants. These intervals of repeated drying alternated with long-lasting intervals of high lake levels, when remains of submerged aquatic plants were deposited in the sediment.

A study in west-central Minnesota shows that, about 8000 years ago, the water level on sandplain lakes was as much as 6 m lower than today (8). A groundwater model for the sandplain suggested that the change could have resulted from a decrease in recharge of about 40 percent combined with a slight increase in evaporation minus precipitation. These results are consistent with the evidence from the pollen analysis of lake sediments that the upland vegetation changed from forest to prairie about this time. The two lines of evidence indicate a climatic change to warmer and/or drier conditions. Pollen studies elsewhere in Minnesota imply that the border of forest and prairie was shifted eastward at least 150 km at this time, even into southwestern Wisconsin (9). With the reversal of the climatic trend about 5000 years ago, the lake levels rose again, and in northern Minnesota the great peatlands began to develop on the flat glacial-lake plains, which previously had been forested or were wet meadows subject to frequent drying, so that peat accumulation was inhibited. Sandplains in west-central Minnesota that had previously been dry prairies developed peatlands in their shallow depressions, and these served as fire breaks for the spread of the very common prairie fires that had kept down the spread of shrubs from the forest edge. The result was the colonization of the prairie plains by shrubs and then by jackpine.

Farther west in the prairie regions of today the past climatic changes resulted not only in a lowering of lake levels but also in an increase in salinity. This is detectable by analysis of diatoms, which are siliceous algae sensitive to water chemistry. Past changes in water chemistry are also demonstrated by analysis of the calcium/magnesium ratios in ostracod shells buried in the sediment deposited in Devils Lake in North Dakota during the last hundred years, when the ratios faithfully reflect the changes in water salinity as recorded by periodic analyses of water samples. Extension of diatom and ostracod analyses to depth in sediment cores from Devils Lake by S.C. Fritz and D.R. Engstrom reveals numerous fluctuations during the past 10,000 years since the lake initially changed from a deep freshwater lake to the brackish/saline conditions of subsequent time.

Lake Modification Resulting from Human Disturbance

The generally gradual postglacial changes in Minnesota's natural vegetation, landforms, and lakes, controlled primarily by climate, were abruptly altered in the 19th century as the land was cleared for agriculture, forests were cut for lumber, soils were eroded by intensive cultivation, and lakes were polluted by nutrient influx from residential, commercial, or agricultural sources. The timing of the changes as recorded in lake sediments can be calibrated by radiometric dating by the lead-210 method or by the identification of the level at which a sharp increase occurs in the pollen of ragweed and other plants of agricultural soil disturbance (for example, the exotic Russian thistle in the prairie areas).

The changes occurred principally after the Civil War, as agriculture expanded from southern Minnesota to the Red River Valley, which was opened for development late in the 1800s, when the clay soils were drained and when the railroad companies promoted homestead settlement to enhance the shipment of grains. Timber cutting in the virgin forests of white and red pine simultaneously expanded to northern Minnesota, until it was slowed by the Depression and by the diversion of labor during World War II, and then by the protection afforded by wilderness designation. But the water quality in lakes was modified most conspicuously by influx of compounds of phosphorus, nitrogen, and other nutrients that promote algal growth and result in changes in water clarity and in the food chain, including the types of fish. Nutrient sources include outseepage from residential septic tanks, effluents from sewage-treatment plants, runoff from fertilized lawns, farm fields, feedlots, and city streets, and discharges from all kinds of commercial and industrial operations. Although efforts have increased to identify and modify the inputs of nutrients and accompanying toxic substances (e.g. metals, pesticides), few lakes in the state have been spared the deleterious side effects of modern civilization. Even those far removed from local pollution sources are potentially subject to far-travelled atmospheric contaminants like mercury and lead derived from combustion of fossil fuels.

Procedures for rehabilitating lakes that have been affected by human action involve first determining the lake condition prior to such modifications. This can rarely be done directly with historical observations, for the anecdotes of early settlers or long-time fishermen may not be reliable. More objective is the stratigraphic analysis of the lake sediment by some of the approaches described above. Thus lake acidity, water clarity, and algal productivity can be inferred from analysis of diatoms and pigments, soil erosion by the proportion of inorganic and organic matter, and metal content by chemical analysis. Some lakes have naturally high levels of nutrients, and other lakes have tea-colored water resulting from the runoff from peatlands or conifer forests. Studies of the water chemistry and diatom populations of Minnesota lakes, for example, show a distinct gradient from northeast to southwest, related to a combination of climate, vegetation, and geology. Thus it is not feasible to try to make a clear-water trout lake out of a polluted lake that had a relatively high nutrient content before disturbance, such as the prairie lakes of western Minnesota (Heiskary and Wilson, this issue).

Lake management can influence water quality, even though a pristine condition as identified by stratigraphic studies might not be attained. But it must be acknowledged that some management techniques are ineffectual, although they are still commonly practiced. One is the application of herbicides like copper sulfate to reduce algal blooms. Such a treatment has only a temporary effect, and it must be repeated frequently. The same goes for the liming of lakes that have been acidified by sulfate in polluted air. Although Minnesota lakes are not strongly affected by acid rain, the method of liming as applied elsewhere has only a temporary effect on acidity and is likely to modify other chemical and biological processes in the lake.

Another temporary measure involves removing the growth of littoral macrophytes by a dredging operation — and this involves the additional problem of disposal of the harvest. An even more severe route is to dredge out the upper part of the soft organic sediment from the entire lake, with the idea that the phosphorus that had been concentrated in these bottom sediments during previous times of severe pollution might have been released to the water by re-solution.

But a more effective long-range strategy in management is to reduce the inputs of nutrients from the drainage basin, both from point sources like sewage effluents or diffuse sources like runoff from fertilized farm fields. An additional strategy is to manipulate the food chain that is based on the nutrient supply — the food chain from algae and other plants to zooplankton to planktivorous fish to the piscivorous fish that may be the most desirable end product in a recreational lake. But decisions are more difficult for particular lakes in cases where nutrient inputs cannot be effectively reduced. For example, it may not be possible to eliminate the blooms of blue-green algae that decrease water clarity and at the same time to reduce the growth of emergent and submerged vegetation that is often considered undesirable in nearshore areas, for the nutrients must be taken up by plants somewhere in the lake.

Conclusions

A geologic and historic context can provide a background for understanding the natural physical, chemical, and biological processes in a lake and the manner in which they have been modified or can be modified by accidental or intentional human interference. Lake sediments are an archive of past events—virtually the only archive in Minnesota suitable for detailed reconstruction of environmental changes covering the past 10,000 to 15,000 years. They are particularly valuable because the radiometric dating of lake sediments provides a valuable chronology. The demonstration through pollen analysis, diatom analysis, and sediment chemistry that the mid-postglacial period was significantly warmer and drier than today is the foundation for testing numerical models of past climate and in turn for providing a possible analogue for the environmental conditions of the 21st century under the influence of the global warming that is predicted as a manifestation of the greenhouse effect. On the local scene, this analogue with its climatic implications may be adapted to predict the distribution and productivity of agricultural crops and timber resources. Because the Minnesota area has been so sensitive in the past to climatic, vegetational, and hydrologic changes and has the archives as demonstrations, it holds a unique position as a study area for both the past and the future.

Acknowledgements

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