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Glacial and Vegetational History of Northeastern Minnesota

H. E. Wright, Jr. and William A. Watts
with contributions by Saskia Jelgersma,
Jean C. B. Waddington, Junko Ogawa,
and T. C. Winter

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CONTENTS

ILLUSTRATIONS

Plates

(In pocket of inside back cover)

TABLES

GLACIAL AND VEGETATIONAL HISTORY OF NORTHEASTERN MINNESOTA[1]

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ABSTRACT

The broad relief features of the northern Minnesota bedrock permitted the digitation of the margin of the Wisconsin ice sheet into several lobes, and the diversity of the bedrock lithology resulted in the drift of each lobe being of different color, texture, and stone content. Moraines, drumlins, outwash plains, proglacial lake plains, diversion channels, and other glacial features provide the opportunity to check the contemporaneity of the advances of different ice lobes—or lack of it.

Of the four ice lobes identified for the Minnesota area, three affected the northeast. The Superior Lobe moved out of the Lake Superior basin. The Rainy Lobe advanced across the upland north of the Lake Superior basin, and the St. Louis Sublobe of the Des Moines Lobe came from far to the west and almost reached the head of the Lake Superior basin.

Four phases of ice movement can be delineated for northeastern Minnesota. In the St. Croix phase, the Superior and Rainy lobes together covered most of the eastern half of the state, forming extensive drumlin fields and terminating at the St. Croix Moraine. During wastage, a great series of southwest-trending tunnel valleys was cut through the drift by subglacial meltwater under hydrostatic pressure, and many were later partially filled with eskers. The Superior Lobe then retreated barely into the Lake Superior basin, and the Rainy Lobe withdrew to near the Canadian border. In the Automba phase that followed, the Rainy Lobe advanced slightly on the upland and formed the Vermilion Moraine. The Superior Lobe expanded out of the Lake Superior basin with configuration different from before, because it was not impeded this time by the Rainy Lobe on its right flank. It sent a long tongue southwestward as far as the Mille Lacs Moraine in the center of the state, and it built the Highland Moraine at the crest of the slope leading up from the north shore of Lake Superior. It also formed drumlins and fluted terrain in its progress toward its terminal moraines. Glacial Lakes Upham I and Aitkin I were dammed on the north side of this long finger of ice.

The Superior Lobe then retreated farther into the Lake Superior basin, and a glacial lake in front of the ice received red clayey sediment from the wasting ice. When the ice readvanced once again in a narrow tongue during the Split Rock phase, it incorporated the

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[1] Contribution No. 86, Limnological Research Center, University of Minnesota.

lake sediments and produced a red clayey till, which formed a veneer over the older glacial landforms.

Once again the Superior Lobe retreated into the basin, and then it readvanced a still shorter distance than before—to the Nickerson Moraine, made of more red clayey till. Meanwhile, the St. Louis Sublobe extended eastward from the Des Moines Lobe, overrode the silty deposits of Glacial Lakes Upham I and Aitkin I, and reached within 25 miles of the Lake Superior basin.

The Superior and St. Louis lobes then began their retreat together. Glacial Lake Upham II formed in front of the retreating St. Louis Sublobe, and its discharge eastward down the newly formed St. Louis River was blocked by the slowly retreating Superior Lobe and diverted southward to the Moose River and ultimately to the St. Croix. Four diversion channels at successively lower elevations can be identified. Finally, with further ice retreat, the St. Louis River entered Glacial Lake Nemadji and then, when the Superior Lobe retreated still more to uncover lower outlets in Wisconsin, the river drained into Glacial Lake Duluth.

During these several epochs of ice-margin fluctuation, which occurred between about 16,000 and 12,000 years ago, the exposed terrain was covered with tundra vegetation, as shown by pollen and plant-macrofossil analyses of the sediment at several lake sites north and west of Lake Superior. The pollen stratigraphy has few features that can be correlated with ice-margin fluctuations, however. Either pollen analysis is not a subtle enough technique to reveal climatically induced vegetational changes in a tundra environment, or the vegetation itself did not respond significantly to climatic change, or the ice-margin fluctuations were caused by some factor not directly or immediately related to climatic change.

The spruce forest that covered much of central and southern Minnesota during the time of Wisconsin ice retreat spread to northeastern Minnesota. It replaced the tundra west of the head of Lake Superior about 11,500 years ago, but it moved northward slowly, reaching Weber Lake, about 70 miles farther northeast, 10,000 years ago. Meanwhile the spruce forest in the south was replaced by birch and alder about 11,000 years ago and then abruptly by jack or red pine, which entered the state from the east in very great numbers about 10,500 years ago. The pine spread rapidly northward, but its dominance in the newly established spruce forest developed much more slowly, and it was not until about 7200 years ago that the spruce forest was completely gone. Meanwhile, alder spread abruptly in the area about 9000 years ago, and oak spread up from the south about 8500 years ago. At about the same time, white pine invaded in quantity from the east. By 7000 years ago even prairie openings occurred in the region.

Reversal of the climatic trend initiated withdrawal of prairie herbs and oak from northeastern Minnesota, and the westward expansion first of white pine, spruce, and larch, and later of red pine and jack pine. Lakes that had previously been intermittently dry (as indicated by macrofossils) became permanent again, and as the lakes became filled with sediment they developed a margin of marsh or bog in the shallow water, and many lakes became converted completely to wetlands.

The changing composition of the forest cover since deglaciation was caused basically by a climatic change to warmer and drier conditions and then the reverse. But the effects were not instantaneous: differential rates of migration of major tree types from

Pleistocene refuges resulted in successive arrivals of potential dominants, so that the forest was continually changing.

The additional factors of progressive leaching of the soil and paludification of lowlands added habitats that were not previously very extensive. These trends have continued to modern times, when lumbering, agriculture, and fire protection have interrupted the natural successions.

INTRODUCTION

The area west and northwest of the head of Lake Superior has had a complicated environmental history since the maximum of the last glaciation. The glacial history ultimately reflects the diversity of bedrock lithology and topography, and the vegetational history reflects the strong climatic gradient of the semi-humid continental interior.

The differential resistance to erosion of areas of bedrock of different lithology had resulted in the formation of lowlands and highlands in preglacial time; the lowlands channeled the lobes of ice that protruded from the continental glacier, especially when the ice was thinner during the waning phases of Wisconsin glaciation. The ice lobe in each lowland therefore produced a glacial drift of distinctive color, texture, and stone content, and the stratigraphic and topographic relations of the several drifts permit the sequence of glacial events to be worked out. The meltwaters of certain lobes were blocked by ice or moraines of other lobes at various times, producing proglacial lakes, spillways, diversion channels, and similar distinctive landforms, thereby permitting the correlation of ice advances of different lobes with one another even without the stratigraphic contact of the tills themselves.

The glacial history is therefore intricate but decipherable, and it provides an interesting lesson in the complexities of glacial action in a region of moderately diverse relief. The outlines of the history were established by Leverett (1932) but greatly modified in recent years by Wright (Farnham and others, 1964; Wright and Ruhe, 1965; Wright and others, 1969). The modifications have been abetted by availability of aerial photographs, which reveal subtle lineaments in the landforms barely visible in the dense forest; of newly completed topographic maps, which document the topographic patterns suggested on aerial photographs and which demonstrate how elevation controls the position of the ice margin and the location of meltwater drainage features; and of radiocarbon dates, which provide a chronological framework of suitable accuracy.

The vegetational history of northeastern Minnesota is equally complex, yet it can be reconstructed because the area is near enough to major vegetational boundaries so that the late- and postglacial shifts in vegetation in response to climatic change can be recorded by pollen and seed analyses. Also, the proximity of the area to the fluctuating late-Wisconsin ice lobes provides a setting for detecting possible periglacial effects on vegetation, as well as for tracing phases of vegetational succession.

The vegetational history was first sampled through pollen studies in the northeastern corner of the state by Potzger (1953), but much more detailed work has subsequently been completed by Fries (1962); McAndrews (Farnham and others, 1964), Baker (1965), Janssen (1968), and Wasylikowa and Wright (1969). The present paper offers pollen and seed diagrams from several new sites and summarizes the entire late-glacial and postglacial vegetational history of the area.

The geologic work has been supported largely by the Minnesota Geological Survey, the paleobotanical analyses by the Hill Family Foundation and the National Science Foundation (Grant GB-3814). The pollen analyses for Kotiranta Lake were made by Saskia Jelgersma, for Anderson Lake by Thomas C. Winter, for Glatsch Lake by Jean C. B. Waddington, and for Rossburg Bog by Jean Waddington and Junko Ogawa. Pollen counts of supplemental cores for radiocarbon samples and for differentiation of pine pollen types were made by Winter, Jean Waddington, and Junko Ogawa. Students and colleagues too numerous to mention have assisted in the lake-sediment coring operations, and many friends of the Pleistocene have tested the glacial history here presented.

GLACIAL HISTORY

Ice Lobes

The Wisconsin ice sheet followed lowlands in its advance through central North America, and from the Great Lakes region to the Dakotas it became digitated into several ice lobes, whose detailed directions of flow were determined by the lowland form and the ice thickness (figs. 1, 2). Within Minnesota the Lake Superior basin on the east and the Red River Valley on the west were the dominant lowlands, together with the modest Red Lakes lowland in the north-central part of the state. All of these affected the delimitation of ice lobes that invaded northeastern Minnesota.

The Superior Lobe moved west and southwest out of the Lake Superior basin at least four times during the Wisconsin glaciation. The Lake Superior bedrock basin, whose surface beneath glacial sediment and water is deeper than 1000 ft. below sea level (Wayne and Zumberge, 1965), must have been greatly deepened by glacial erosion; before glaciation it was a stream-cut lowland above the sea level of the day, probably draining eastward through the other Great Lakes lowlands. The Superior Lobe during the time of maximum Wisconsin glaciation extended southwestward across a bedrock divide near Sandstone in Pine County (about 1100 feet above sea level) into the Minneapolis basin (elevation about 800 feet).

The Superior Lobe in most of its area carried a till with a distinctive red color, derived from the comminuted particles of the late-Precambrian red sandstone and shale (fig. 3) that form the bedrock southwestward from Duluth and underlie most of the Lake Superior basin itself (White, 1966). Other rock types, derived largely from the North Shore of Lake Superior, are red and purple felsite as well as basalt, which includes a distinctive amygdaloidal form as well as the amygdaloidal agates themselves. Frag-

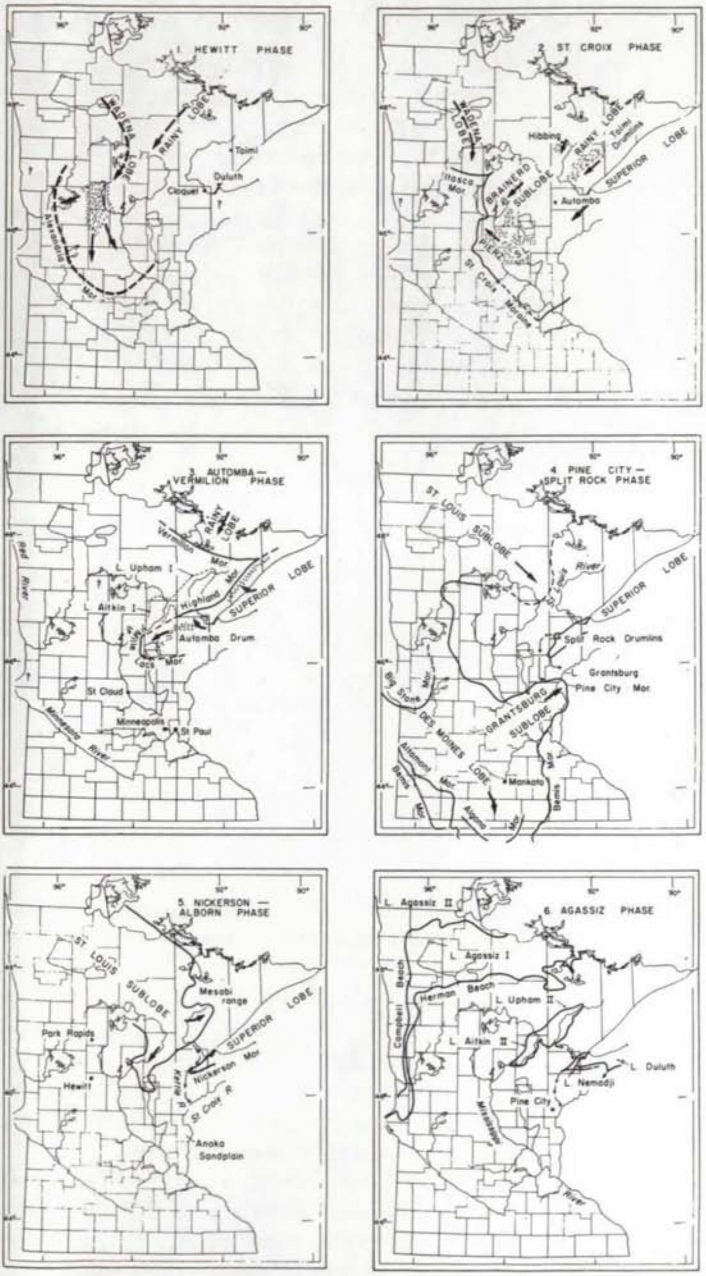


Figure 1. Maps of Minnesota showing extent of ice lobes during various phases of Wisconsin glaciation. Short dashes indicate drumlins.

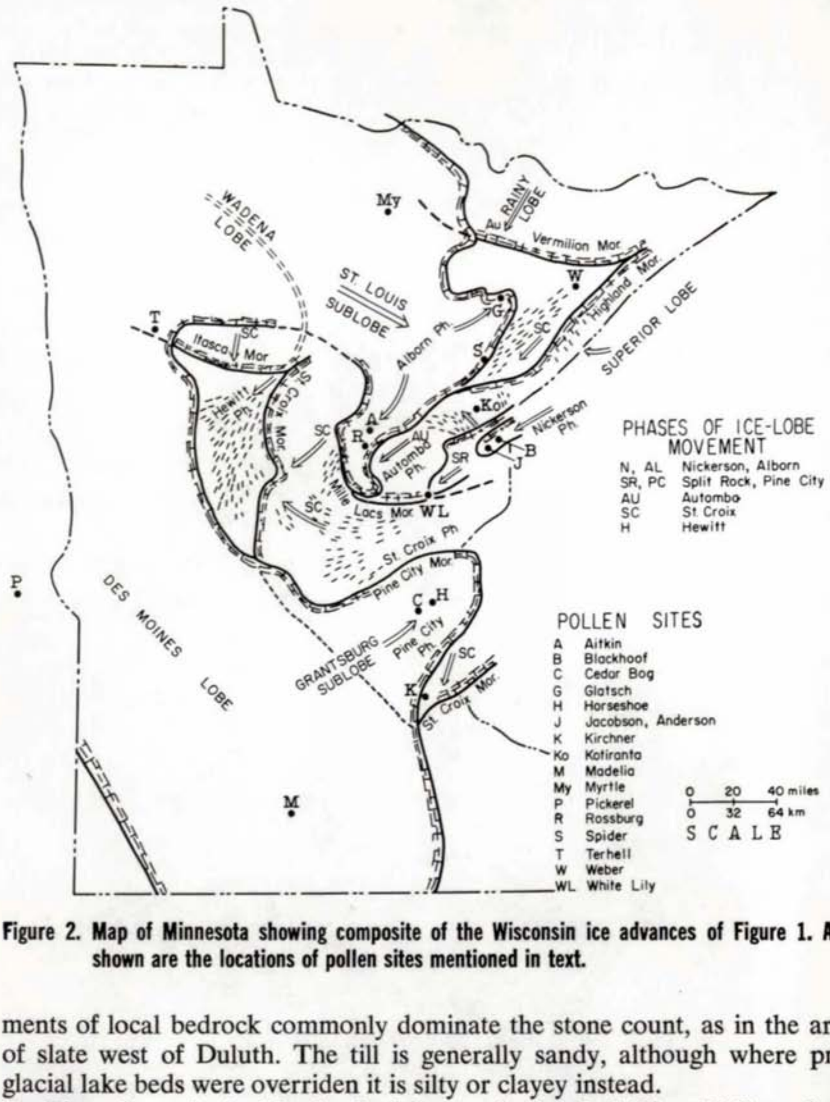


Figure 2. Map of Minnesota showing composite of the Wisconsin ice advances of Figure 1. Also shown are the locations of pollen sites mentioned in text.

ments of local bedrock commonly dominate the stone count, as in the area of slate west of Duluth. The till is generally sandy, although where proglacial lake beds were overriden it is silty or clayey instead.

The other principal lowland of the north, the Red River Valley, channeled the Des Moines Lobe southward to central Iowa from the Paleozoic carbonate terrane of Manitoba and the Cretaceous shale of northwestern Minnesota, and its St. Louis Sublobe protruded eastward across the Red Lakes Lowland almost to Lake Superior. Near its terminus this sublobe also carried reworked lake beds in part of its load, producing a calcareous till ranging in color from light brown to reddish brown. The till that is uncontaminated with lake beds has the typical silty light-brown character (gray where unoxidized) of its parent Des Moines Lobe; it is rich in fragments of Cretaceous shale as well as Paleozoic limestone and dolomite.

In the upland area between the Superior Lobe and the St. Louis Sublobe, advancing from the northeast across the Rainy River and the Mesabi Iron Range, was the Rainy Lobe. Its drift is gray to brown, non-calcareous, and sandy to stony, largely because of the high content of gabbro or other crystalline rocks from which most of it was derived.

The following account of the glacial history considers the successive advances of the different ice lobes and their relations to one another. The times of ice advance are informally termed phases, which have indefinite limits that can only locally be defined from stratigraphic or topographic evidence. Phases are named from conspicuous moraines, drumlins, or tills produced during the ice advances. The phase name from one ice lobe is carried to another where the correlation is reasonably certain (*e.g.*, St. Croix

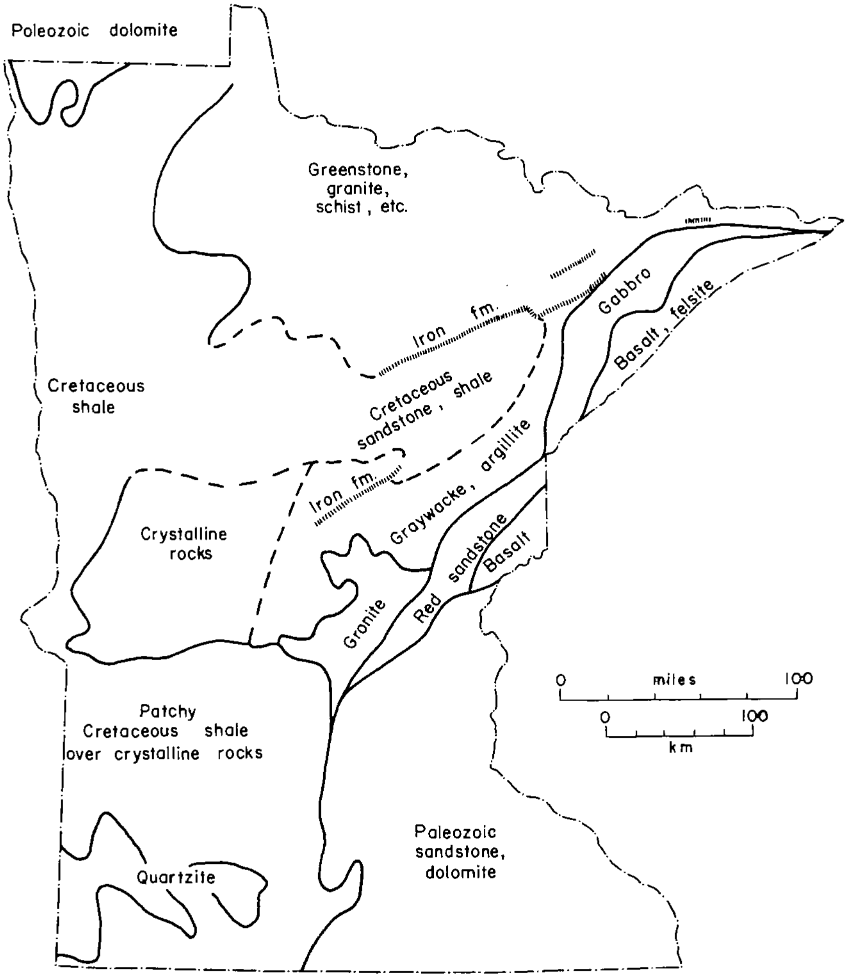


Figure 3. Bedrock map of Minnesota. From Minnesota Geological Survey.

phase of the Superior Lobe is used also for the Rainy Lobe because the two parallel ice advances terminated in the same moraine). Otherwise, separate names are used. The history recounted here concerns only northeastern Minnesota. A less detailed account of the history for the entire state, with similar format, has appeared previously (Wright and Ruhe, 1965).

St. Croix Phase

Although pre-Wisconsin glacial drifts may be exposed in the deep open pits of the Mesabi Iron Range, the oldest Wisconsin drift with extensive surface expression in northeastern Minnesota is that of the Toimi Drumlin Field of the Rainy Lobe (pl. 1). This consists of about 1400 drumlins trending southwest in eastern St. Louis and western Lake counties. The drumlin field as presently exposed is 70 miles long and up to 25 miles broad; it descends in elevation from more than 2000 ft. above sea level in the northeast to 1300 ft. in the southwest.

The Toimi Drumlin Field is truncated abruptly on the north by the Vermilion Moraine, which was formed by readvance of the Rainy Lobe during a later phase. It is buried on the southeast and south by the Highland Moraine of the Superior Lobe (fig. 4), with a transitional zone visible in

Figure 4. Section of topographic map of Whyte quadrangle of U.S. Geological Survey. Toimi drumlins (Rainy Lobe), with SE trend in the upper left part of the area, are truncated by the Highland Moraine (Superior Lobe) diagonally across the center. The Highland flutes (NW trend) are shown in the lower right.

which the Toimi drumlins were transversely grooved or only partially buried by the Superior Lobe (figs. 5, 6).

On the west the drumlin field is buried irregularly by generally thin drift of the St. Louis Sublobe and by sediments of Glacial Lake Upham, but many of the drumlins show through the blankets.

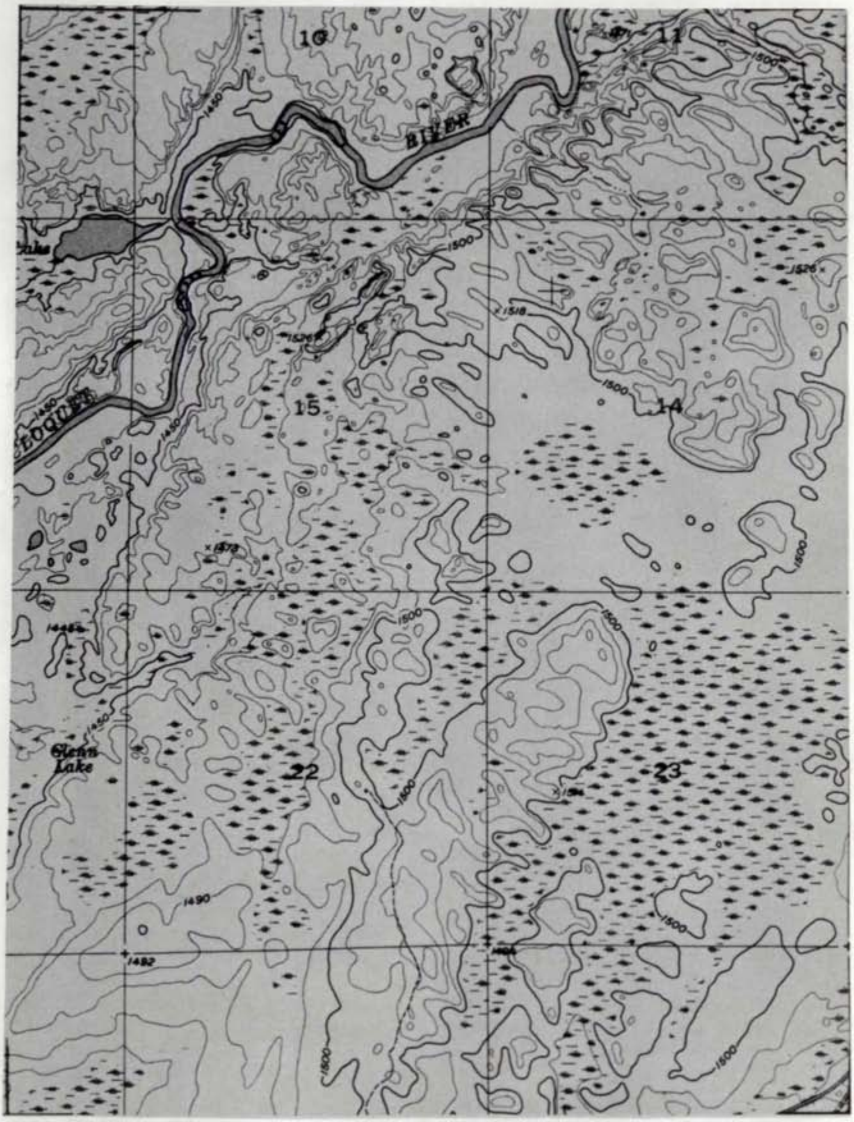


Figure 5. Topographic map of Toimi drumlins of Rainy Lobe, 15 miles northwest of Two Harbors, which have been cross-cut by the Superior Lobe of the Automba phase. From Pequaywan quadrangle map of U.S. Geol. Survey. See Figure 6 for photograph of similar drumlins 5 miles west.

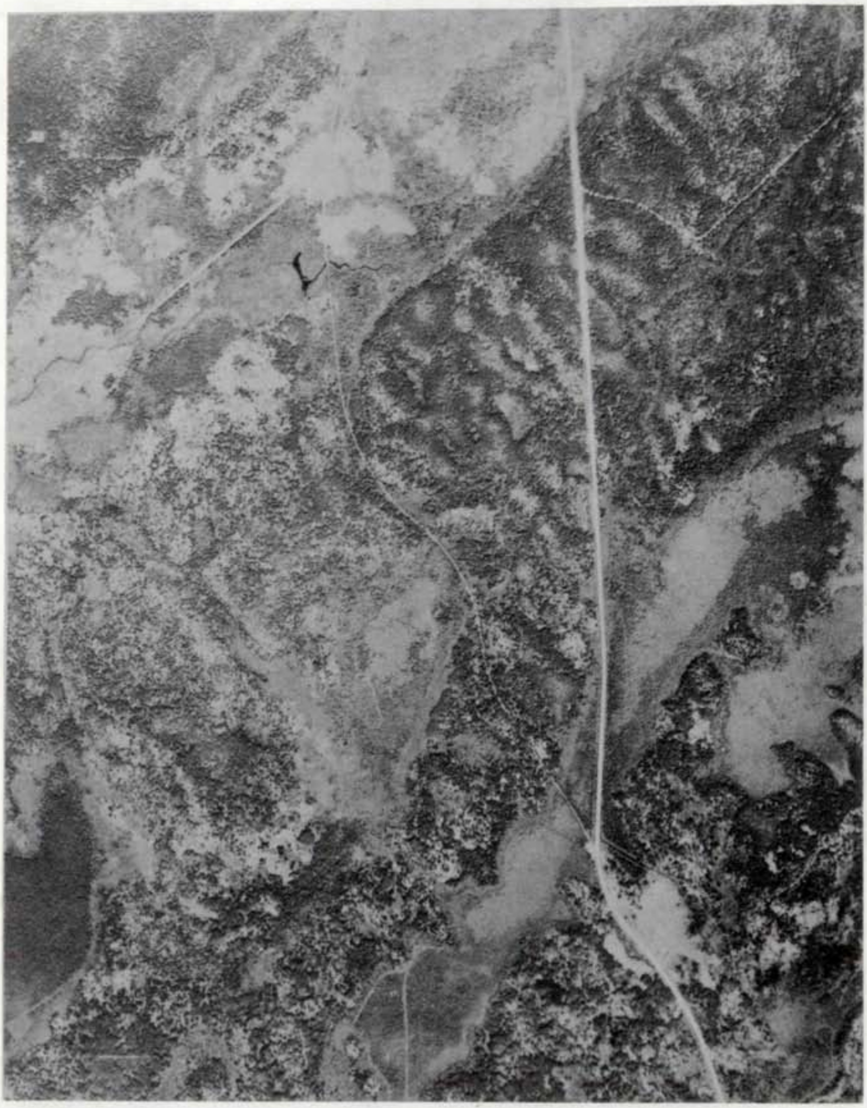


Figure 6. Air photograph of drumlins similar to those of Figure 5. Photo CIR-1-52 taken in 1939 by U.S. Dept. Agriculture. Distance across the top is about 1.5 miles.

The group of about 75 drumlins between Keewatin and Buhl on the Mesabi Iron Range at the northern margin of overlap of the St. Louis Sublobe drift (Cotter and others, 1964) is probably an outlier of the Toimi field, as also may be about five drumlins southwest of Eveleth.

The Toimi drumlins (fig. 7) are generally 1-2 miles long, ¼ mile wide, and 30-50 ft. high (see especially the Markham, Brimson, and Whyte quadrangles). Some have oblique saddles across the top, dividing the crest into segments *en echelon*. Most are symmetrical, although a few are streamlined, with the blunter, higher end in the up-glacier direction. They are made of gray, sandy, stony till rich especially in fragments of Duluth Gabbro or its differentiates (anorthosite, red syenite, diabase), which form the bedrock of much of the area beneath the drumlin field. Huge boulders of gabbro commonly dot the surface.

Weber Lake, one of the paleobotanical sites described below, is located in the northern part of the Toimi Drumlin Field, 11 miles south of the Vermilion Moraine.

The Toimi Drumlin Field was formed by the Rainy Lobe in its advance southwestward across the general upland (elevation 1500-1800 ft.) between the North Shore Highland (2000 ft.) on the east and the Red Lakes Lowland (1200 ft.) on the west. The Superior basin was occupied at this time

Figure 7. Air photograph of Toimi drumlins of Rainy Lobe near Salo Lake, 5 miles southwest of Toimi, Brimson quadrangle, St. Louis County. The drumlin crests here are about ½ mile apart. Photo 112-2112 of Army Map Service (1953).

by the Superior Lobe; the Red Lakes Lowland was invaded from the northwest by the Wadena Lobe, which was in fact blocked in its eastward progress by the Rainy Lobe and held at the Itasca Moraine (Wright, 1962). The Rainy Lobe extended to central Minnesota, where it formed additional drumlin fields, terminating at the St. Croix Moraine (Schneider, 1961). Its drift this far west is not gray, however, because rocks other than gabbro dominate the stone counts, and the till has readily oxidized to brown. One cannot trace the Rainy Lobe drift continuously from the Toimi Drumlin Field to the St. Croix Moraine because much of the intervening area is covered with younger drift.

This ice advance, along with the contemporaneous and parallel advance of the confluent Superior Lobe just to the southeast, constitutes the St. Croix phase, the second in the sequence of Wisconsin glacial phases in Minnesota (Wright and Ruhe, 1965). [The first is represented by the Wadena Drumlin Field of the Wadena Lobe (Wright, 1962), which is overlapped in central Minnesota by the St. Croix Moraine.] The adjacent Rainy and Superior Lobes in this phase can be visualized as representing two threads of ice flow within a broad bulge of the ice sheet—one moving southwest along the Lake Superior basin, the other moving southwest on the Rainy River upland. The two threads were separated subglacially by the North Shore Highland, but the ice surface was uninterrupted. Where this highland terminated near Duluth, the two separate threads merged just as do two branches of a valley glacier, and the broad lobe fanned out of the Minneapolis lowland to terminate at the St. Croix Moraine, which contains red Superior Lobe till in its eastern arm and brown Rainy Lobe till in the west, with a transitional zone of mixing and interbedding that represents intermingling of the threads of flow.

The minimum age for the St. Croix phase of the Rainy Lobe is set by the date of 14,690 ± 390 years before the present (B.P.) (W-1763) on the basal organic sediments of Weber Lake. Because a still older date is available for Kotiranta Lake, which is associated with a glacial phase younger than the St. Croix phase, the latter is set at 16,000 years ago, and it may be older. The oldest date on the St. Croix Moraine itself is a minimal date on basal lake sediments—13,220 ± 200 B.P. (Y-1326) at Kirchner Marsh south of Minneapolis.

Automba Phase

The Rainy and Superior Lobes wasted from the St. Croix Moraine and from eastern Minnesota generally (and the Wadena Lobe from the Itasca Moraine) during what must have been a major interstadial interval of the Wisconsin glaciation. In the beginning of the wastage episode, a system of southwest-trending tunnel valleys, parallel to the gradient of the ice surface, was eroded into the drift by subglacial streams under the high hydrostatic pressure occasioned by the great thickness of ice. The major tunnel valleys were formed under the Superior Lobe. Some are as much as ½ mile wide and 100 ft. deep and may be traced for almost 100 miles to and probably through the St. Croix Moraine. Many of them contain narrow eskers, formed as thinning and stagnation of the ice reduced the hydrostatic pressure and brought about deposition in the by-now much smaller tunnels.

The distance of ice retreat before the Automba readvance is not known. Little active ice may have remained in Minnesota at this time, except perhaps in the low Lake Superior basin. Stagnant ice was abundant, however, especially in moraines and outwash plains (Florin and Wright, 1969). The Rainy Lobe withdrew at least as far north as the Vermilion Moraine, so a retreat of 200 miles or more from the St. Croix Moraine was involved.

The Superior Lobe, on the other hand, could not have retreated very far north of the bedrock drainage divide between the Superior and Minneapolis basins (near Sandstone in Pine County, about 100 miles north of the St. Croix Moraine). If it had, then a proglacial lake would have formed north of the divide, and the fine-grained sediments of such a lake would have been incorporated in the drift of the Automba ice advance, just as they were during the later phases.

When the Superior Lobe readvanced, however, it had a significantly different alignment, for it advanced west-southwest and west out of the head of the Lake Superior basin rather than straight southwest, as previously. It apparently reached as far west as the Mille Lacs Moraine, which bounds Mille Lacs Lake on the west and south in central Minnesota—an advance of 50 miles from the Superior lowland north of Sandstone.

The reason for the more westerly course of the Superior Lobe in the Automba phase is not entirely clear. Certainly the Rainy Lobe was no longer present this far south to contain the Superior Lobe on its right flank, as it had done during the St. Croix phase. But the course that was followed was not topographically the lowest course, for the ice climbed over the bedrock escarpment near Denham, which exceeds 1300 ft. in elevation above sea level, whereas the divide at Sandstone leading to the Minneapolis basin (followed by the ice in the earlier phase) is less than 1200 ft. Conceivably drift-filled dead ice remaining in the area of the bedrock divide near Sandstone could have provided a sufficiently immobile barrier to southward ice movement.

The westward course of the Superior Lobe in this phase is recorded principally by the Automba Drumlin Field and by the Highland Moraine and its connections with the Mille Lacs Moraine. About 200 drumlins occur in western Carlton County (see principally the Cromwell quadrangle) with trend fanning from N. 30° W. to N. 70° W. Farther southwest, in Aitkin County, the trend apparently swings still more to the west and then to the southwest, although lack of topographic maps inhibits clarification of features suggested by aerial photographs. The numerous promontories that jut southwestward into Lake Mille Lacs are drumlins of this group.

In the other direction, to the northeast, the drumlins are partially obscured by younger outwash in north-central Carlton County (Barnum and Cloquet quadrangles), but northeast of Cloquet and the St. Louis River an additional 125 occur, with trend about N. 30° W.

The average Automba drumlin is about ½-1 mile long, ⅛ mile wide, and only 25 ft. high, so it is a less conspicuous feature of the landscape than a Toimi drumlin.

Eastward from Two Harbors for about 50 miles, along the slope leading from Lake Superior up to the North Shore Highland, a fluted glacial topography is conspicuous (figs. 4, 8). The flutes are about ½ mile long, ¼ mile apart, and generally only 5-20 ft. high. They consist either of eroded bedrock or of linear drift accumulations resembling drumlins. Although their trend is generally perpendicular to the north shore, local divergences of a few degrees imply obstruction of basal flow by rock hills.

The flutes were formed when the right flank of the Superior Lobe rose laterally out of the basin, moving at right angles to the present shore, and at right angles to the axis of the ice lobe. The flutes mark the highland crest as far east as Cook County, where they were described by Sharp (1953) and attributed to movement of the Rainy Lobe toward the shore rather than of the Superior Lobe away from the shore.

The fluted terrain terminates clearly in the Highland Moraine, which sharply overlaps the edge of the Toimi Drumlin Field, as mentioned previously. The topographic contrasts of the fluted terrain, the Highland Moraine, and the Toimi drumlins are most clearly delineated on the topographic map of the Whyte quadrangle (fig. 4). Actually, the Superior Lobe at this time locally extended beyond the prominent part of the Highland Moraine far-

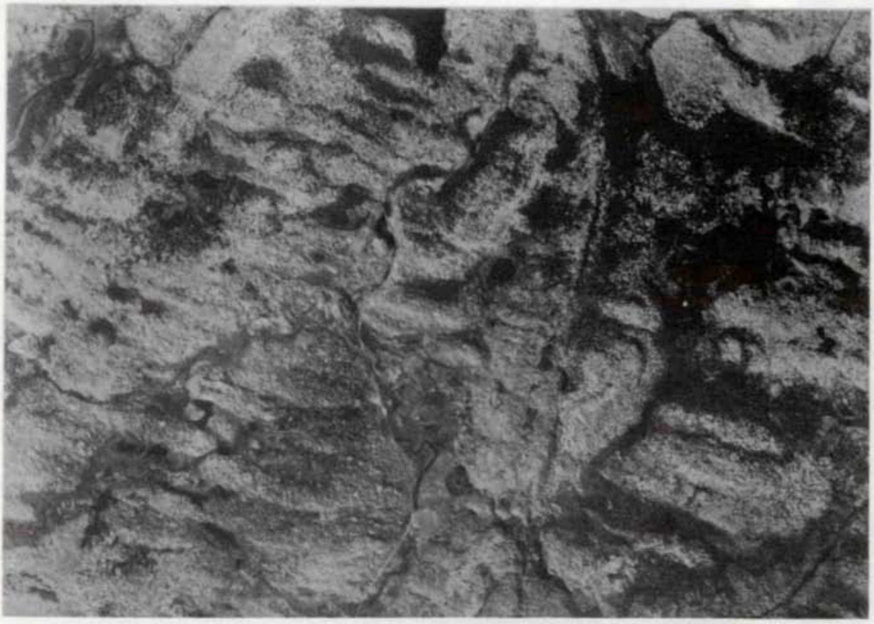


Figure 8. Air photograph of fluted bedrock and drift 12 miles northeast of Finland, formed by Superior Lobe (Automba phase) moving northwest out of Lake Superior basin. Photo 112-2087 of Army Map Service (1953). Distance across top is about 3 miles.

ther across the Toimi Drumlin Field, for some of the Toimi drumlins beyond the moraine have transverse flutes and a veneer of Superior Lobe till (figs. 5, 6).

Northeastward the Highland Moraine forms an interlobate junction with the contemporaneous Vermilion Moraine of the Rainy Lobe, amidst the rugged bedrock ridges east of Isabella in Lake County (see Isabella and Cramer quadrangles). The interlobate area is marked by eskers and associated rock gorges that are traceable eastward to the series described by Sharp (1953) in Cook County.

Southwestward the Highland Moraine may be projected along its trend to the Cromwell and Wright moraines of Leverett (1932), which terminate and interrupt the Automba Drumlin Field. These moraines in turn project southwestward to a segment of the Mille Lacs Moraine.

The Highland flutes, the Automba Drumlin Field, and the Highland-Mille Lacs morainic trend thus delineate the right half of the Superior Lobe during the Automba phase. The lobe was about 35 miles broad after it left the head of the Superior basin (width from the Highland Moraine to Sandstone). The elevation of its right-hand margin decreased from 2000 ft. above sea level in Cook County to 1300 ft. at the Mille Lacs Moraine in a distance of 175 miles.

The till of the Superior Lobe in its Automba phase is generally red and sandy, being characterized by fragments of Precambrian red sandstone and shale. This till cannot be distinguished from that of the St. Croix phase of the Superior Lobe. North of the St. Louis River the till loses much of its red color, because the local bedrock consists of basalt, gabbro, or slate. In the Highland Moraine and the adjacent fluted terrain, for example, the till is brown because of the dominance of basalt fragments, but a local reddish tinge of the drift is attributable to fragments of the red-syenitic differentiate of the Duluth Gabbro.

The Superior Lobe in the Automba phase, in its expansion to the Mille Lacs Moraine, blocked the normal southward drainage of the area to the north and formed two large proglacial lakes. The area now tributary to the St. Louis River in St. Louis County drained into Glacial Lake Upham I. This lake must have been confluent, through the low area north of Jacobson, with Glacial Lake Aitkin I, which took the drainage that now feeds the upper Mississippi River in northern Aitkin and eastern Itasca counties. Meltwater from the Highland Moraine must have brought brown clay and silt into Lake Upham, and additional outwash came from the contemporaneous Rainy Lobe at the Vermilion Moraine, which formed an interlobate junction with the Highland Moraine in eastern Lake County. This outwash can be traced along sandplains winding among the Toimi drumlins, especially along the Cloquet River and its tributaries. At the same time, outwash from the Superior Lobe in its westward extension to Mille Lacs Lake must have drained northward into both Lake Upham and Lake Aitkin; the clayey component of this outwash must have been red, reflecting the red coloring matter of this portion of the Superior Lobe drift. Lake Aitkin probably also received drainage from the northwest from the advancing St. Louis Sublobe, which contributed gray calcareous clay and silt..

Lake Aitkin I presumably drained southward around the end of the Mille Lacs Moraine to the Mississippi River near Brainerd, but its exact course cannot be determined because of burial by younger drift. As the Superior Lobe withdrew at the end of the Automba phase, Lake Upham may have reversed its drainage from westward (into Lake Aitkin) to eastward, forming outlet channels via Spider Creek, Baden, and Hellwig Creek to the St. Louis River (Brookston N.W., Alborn, Payne, and Independence quadrangles). This means that the Superior Lobe had withdrawn far enough into the Superior basin to allow this drainage to go into the St. Croix River system (as it did after a later glacial phase) or into Lake Superior itself (as today). These outlet channels have since been partially buried by younger drift.

Split Rock Phase

The Superior Lobe retreated at the end of the Automba phase far enough into the Lake Superior drainage basin to bring about the formation of one or more proglacial lakes between the ice front and the drainage divide near Sandstone. The lakes were large enough and deep enough to accumulate red clay and silt. When the Superior Lobe advanced once again in the Split Rock phase, it incorporated the lake beds into the ice and ultimately deposited red till that is characteristically clayey or silty. The ice readvanced southwestward in a narrow tongue, being bounded on the west by the bedrock escarpment near Denham. It deposited a discontinuous veneer of till on eskers and tunnel valleys of earlier glacial phases, notable near Finlayson in northern Pine County. For example, near Indian Lake, ½ mile southwest of Finlayson, a small esker that was formed in a shallow tunnel valley during wastage of the Superior Lobe in the St. Croix phase has two caps of red till. The lower cap, consisting of about 10 ft. of red sandy till, may be assigned to the Automba phase, and its stone fabric implies east-west movement of ice. The upper till is less than 3 ft. thick, but it is very clayey and poor in stones. The fabric indicates ice movement from the northeast. This till is interpreted as the result of ice advance over proglacial lake clays during the Split Rock phase.

The limits of the red clayey till in Pine County are approximately shown on the Pine County soils map (Simmons, 1935). From the west side of the tongue, a small bulge protruded up the Split Rock River valley, which forms a re-entrant in the Denham escarpment, and here the ice shaped a drumlin field consisting of about 50 small drumlins and reaching an elevation of about 1250 ft. (Moose Lake quadrangle). These Split Rock drumlins average about 2000 ft. long, 500 ft. wide, and 20 ft. high; they trend to the west. Their size, shape, and trend differ from those of the Automba Drumlin Field just to the north.

Meltwater from the protrusion up the Split Rock lowland fed a small proglacial lake that drained to the west and thence south down the Snake

River. Meltwater from the point of the main tongue near Finlayson led into the Grindstone River. The latter deposited a delta in Glacial Lake Grantsburg, which was present in east-central Minnesota during the Pine City phase of the Grantsburg Sublobe (Wright and Ruhe, 1965). This relation demonstrates the contemporaneity of the Split Rock and Pine City glacial phases.

Northeast from the Split Rock Drumlin Field the ice-front position is marked by two roughly parallel ice-contact slopes facing southeast, with associated outwash plains and eskers. The older one borders the outwash plain at Sawyer at an elevation of about 1300 ft. The younger one, to which the term Cloquet Moraine was applied by Leverett (1932), is fronted by the Cloquet Outwash Plain (at about 1280 ft.), with its five feeding eskers between Cloquet and Bob Lake (fig. 9). The Sawyer outwash (in which the pollen site of Kotiranta Lake is located) was graded in part to the west, first burying and then filtering through the Automba Drumlin Field to the

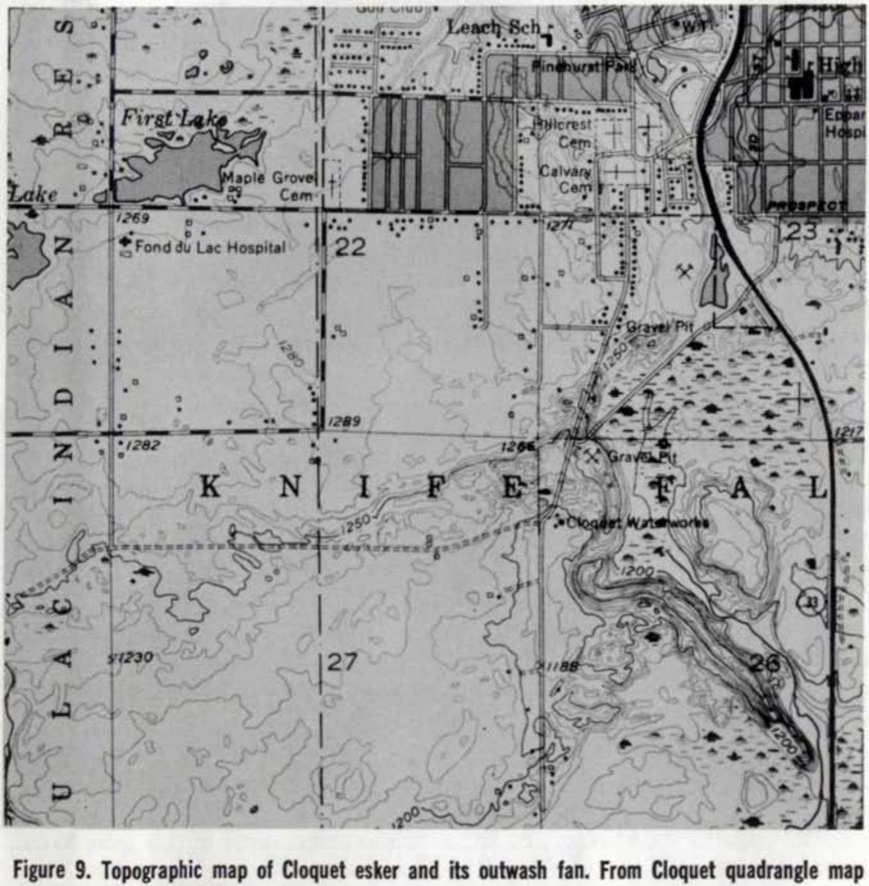


Figure 9. Topographic map of Cloquet esker and its outwash fan. From Cloquet quadrangle map of U.S. Geol. Survey.

Split Rock lowland, where it must have circumvented the Split Rock bulge of the ice and joined local outwash in a course westward to the headwaters of the Snake River. But most of the Sawyer outwash, as well as all of the Cloquet outwash slightly later, moved northeastward to the site of the St. Louis River, and thence westward to the Lake Upham basin near Floodwood, which at this time must have drained westward to the Mississippi River *via* Glacial Lake Aitkin.

The front of the Superior Lobe in the Split Rock phase extended from the Sawyer or Cloquet positions across the site of the St. Louis River and spread red clayey till on a small area north of Esko at the base of the North Shore highland, at elevations below 1300 ft. From here northeastward along the lake basin all the way to Cook County (Sharp, 1953), the Superior Lobe was confined to the base of the steep north shore, where it left its conspicuous mark of red clayey till—still indicating that in the recession that preceded the Split Rock phase the ice had withdrawn into the basin far enough to allow the formation of thick beds of red lake clay.

The advance of the Superior Lobe in the Split Rock phase may have been a relatively abrupt event—in fact a surge (Wright, 1969). By the end of the Automba phase the ice had withdrawn slightly across the drainage divide into the Lake Superior basin, and the terminal area became so thin that it was frozen to its base. (The paleobotanical studies, discussed later, indicate tundra in the region at this time, and thus temperatures low enough to keep the ground frozen, even under the ice.) The ice in the main part of the basin, however, was 2000-3000 ft. thick at this time, and geothermal heat was sufficient to melt the base and permit basal slip—the most effective mechanism of glacier flow. Ice thus could pile up behind the frozen terminal area, which thus served as a dam, and when the pressure exceeded the strength of the dam the entire mass could move forward rapidly in a kind of surge.

The minimum radiocarbon age for the Split Rock phase is set by the dates of 13,480±350 B.P. (W-1762) and 16,150±550 B.P. (W-1973) on the bottom sediments of Kotiranta Lake, which is an ice-block depression on the Cloquet Outwash Plain. Also relevant is a minimal date for the contemporaneous Pine City phase, namely 13,530±240 B.P. (Y-1978) for the basal organic sediment at Horseshoe Lake on the Anoka Sandplain, which was formed immediately after drainage of Lake Grantsburg during wastage of the Grantsburg Sublobe. These dates, along with those at the Aitkin site mentioned below, imply that the Split Rock phase is much older than the Valders phase of the Lake Michigan Lobe, despite the fact that the red clayey till is lithologically very similar to the Valders till at its type locality in eastern Wisconsin.

Nickerson and Alborn Phases

The Superior Lobe retreated from its maximum stand in the Split Rock phase and readvanced to form the Nickerson and Thomson moraines. The net retreat was about 20 miles. The point of the narrow lobe at this time was located a few miles southwest of Moose Lake village, Pine County, at an elevation of about 1200 ft., thus about 50 ft. lower than the ice limit at the Split Rock phase. The Nickerson Moraine trends from this point eastward for 20 miles to Nickerson (Barnum and Bruno quadrangles), beyond which it becomes lost on the steep south slope of the Lake Superior basin. The Nickerson Moraine is characterized by extremely sharp and irregular topography in red stone-poor clayey till, exposed in deep road cuts along the northern boundary of Pine County. The ice advance may have involved one or more surges, for the topographic and thermal relations were as favorable as in the Split Rock phase (Wright, 1969). The pollen sites of Jacobson and Anderson Lakes are located in the Nickerson Moraine.

Outwash fronted the Nickerson Moraine along the Willow River and produced the well-developed pitted plain near Sturgeon Lake. It did not extend southwest to the Grindstone River, as outwash from the ice had done during the Split Rock phase that preceded. Instead, it was captured by the Kettle River, which drains directly southward. The Kettle River now plunges into a rock gorge shortly below the point of capture, and the gorge emerges at the St. Croix River well below the level of the Anoka Sandplain. Although the gorge was probably cut mostly at a later date, when the river carried the outlet waters of large proglacial lakes, the relations imply that the Anoka Sandplain (which replaced Lake Grantsburg) was no longer active and that the Pine City phase of the Grantsburg Sublobe had therefore closed.

From its terminal point at Moose Lake, the northwestern margin of the Superior Lobe in the Nickerson phase extended as the Thomson Moraine northeastward across the site of the Moose River to Barnum and Mahtowa, where its limits can still be identified by the presence of red clayey till. Beyond this to Carlton, however, the till of the Thomson Moraine is not clayey in texture. Perhaps the readvancing ice in this segment no longer had access to proglacial lake clays.

Meltwater from the Thomson Moraine built an outwash plain (Wright and others, 1970), since deeply dissected, that was graded from about 1200 ft. at the moraine in the Cloquet quadrangle around the point of the lobe *via* Glaisby Brook to the Kettle River (Barnum and Moose Lake quadrangles).

Contemporaneous with the Nickerson phase of the Superior Lobe was the Alborn phase of the St. Louis Sublobe. This ice, as an offshoot of the Des Moines Lobe, had probably been advancing from the northwest for some time. It did not reach its maximum until after the Superior Lobe had withdrawn at the end of the Split Rock phase, as is indicated by the drainage relations—the Superior Lobe drained up the St. Louis River to the Mississippi River *via* the Upham and Aitkin basins, which therefore could not yet have received the St. Louis Sublobe. When the ice did reach its maximum in the Alborn phase, it incorporated the lake sediments of Lakes Aitkin I and Upham I, and deposited the silty to clayey Alborn till around the margins of these basins. Along the eastern margins of the Upham basin the till overlaps Toimi drumlins; it is reddish-brown because of the content of red clay that had been deposited in the Upham basin by the Superior Lobe during the Automba phase. On the northern margin of the Upham basin it covers the Mesabi Iron Range and laps onto the Giants Range to the north to an elevation of 1550 ft.; it even protrudes through the range at a gap near Buhl; this till is also reddish-brown, and locally it contains lenses of light-brown calcareous till with the fragments of Cretaceous shale that are diagnostic of drift of the St. Louis Sublobe west of the area of lake-clay contamination.

On the west side of the Aitkin basin the till is brown and silty, in contrast to the underlying sandy till of the Rainy Lobe. On the south side of the Aitkin basin the till laps on to the Mille Lacs Moraine of the Automba phase. Here the clayey or silty till is red-brown or light brown or brown; in some cases it apparently is mixed, in other cases it occurs in discrete stratigraphic units separated by pebble layers. Schneider (1965) has attempted to work out the stratigraphic complexities of this area, and he postulates five or even seven separate ice advances by three confluent ice lobes (Superior, Rainy, and St. Louis). In the present interpretation it is visualized that the sediments of Lakes Aitkin I and Upham I ranged from red to light brown, depending on whether the source had been the red drift of the Automba phase of the Superior Lobe, the gray (oxidized light brown) drift of the St. Louis Sublobe, or possibly the brown drift of the Rainy Lobe (which during the Automba phase stood at the Vermilion Moraine and may have sent outwash to Lake Upham through the Embarrass gap in the Giants Range or down the Cloquet and St. Louis rivers). Thus, when the St. Louis Sublobe advanced over these lake beds its till acquired variable color. In almost all areas the silty or clayey stone-poor till contains lenses or inclusions of "pure" shale-bearing light brown till that typifies the drift of the St. Louis Sublobe west of the area of incorporation of lake beds.

On the southeast margin of the Upham basin the St. Louis Sublobe built a terminal moraine that cuts obliquely across the Toimi drumlins of the Rainy Lobe and laps onto the Highland Moraine and its southwestward extensions. This feature, mapped in part by Baker (1964), is here named the Culver Moraine. It is fronted by outwash that grades to the St. Louis River at 1290 ft. The stratigraphic relations are clearly displayed on the long roadcut north of the St. Louis River at Brookston, where gray Rainy Lobe till (Toimi drumlins) is overlain by red sandy Superior Lobe till (Highland Moraine), and this by granite-rich outwash from the terminal moraine of the St. Louis Sublobe 5 miles to the north. (The section is capped by 2 ft. of loess, which follows the slope down to a lower terrace of the St. Louis River.) Because all the ground south of the St. Louis River valley exceeds 1300 ft. in elevation, the outwash could only have moved eastward down this valley toward Lake Superior. In the Split Rock phase of the Superior Lobe, the area of the lower valley had been completely blocked by the ice—in fact the drainage at that time was westward *up* the St. Louis River, as previously explained. After the Superior Lobe withdrew the 20 miles from the ice-contact front near Sawyer (Split Rock phase) to the Thomson Moraine (Nickerson phase), outwash from the St. Louis Sublobe formed the beginnings of the St. Louis River. It joined outwash from the Thomson Moraine near Scanlon, and together these meltwaters followed the margin of the Superior Lobe southwestward to the Kettle River. These relations demonstrate that the maxima of the two sublobes of the Des Moines Lobe were not contemporaneous: the St. Louis Sublobe maximum (Alborn phase) was younger than the Split Rock phase of the Superior Lobe, whereas the Grantsburg Sublobe maximum (Pine City phase) was contemporaneous with the Split Rock phase.

Four pollen sites are associated with the Alborn phase. The Rossburg site is on Alborn drift north of Mille Lacs Lake. The Spider Creek site (Baker, 1965) is in an outlet channel of Glacial Lake Upham I; the channel was dammed on the east by the moraine of the Alborn till and on the west by a beach deposit of Lake Upham II, which formed as the St. Louis Sublobe retreated. Glatsch Lake is an ice-block depression near the north shore of Lake Upham II. The Aitkin site is near the southern end of Lake Aitkin itself.

Glacial Lake Upham II had its outlet at 1280 ft. near Floodwood down the St. Louis River, which, freed of its sediment load, thereupon began to dissect the older outwash. It passed Scanlon at an elevation of about 1200 ft., there cutting a boulder-covered terrace in the till (Wright and others, 1970). The river was still diverted by the Superior Lobe, which was standing then at the Thomson Moraine (Nickerson phase). It cut a channel to the Kettle River *via* Glaisby Brook at 1190 ft. This channel was not so wide as later diversion channels of the same river, because Lake Upham at this time was still small and did not supply much water.

Subsequent diversion channels of the St. Louis River are recorded primarily in the Cloquet and Barnum quadrangles (Wright and others, 1970). They formed successively as the Superior Lobe retreated. The channel at 1190 ft. is still only ¼ mile broad, but the channels at 1150 and 1130 are double that breadth. All channels after Glaisby Brook were cut through the point of the Nickerson-Thomson Moraine, thus establishing the present course of the Moose River past the village of Moose Lake and into the Kettle River, the retreating lip of whose gorge must have provided the base level for the dissection.

When the last diversion channel in the series was abandoned, the Blackhoof pollen site was opened (Wasylikowa and Wright, 1969). At this time the Superior Lobe had retreated inside the entire Thomson Moraine, and the St. Louis River entered the narrow proglacial Lake Nemadji, which itself had the last outlet to the Moose River, at an elevation of 1050 ft.

The radiocarbon age of the Alborn-Nickerson phase (12,000 B.P.) is based on a pair of wood dates from peat buried in the upper part of the Lake Aitkin II deposits 3 miles north of Aitkin in central Minnesota (Farnham and others, 1964). If this lake is contemporaneous with Lake Upham II and resulted from withdrawal of the St. Louis Sublobe from its maximum stand, then the dates apply to the Alborn and Nickerson phases. Those dates, 11,710±325 B.P. (W-502) and 11,560±400 B.P. (W-1141), imply that the Alborn and Nickerson phases pre-date the Two Creeks interstadial

Table 1. Chronology and correlation of glacial features in northeastern Minnesota, with radiocarbon dates

		Des Moines Lobe	
Superior Lobe	Rainy Lobe	Grantsburg Sublobe	St. Louis Sublobe
NICKERSON PHASE			
Glacial Lake Duluth			
Glacial Lake Nemadji			
St. Louis River diversions		Kettle R. gorge	Glacial Lakes Aitkin II and Upham II (>11,560, >11,710)
6. Carlton-Blackhoof (>10,420, >10,630)			
5. Scanlon			
4, 3. unnamed channels			
2. Glaisby			
1. unnamed channel			
Thomson Mor., Nickerson Mor. (>10,400 Jacobson, >10,800 Anderson), Willow R. Outwash Plain			Culver Mor. (11,100,* 11,330* Mariska)
SPLIT ROCK PHASE		PINE CITY PHASE	
Cloquet Mor. & Outwash Pl.		Anoka Sandplain (>13,530 Horseshoe)	
Sawyer Outwash Plain (>13,480, >16,150* Kotiranta), Split Rock Drumlin Field		Pine City Mor., Glacial Lake Grantsburg	
AUTOMBA PHASE			
Gl. Lakes Aitkin I and Upham I, Highland-Mille Lacs Mor., Automba Drumlin Field, and Highland flutes	Vermilion Mor.		
ST. CROIX PHASE			
St. Croix Mor. (>13,220 Kirchner)	Toimi Drumlin Field (>14,690 Weber)		

*Rejected date

interval of the Lake Michigan Lobe, and that the red clayey till of the Nickerson Moraine (as well as that of the Split Rock phase that preceded) do not correlate with the Valders red clayey till of northeastern Wisconsin, as previously supposed (Wright, 1955).

These correlations are opposed by radiocarbon dates of wood from the Alborn till at the Mariska Mine near Gilbert on the Mesabi Iron Range. These dates (11,330±350 B.P., W-827; 11,100±400 B.P., W-1140) imply that the Alborn phase might in fact correlate with the Valders. Supporting this alternate interpretation are the dates from the basal organic sediment at Jacobson Lake (10,400±300 B.P., L-794 F) and Anderson Lake (10,800±300 B.P., L-194 A-D) in the Nickerson Moraine, and the dates on the basal peat from the Blackhoof pollen site (10,630±500 B.P., W-1677, and 10,420±300 B.P., W-1714), which is located on the last diversion channel of the St. Louis River before Lake Nemadji and is thus younger than the Nickerson Moraine. The dates on the Nickerson Moraine lakes are minimal, of course, because stagnant ice may have persisted in the moraine long after retreat of the active ice (Florin and Wright, 1969). On the other hand the Blackhoof site is on a broad drainage channel that was eroded deeply through the Thomson Moraine and was presumably (but not certainly) free of stagnant ice. Nonetheless, the first dating—Nickerson phase at about 12,000 B.P. and thus pre-Valders—is accepted as the more likely. Perhaps the Thomson Moraine, like the Nickerson, held stagnant ice for 1500 years after the 12,000-year-old maximum of the Nickerson phase, and was only gradually eaten away at its front by the diverted St. Louis River. In this case the Blackhoof channel may not have formed until 10,500 years ago. Certainly the several separate diversion channels are deep and wide enough to have taken 1500 years to form as a set. This explanation is supported by the C-14 date of 10,220±500 B.P. (M-359) for Glacial Lake Ontonagon, which was a lake contemporaneous with Lake Nemadji farther east along the south side of the Lake Superior basin; the ice must have filled most of the basin until this time.

Conclusions on Glacial History

The several phases of ice advance, involving four different ice lobes and sublobes, provide an intricacy in stratigraphic and geomorphic detail that can be worked out because of the contrasting lithology of the drifts and because of the interaction of the meltwater streams from the different lobes. Available radiocarbon dates put almost the entire history in late-Wisconsin (but pre-Valders) time. Although in most cases different ice lobes reached their maximum positions about the same time, as far as can be determined from the geomorphic detail this was not true in other cases. Table 1 shows the correlations.

The radiocarbon dates indicate that the entire sequence from the St. Croix phase to the Nickerson phase occurred before 11,500 years ago. The question arises whether these ice-margin fluctuations in Minnesota, be they contemporaneous from lobe to lobe or not, are a result of regional climatic changes that might be recorded in some other way. Thus the pollen studies are pertinent, for vegetation may also be sufficiently sensitive to climatic change to provide an answer to the question. The sites investigated were chosen in part to relate to the glacial history. Thus Weber Lake lies in the Toimi Drumlin Field of the St. Croix phase. None of the sites is on drifts of the Automba phase that followed next. Kotiranta Lake is on an outwash plain of the Split Rock phase. The Spider Creek, Glatsch, Rossburg, and Aitkin sites were opened just after the maximum of the Alborn phase. Jacobson and Anderson lakes are on the moraine of the contemporaneous Nickerson phase. The Blackhoof site dates from late in the Nickerson phase. Thus the basal levels of the pollen sites have the chance of recording vegetational changes contemporaneous with ice-margin fluctuations.

Several of the pollen sites are ice-block depressions, which may not have melted out to receive organic sediment until long after retreat of the active ice from the region (Florin and Wright, 1969). The basal organic sediment may therefore not necessarily record the vegetational conditions immediately after the ice left the region, and the C-14 date from that sediment may therefore be a minimal date for the phase of glaciation that preceded. Of the sites under consideration, Kotiranta Lake is certainly in an ice-block depression on the Sawyer outwash plain. Jacobson and Anderson lakes, in the heart of the Nickerson Moraine, and the Rossburg site, in the Mille Lacs Moraine, may have had a similar origin. The Spider Creek site (Baker, 1965) was apparently open very soon after ice retreat, for it was closed at one end by a beach bar of Lake Upham II. Glatsch Lake, just above the shoreline of Lake Upham, may still have been filled with buried ice during the time of Lake Upham II. The Aitkin site (Farnham and others, 1964) has no problem with buried ice, which could not have persisted under such a large lake as Lake Aitkin. Likewise at the Blackhoof site (Wasylikowa and Wright, 1969) the peat formed after abandonment of a large river that eroded through a moraine.

VEGETATIONAL HISTORY

Introduction

Northeastern Minnesota today lies in an area of mixed coniferous and deciduous forest (fig. 10), namely the Great Lakes-St. Lawrence forest region of Rowe (1959), which is characterized by *Pinus strobus* and *P. resinosa* in addition to the typical species of the boreal forest of adjacent Canada *(Pinus banksiana, Picea glauca, P. mariana, Abies balsamea, Betula papyrifera, Populus tremuloides,* and *P. balsamifera)* and the typical species of the deciduous forest to the south *(Fraxinus nigra, F. pennsylvanica, Quercus rubra, Q. macrocarpa, Acer saccharum, A. rubrum, Ulmus americana, Tilia americana, Ostrya virginiana,* and other trees). This mixed forest is about 200 miles broad in northeastern Minnesota; its composition is not uniform, for the more thermophilous deciduous trees drop out successively northward. Some, however, continue into the boreal forest as minor components.

The relatively narrow breadth of the Great Lakes Forest and the adjacent deciduous forest in Minnesota is a product of the relatively steep climatic gradient on the northeast side of the "prairie peninsula." Several trees important in the forests to the east barely extend to Minnesota, such as *Fagus grandifolia, Tsuga canadensis,* and *Betula lutea,* which are restricted by the more continental climate or perhaps by slowness of migration in postglacial time from eastern refuges.

The sharpness and narrowness of these vegetational bands in Minnesota make the region favorable for study of geographic shifts of the bands in

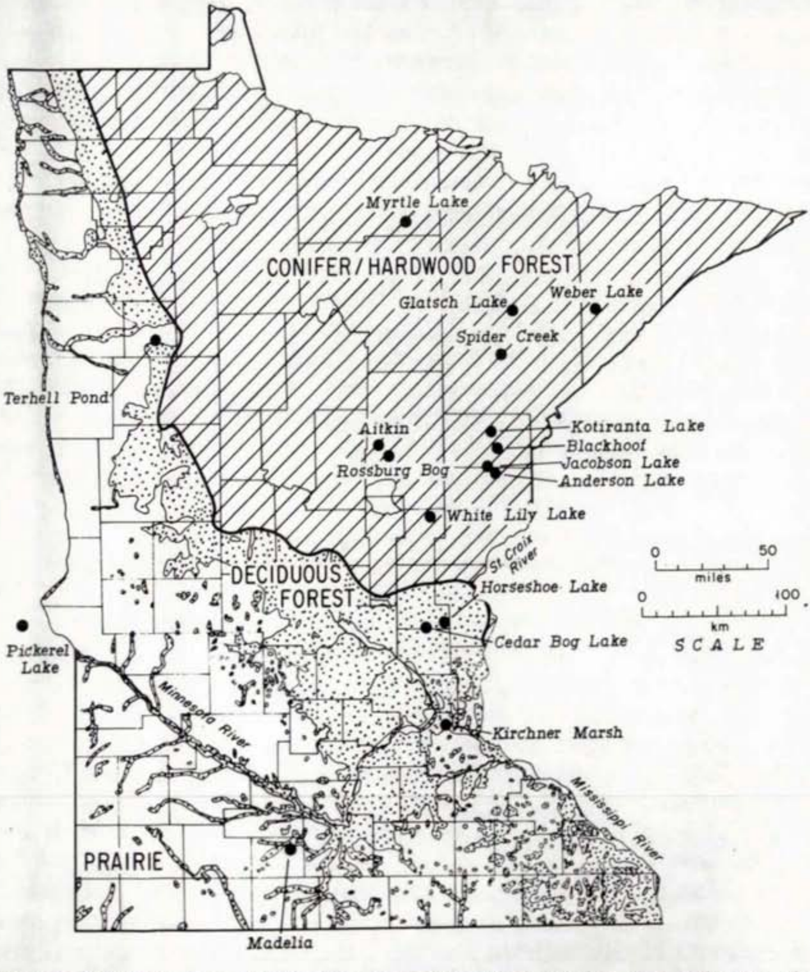


Figure 10. Vegetation map of Minnesota, showing location of pollen sites and other places mentioned in the text. Vegetation from Upham (1884).

response to climatic change through late-glacial and postglacial time. It also becomes possible to study the compositional changes within each band, because all the tree species in a forest do not behave the same under the dynamic conditions imposed by changing climate and changing edaphic controls. Even with relatively static conditions after a climatic change, forest composition may be modified as a result of differential rates of immigration of major tree species.

The objective of the following section is to trace the vegetational history in northeastern Minnesota through late-glacial and postglacial time, to relate it to the history of adjacent regions, and to work out the patterns of climatic and edaphic change for the region. The method of study includes both pollen analysis and plant-macrofossil analysis of lake sediments, controlled by radiocarbon dating. Pollen analysis gives primarily the picture of regional upland vegetation, and the similarities and differences in the pollen profiles from site to site reveal the gradients of vegetational change. Analysis of seeds and other plant macrofossils, on the other hand, pertains largely to local conditions within a lake or on its immediate margins. But a lake itself, with its changing water levels, water chemistry, trophic status, and morphometry, reflects environmental conditions with fair accuracy. Together, pollen and macrofossils give a balanced picture of environmental history.

Apart from the early surveys on the pollen sequence by Potzger (1953), the first detailed study of vegetational history in northeastern Minnesota was that of Fries (1962) at Weber Lake, in the dominantly coniferous part of the Great Lakes Forest. This site was selected in part because it was located in an enclave among ice lobes, and in part because it was approached but not overriden by ice from several directions three times after it became open. Thus the lake is ideally located to examine the relations between ice-margin fluctuations and vegetational history. In the present study, plant macrofossils of the basal sediments were analyzed to supplement Fries' pollen diagrams, two of which have been combined and redrawn for easier comparison with the diagrams newly presented here (pl. 6).

The next investigation, of the sediments of Glacial Lake Aitkin on the dominantly deciduous side of the Great Lakes Forest (Farnham and others, 1964), not only extended the pollen zonation to the southwest but also provided a key radiocarbon date for correlation with the glacial sequence. Then the late-glacial pollen and macrofossils from a pond at Spider Creek, closer to Weber Lake but related in origin to the Glacial Lake Aitkin-Lake Upham history, were studied by Baker (1965), who demonstrated the occurrence of tundra plants and also the absence of spruce and larch in the early history of the area.

The following section describes principally the pollen and macrofossils (1) at a pair of sites (Jacobson and Anderson lakes) in the Nickerson Moraine south of Glacial Lake Duluth in the Great Lakes Forest; (2) at Kotiranta Lake, on outwash older than the Nickerson Moraine west of Duluth and in the dominantly coniferous section of the Great Lakes Forest;

(3) at Glatsch Lake, at the south edge of the Mesabi Iron Range on the margin of Glacial Lake Upham and also in the coniferous part of the Great Lakes Forest; and (4) at Rossburg Bog, near the outer margin of the mixed coniferous-deciduous forest. This section of the text also integrates the findings of all previous investigations in northeastern Minnesota and sets the region in the context of the phytogeographic and climatic history of the rest of the state. The late-glacial stratigraphy at the Blackhoof site, in a drainage channel related to Glacial Lake Upham and also primarily in the conifer forest, is reported separately (Wasylikowa and Wright, 1969), as is an entire profile from Myrtle Lake, located on a big conifer bog on the Glacial Lake Agassiz plain (Janssen, 1968).

Methods

At Jacobson Lake, two cores were taken with a modified Livingstone piston sampler (Cushing and Wright, 1965). The lower part of the sediment section was recovered in Core 1, which came from the edge of the fringing mat of *Calamagrostis* on the northern margin of the lake. The core terminated in red clayey till. The upper part of the sediment was not sampled at this point because it was largely peat, and gyttja was preferred for pollen and seed analysis. The upper sediment was therefore cored instead at an offshore point near the middle of the basin, about 80 m south of the site of Core 1 but only a few meters from the sedge mat that covers the lake on the east. The two cores overlap over a thickness of about 3 m (pl. 2, 3); analysis of the duplicated portion provided the opportunity to duplicate the pollen and seed sequences for at least a short section, and thereby to introduce the consideration of problems of local dispersal of seeds.

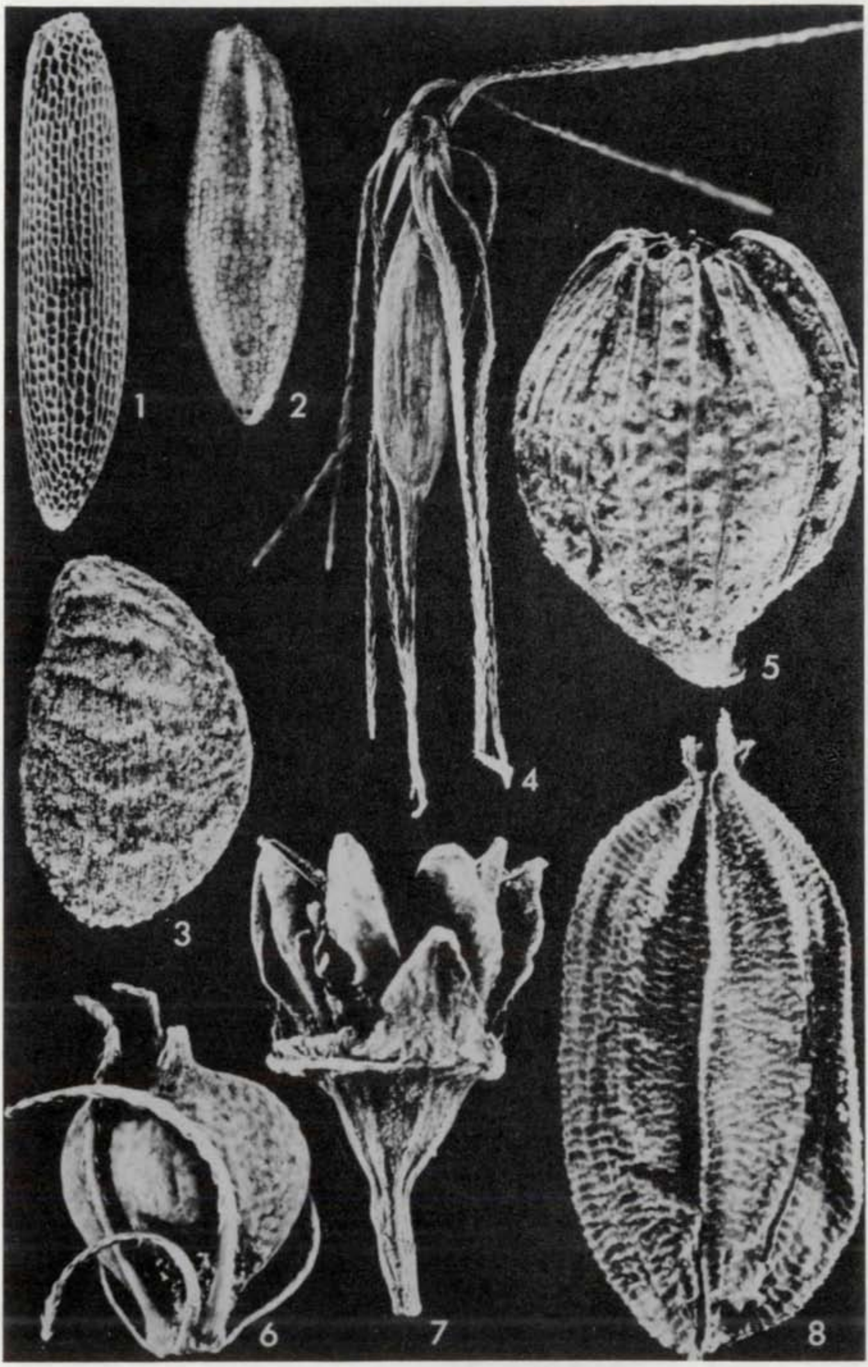
Anderson Lake, 1 mile southeast of Jacobson Lake, was cored to examine replication of the regional pollen rain for the early part of the sequence. Only the basal part of the sediment section was therefore cored, also with a 2-inch Livingstone piston corer. The core terminated in red clayey till.

Kotiranta Lake (pl. 4) was cored on the north side from the edge of the narrow floating sedge mat that rims the lake and is in turn surrounded by a bog of *Picea mariana* (black spruce). A supplemental core taken at the center of the lake showed about the same thickness of sediment. The cores terminated in coarse sand characteristic of the outwash plain in which the lake is located.

Glatsch Lake (pl. 5) was cored in the center with a 2-inch Livingstone sampler. Only the basal 2 m of organic sediment was taken. The core terminated in sand.

Rossburg Bog (pl. 5) was cored near the center (station 2 of Swain, 1967). The peat of the upper half is underlain by gyttja, and this by clay.

Cores were extruded in the field and handled in the manner described by Wright and others (1964). Samples were prepared and counted according to standard methods (Faegri and Iversen, 1964). A sum of 300 pollen grains was counted for most spectra, in addition to pollen of aquatic plants, which were excluded from the pollen sum.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Differentiation of *Pinus* pollen types at Jacobson and Weber lakes and Rossburg Bog was made on the basis of the presence of verrucae in the furrow of *Pinus strobus* (Haploxylon type) and their absence in *P. banksiana/resinosa* (Diploxylon type), as described by Ueno (1958) and Cushing (1963).

For macrofossil analysis at Jacobson and Anderson, 10-cm segments of core were washed through screens with openings of 0.4 and 0.1 mm. Fossils were picked and stored wet according to procedures described by Watts and Winter (1966). Identifications were based on comparison with a large reference collection mostly obtained from the University of Minnesota Herbarium. Conventions for applying a species name or qualifying with the prefix "cf." or the postscript "type" follow those explained in Watts and Winter (1966). All plant names follow Fernald (1950) except for *Nuphar* (Watts and Winter, 1966).

Photographs of representative or critical fossil types were taken by R. C. Bright of the Bell Museum of Natural History of the University of Minnesota (figs. 11-14). For this purpose the fossils were slowly dried under a bell jar, coated with ammonium chloride, and mounted on a needle (Bright and Woo, 1969).

In the macrofossil diagram of Jacobson and Anderson Lakes (pl. 3) the numbers of seeds for each 10-cm sample (about 200 cc) are shown by black bars; needle bases of *Picea* and needle tips of *Larix* are shown by white bars. Needles of *Pinus* and *Abies*, as well as leaves, bracts, and capsules of other plants, are tallied only as *present*, largely because of their fragmentary nature and uncommon occurrence.

The sum of seeds (and fruits) for each 10-cm core segment ranged from only a few up to more than 700. About half the samples had more than 100 specimens. In order to provide an idea of the relative abundance of individual species, percentage curves were also drawn, after the sums of adjacent spectra were combined where necessary to establish a total generally of 100 or more specimens for each point. The groups of levels that were combined to constitute the percentage spectra are shown by a special column at the far right of the seed diagram. Needles were not included in the sum.

The taxa on the seed diagram for Jacobson Lake (pl. 3) are arranged in ecological groups as well as in order of appearance in the stratigraphic sequence. The ecological groups resemble principally those established by Curtis (1959) for Wisconsin.

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Figure 11. Plant macrofossils from Jacobson Lake

1. **NAJAS GRACILLIMA X25. core J2, depth 475-485 cm**
2. **NAJAS FLEXILIS X25. core J2, depth 475-485 cm**
3. **RANUNCULUS section BATRACHIUM X25. core J1, depth 840-850 cm**
4. **DULICHIUM ARUNDINACEUM X15. core J2, depth 350-360 cm**
5. **CAREX LASIOCARPA X25. core J2, depth 525-535 cm**
6. **SCIRPUS PURSHIANUS X25. core J2, depth 240-250 cm**
7. **SPIREA ALBA fruit X25. core J2, depth 535-545 cm**
8. **LACTUCA CANADENSIS X25. core J2, depth 865-875 cm**


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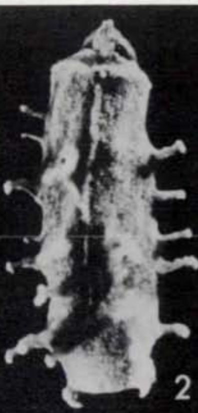
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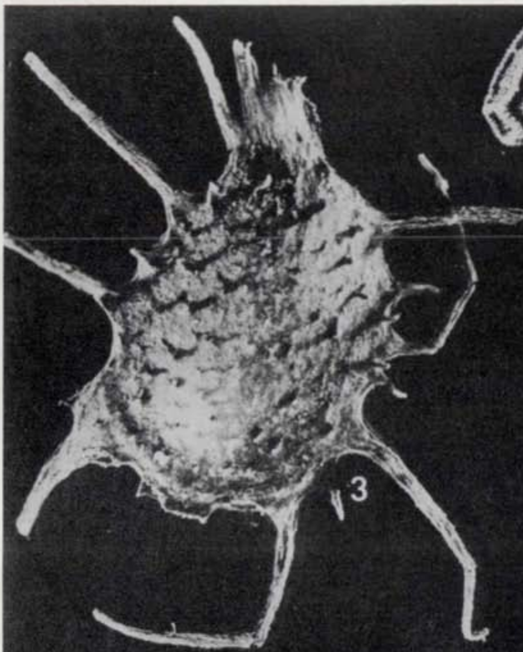
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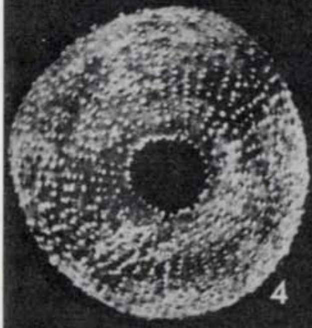
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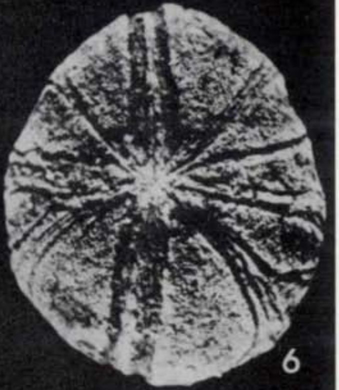
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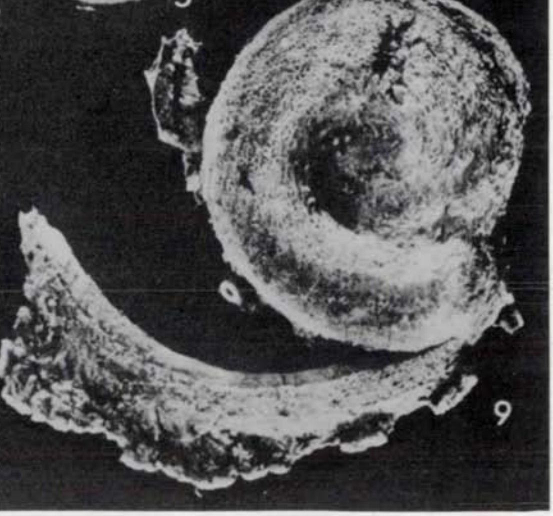
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For the Kotiranta, Weber, and Glatsch cores, macrofossils were washed in the same manner, but the total number of specimens recovered was insufficient for diagrammatic presentation.

The Modern Vegetation Around Jacobson Lake

Because so much information on local vegetational succession was yielded by the macrofossil analysis at Jacobson Lake, it was considered desirable to examine in some detail the modern vegetation around the lake. Ecologic groupings were established to assist in ordering macrofossil data into a diagram and also to help in determining some unknowns that remained when the routine macrofossil analysis was complete. In fact *Spiraea alba* and *Campanula uliginosa* type were released from the tally of unknowns when a species list of the living flora was compiled. The modern flora was recorded by Watts and Brian Seddon in mid-September 1965. Dr. Seddon's assistance is gratefully acknowledged.

Jacobson Lake is oval in shape, with its longest axis trending north. The lake has steep slopes around it except at the north end, where a *Calamagrostis* meadow occurs. Between the lake and the forested upland at the south end is a narrow peaty area, which is also forested. The northern part of the lake is surrounded by farmland, mostly hay-meadows.

The remnant of upland forest at the south end of the lake contains *Tilia americana, Acer saccharum, A. spicatum, A. rubrum, Betula papyrifera, Abies balsamea, Picea glauca, Corylus cornuta, Populus tremuloides, Quercus rubra, Cornus alternifolia,* and *Diervilla lonicera,* among the trees and shrubs. A large specimen of *Quercus alba* is present in a meadow beside the lake. The herbaceous flora includes *Lycopodium obscurum, L. lucidulum, Gymnocarpium dryopteris, Thelypteris phegopteris, Clintonia borealis, Trillium cernuum, Polygonatum* sp., *Hepatica* sp., *Aquilegia canadensis, Aralia racemosa, A. nudicaulis, Osmorhiza claytoni, Trientalis borealis, Pyrola elliptica, Circaea* sp., *Galium triflorum, Mitella nuda, Rubus pubescens, Aster macrophyllus, Solidago flexicaulis,* and *Carex* cf. *aurea.* This woodland resembles the northern mesic forest of Wisconsin (Curtis, 1959, p. 534).

Where the peat at the southern end of the lake adjoins the upland, a distinct kind of woodland is characterized by *Fraxinus nigra* and *Ulmus* spp. with luxuriant ferns and tall herbs. Trees and shrubs noted are *Fraxinus nigra, Ulmus americana, U. rubra, Acer rubrum, A. saccharum, A. spica-*

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Figure 12. Plant macrofossils from Jacobson Lake

1. **UTRICULARIA sp. X25. core J2, depth 605-615 cm**
2. **MYRIOPHYLLUM FARWELLI X25. core J2, depth 400-410 cm**
3. **CERATOPHYLLUM ECHINATUM X10. core J2, depth 350-360 cm**
4. **BRASENIA SCHREBERI X15. core J2, depth 100-115 cm**
5. **SELAGINELLA SELAGINOIDES megaspore X50. core J1, depth 895-905 cm**
6. **CORNUS RACEMOSA type X15. core J1, depth 495-505 cm**
7. **DIERVILLA LONICERA X25. core J2, depth 125-135 cm**
8. **HYPERICUM VIRGINICUM X25. core J2, depth 230-240 cm**
9. **POTAMOGETON GRAMINEUS X25. core J2, depth 125-135 cm**

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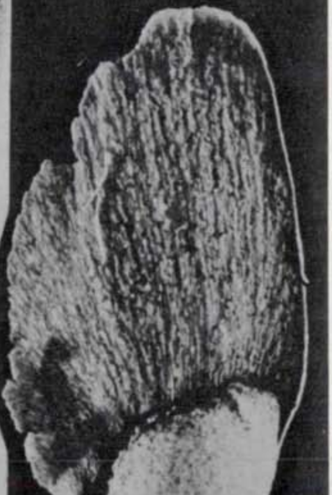

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tum, Corylus cornuta, and *Ribes americanum.* The herbs include *Athyrium filix-femina, Dryopteris spinulosa, D. cristata, Equisetum sylvaticum, Carex intumescens, C.* sect. *ovales, Maianthemum canadense, Clintonia borealis, Polygonatum canaliculatum, Arisaema stewardsonii, Caltha palustris, Aralia racemosa, Lycopus uniflorus, Scutellaria lateriflora, Rubus pubescens, Viola nephrophylla, Lactuca biennis,* and *Solidago gigantea.*

This *Fraxinus-Ulmus* stand grows on shallow peat or wet mineral soil. On deep peat beside the lake a considerable diversity of woodland types exists. There are two basic types: stands of alder with tall herbs and luxuriant ferns, and conifer woodland with low herbs and *Sphagnum.* Intermediate types are too numerous to list here.

On the west side of the lake is a small stand of conifer woodland dominated by a mixture of *Larix laricina, Picea glauca,* and *Abies balsamea.* A few specimens each of *Acer rubrum, A. spicatum, Pinus strobus, Betula papyrifera, Populus tremuloides, Fraxinus nigra, Ulmus americana, Alnus rugosa,* and *Amelanchier* sp. occur. The ground flora has conspicuous abundance of *Sphagnum* sp., *Lycopodium annotinum, L. clavatum, Osmunda cinnamomea, Coptis groenlandica, Clintonia borealis, Maianthemum canadense,* and *Carex trisperma.* Also present are *Athyrium filix-femina, Dryopteris spinulosa, Pteridium aquilinum, Ledum groenlandicum, Vaccinium angustifolium, Aralia nudicaulis, Rubus* sect. *Eubatus, R. idaeus, Galium asprellum, Lycopus uniflorus, Bidens frondosa,* and *Iris versicolor.* This community is reminiscent of the northern wet forest of Curtis (1959, p. 544). The community appears to be in the process of degeneration and replacement at Jacobson Lake. One has the impression that the conifers have relatively recently invaded a more open bog-like community rich in *Sphagnum* and ericaceous shrubs, which are now being shaded out and invaded by herbs of more mesic lowland woodland.

The alder thicket is a tall shrub community. *Alnus rugosa,* growing to a height of perhaps 5 m, is dominant in dense, almost pure stands. A few specimens of *Fraxinus nigra, Acer rubrum, Betula papyrifera, Pinus strobus, Aronia melanocarpa,* and *Amelanchier* sp. occur in a stand that was recorded on the west side of the lake. The understory of this community is dominated by tall herbs and large ferns growing to perhaps 1 m in height. Species recorded are *Osmunda cinnamomea, Onoclea sensibilis, Athyrium filix-femina, Dryopteris cristata, Lycopus americanus, Spiraea alba, Rubus idaeus, R.* sect. *Eubatus, R. pubescens, Solidago gigantea, Aster umbellatus, A. puniceus, Cicuta maculata, Viola* cf. *cucullata, Galium asprellum, Calamagrostis canadensis, Glyceria canadensis, Carex* cf. *normalis, C. intumescens, C. trisperma, Trillium cernuum, Maianthemum canadense,* and

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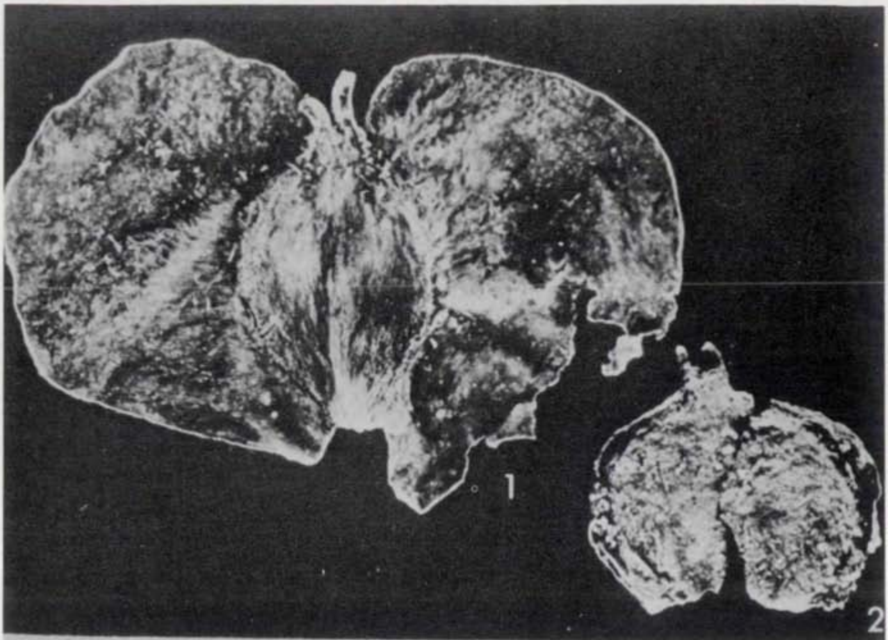
Figure 13. Plant macrofossils from Jacobson Lake

1. **ABIES BALSAMEA X15. core J2, depth 430-440 cm**
2. **PINUS RESINOSA X15. core J1, depth 550-560 cm**
3. **PICEA sp. X25. core J1, depth 895-905 cm**
4. **ABIES BALSAMEA wing X15. core J2, depth 430-440 cm**
5. **LARIX LARICINA fruit with wing X15. core J2, depth 100-115 cm**



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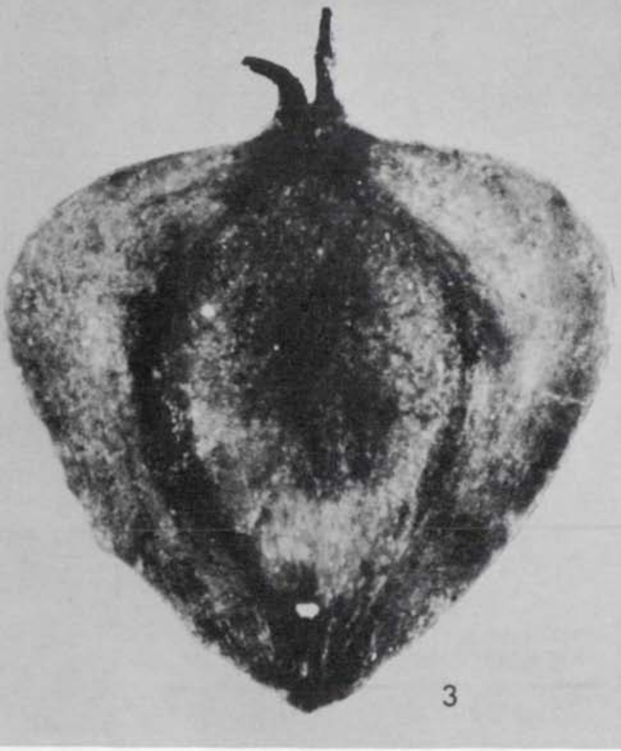

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Arisaema stewardsonii. This community closely resembles the alder thicket community of Curtis (1959, p. 577).

In stands intermediate between alder thicket and northern wet forest, the following additional species were noted: *Cornus canadensis, Impatiens biflora, Urtica gracilis, Sambucus* cf. *pubens, Polygonum cilinode, Sorbus americana, Ilex verticillata,* and *Prunus serotina.*

The alder thicket grades into a community, here called alder swamp, that exists in shallow water around perhaps two-thirds of the lake's circumference. It consists of a discontinuous and rather open floating mat of vegetation in which *Chamaedaphne calyculata* and *Potentilla palustris* are very conspicuous. At the landward side isolated small alder bushes grow in shallow water. Their bases and the patches of soft muck between them have a characteristic flora consisting of *Spiraea alba, Salix* sp., *Iris versicolor, Rumex orbiculatus, Menyanthes trifoliata, Cicuta bulbifera, Hypericum virginicum, Lycopus uniflorus, Scutellaria lateriflora, Lysimachia thyrsiflora, Bidens* cf. *frondosa, Thelypteris palustris, Calamagrostis canadensis, Viola* sp., *Galium asprellum, Carex diandra,* and *Sphagnum* sp. Occurring locally in the shade of the alders are *Carex rostrata* and *Typha latifolia.*

External to the floating mat is a zone of floating-leaved aquatics, predominantly the water-lilies *Brasenia purpurea, Nymphaea tuberosa,* and *Nuphar lutea. Lemna minor* and *Spirodela polyrhiza* also occur abundantly in shallow water in the alder thicket zone. Of submerged aquatics *Ceratophyllum echinatum* (one fruiting specimen) and *Utricularia vulgaris* are ubiquitous. An aquatic moss (probably *Acrocladium* sp.), the floating liverwort *Riccia natans,* and a green alga (cf. *Cladophorales*) are also abundant. There was no opportunity to examine submerged vegetation.

The portion of the lake margin not occupied by alder swamp and alder thicket has a fringing stand of *Typha latifolia* (cattail), behind which is a stand of several willow species, including *Salix discolor* and *S. pedicellaris.* This vegetation is referred to as cattail marsh (Curtis, 1959, p. 391). At the margin are *Hypericum virginicum* (common), *Eleocharis smallii, Calla palustris, Sagittaria* sp., *Scirpus cyperinus, Carex rostrata, Impatiens biflora,* and *Glyceria canadensis.*

Immediately behind the cattail stand is the large meadow of *Calamagrostis canadensis* that has been referred to earlier. The grass occurs in a dense stand 1-2 m high growing on peat only slightly elevated above the lake level. Tall herbs are scattered through the meadow. These include *Geum* cf. *macrophyllum, Scutellaria lateriflora, Mentha arvensis, Epilobium leptophyllum, E. palustre, E. glandulosum, Lysimachia terrestris, Campanula uliginosa, Bidens* cf. *connata, B. cernua, Polygonum coccineum, P. sagittatum, Aster puniceus, A. umbellatus, A. paniculatus* var. *simplex,* and

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Figure 14. Plant macrofossils from Jacobson Lake

1. **BETULA PAPYRIFERA X25. core J2, depth 495-505 cm**
2. **BETULA cf. GLANDULOSA X25. core J1, depth 895-905 cm**
3. **BETULA LUTEA X25. core J2, depth 190-200 cm**

Eupatorium maculatum. This community is clearly Curtis' northern sedge meadow (Curtis, 1959, p. 373).

The lists presented here are not exhaustive, and it is likely that a visit at another season would have yielded more information about *Carex* species, which had largely dropped their fruits in September. Yet it is striking that a number of conspicuous species recorded in the macrofossil diagram (e.g., *Scheuchzeria, Sarracenia, Vaccinium macrocarpon*) were not found at Jacobson Lake, despite careful search. The possibility of recent loss of open bog communities caused by colonization of coniferous trees has already been suggested and is referred to later in the text.

The diversity of the present vegetation on peat around the lake suggests that succession from open water to forested peat may take place by more than one route. One possible route is from open water *via* floating-leaved aquatics to cattail swamp, then to northern sedge meadow, with ultimate colonization of the sedge-meadow by alder thicket. In fact it is possible that the northern sedge meadow that adjoins cultivated land is a secondary community recently created by removal of shrubs in the course of forest clearance. A second route involves floating-leaved aquatics being invaded in shallow water by species of the alder swamp community, this giving way directly to northern wet forest with patches of open bog.

In the macrofossil diagram, species have been referred to ecologic groups, with the use primarily of terminology and species lists of Curtis (1959). Alder swamp is a new term, as is the weed group. The diagram is designed around the idea of two possible succession routes. A central panel summarizes the diagram. The succession to alder thicket begins at the panel and extends leftward, whereas succession to northern wet forest extends to the right. The more strictly upland species of the northern dry forest are placed to the extreme right of the diagram. It will be seen that the succession of cattail marsh to alder thicket extended throughout postglacial time, but that the second type of succession took place only in the late postglacial.

Biostratigraphic Zonation

Introduction. The pollen diagrams are zoned at significant points of inflection of major pollen curves to facilitate description of the various sites. Studies elsewhere in Minnesota have shown that the regional phytogeography has had strong gradients ever since the area was first revegetated after deglaciation. Furthermore, vegetational change is dynamic and involves the interaction of different plant species migrating at different rates in response to climatic change (Wright, 1968a). Therefore the characteristics of pollen zones differ from site to site.

When a large number of sites has been studied and dated, a regional pollen zonation can be established to represent the geographic and dynamic aspects of the vegetational development. Such a zonation for late-glacial and early postglacial time has been proposed by Cushing (1967). The zone names are taken from diagnostic pollen types that distinguish the zones, and they thus qualify as assemblage zones according to the Code of Stratigraphic

Nomenclature. This terminology will be used for correlation, but for the description of the pollen sequence at individual sites (or pairs of closely spaced sites), a numbered sequence will be used, with a prefix of letters to designate the site. Thus the Jacobson and Anderson sites, which are a mile apart and show identical zonation, are designated as JL, Kotiranta Lake KL, Glatsch Lake as GL, Weber Lake as WL, and Rossburg Bog as RB. This procedure follows that utilized by Cushing (1964, 1965, 1967) for Andree Bog (AB), Cedar Bog Lake (CBL), Horseshoe Lake (HL), and White Lily Lakes (WLL), and that of Janssen (1968) for Myrtle Lake (ML).

Pollen zones largely reflect the upland vegetation. Seed diagrams reveal the local conditions in and around the lake and on the adjacent hill slopes. Although some seed diagrams can be zoned independently, their interpretation is much facilitated if they are studied in the context of a pollen sequence. Consequently, in the present study the pollen zones are indicated also on the seed diagrams, and the features of both diagrams are described zone by zone.

Zone JL-1: Jacobson and Anderson Lakes. The sediment of zone JL-1 consists largely of silty gyttja.

Zone JL-1 as a whole at both sites is dominated by *Picea* pollen, with *Betula* and *Larix* important (pl. 2). It represents the *Picea-Larix* assemblage zone of Cushing (1967). Conspicuous by their very low percentages (compared to the zone above) are *Abies, Pinus, Fraxinus, Ulmus, Quercus, Ostrya* type, and *Corylus*. Among the herbs, Cyperaceae is the dominant type, especially near the base of Anderson. *Artemisia* and Gramineae differ little from the zone above, and *Ambrosia* is only slightly less. *Botrychium* and *Selaginella* are relatively conspicuous. Among the aquatic and marsh plants *Ranunculus, Myriophyllum, Potamogeton, Sphagnum,* and *Sparganium* type are relatively important, as well as *Pediastrum* (counted at Anderson only).

The seed diagram for zone JL-1 provides extra information about the environment (pl. 3). The basal 25 cm at Jacobson Lake is marked by an accumulation of terrestrial plant debris including twigs, cones, needles, leaves, and seeds. Conspicuous are remains of *Picea, Larix laricina, Betula* cf. *glandulosa, Viola pallens, Fragaria virginiana* type, and the moss *Selaginella selaginoides*. The species of *Picea* could not be identified from seeds or needles, but two cones of *P. glauca* were found. This relatively coarse material, mixed in a matrix of pink silt, is considered to represent the floor of a conifer forest, either *in situ* or slightly transported. Similar debris at Kirchner marsh in southeastern Minnesota contains terrestrial diatoms as well (Florin and Wright, 1969). Apparently the block of stagnant glacial ice that ultimately localized the lake was covered by forest and had just begun to melt, allowing the accumulation of forest floor debris.

Above the basal layers of plant debris, the sediment of zone JL-1 consists of silty gyttja. By this time the buried ice block had melted completely and an open lake had formed. The aquatic plants in these sediments include *Ranunculus* sect. *Batrachium, Myriophyllum exalbescens* type, *Potamogeton amplifolius, P. pusillus,* and *Sparganium chlorocarpum.* The Cyperaceae recorded in the pollen counts is apparently *Carex aquatilis* and *C. rostrata.* These two species dominate the aquatic flora in the basal sediments not only here but also in other sites in the region, *e.g.*, Pickerel Lake (Watts and Bright, 1968), so the group is termed "pioneer aquatics."

Zone JL-1 as a whole represents a newly developed lake partly rimmed by wet ground containing *Larix laricina, Betula glandulosa,* and perhaps *Picea mariana.* The marginal vegetation was not sufficiently complete to screen out the mineral sediment washed into the basin from the hill slopes, however, for the sediments are silty, and the C-14 dates indicate that sedimentation was rapid. The upland may have carried *Picea glauca* and *Betula papyrifera.*

Nothing in the pollen or macrofossils of zone JL-1 indicates tundra vegetation, unlike the basal layers at Kotiranta and other more northerly sites, where the high pollen values of Cyperaceae are accompanied by high *Artemisia* pollen as well as by macrofossils of tundra indicators, and where macrofossils of conifers are absent (Baker, 1965; Watts, 1967). This does not necessarily mean that tundra plants were absent in the Jacobson area immediately after ice retreat. It may mean instead that these two sites were still filled with buried ice for many hundreds of years after active ice formed the moraine in which they are located (Florin and Wright, 1969). The C-14 dates indicate that the basal sediments at Anderson and Jacobson Lakes are at least 3000 years younger than those at Kotiranta Lake. It is therefore probable that zone 1a of Kotiranta (see below) is simply not represented at Anderson and Jacobson.

Zone KL-1: Kotiranta Lake. Zone KL-1 at Kotiranta Lake has two portions. The lower 70 cm (KL-1a) consists of silty clay, resting on sand. Distinct layers of coarse plant detritus occur locally at the contact. As with Jacobson Lake, the detrital layer implies deposition in a shallow pond formed by the incipient melting of glacial ice, which had been buried in this case by outwash sands. The melting was earlier, however, for a radiocarbon date for the top 5 cm of zone KL-1a is 11,500±600 B.P. (W-1059), and dates for a deeper section are 13,480±350 B.P. (W-1762) and 16,150±550 B.P. (W-1973). (The last-named date is surprisingly old; the silty sediment that was dated contained very little organic matter; until it is confirmed by another date, it will be designated with a query.)

Zone KL-1a (pl. 4) is marked by about 50% NAP, especially Cyperaceae, Gramineae, *Artemisia* and other Compositae (presumably mostly *Ambrosia*), and Ericales. It represents the regional Compositae-Cyperaceae pollen assemblage zone. Of the trees, pollen of *Picea* (about 40%) is dominant, with a few percent each of *Pinus, Betula, Fraxinus, Ulmus, Quercus,* and *Ostrya* type, as well as *Salix, Populus,* and *Juniperus* type. Macrofossil analyses show no needles of *Picea* or *Larix* or of the other trees mentioned. They do show a few fragments of plants now common in tundra regions (table 2): *Dryas integrifolia, Salix herbacea, Juncus balticus, Vaccinium uliginosum* var. *alpinum,* and probably *Rhododendron lapponicum* (see Baker, 1965, for distribution maps). The two last-named species may have been responsible for much of the Ericales pollen recorded.

Table 2. Tundra-type plant macrofossils at northeastern Minnesota sites at levels below the first occurrence of *Picea* and *Larix* needles. Spider Creek identifications from Baker (1965), Blackhoof from Wasylikowa and Wright (1969).

	Weber Lake	Glatsch Lake	Spider Creek	Kotiranta Lake	Blackhoof
Dryas integrifolia	x		x	x	x
Salix herbacea	x		x	x	
Juncus balticus			x	x	
Vaccinium uliginosum var. *alpinum*			x	x	
Betula glandulosa	x	x	x		x
Silene acaulis	x				
Rhododendron lapponicum			x	x?	
Carex trisperma			x		
Carex capillaris			x		
Stellaria humifusa (or *Cerastium alpinum*)			x		
Potentilla nivea			x		
Arenaria cf. *humifusa*			x		

Although all five of the arctic plants listed have outlying stations in the boreal or even the temperate forest (*Rhododendron lapponicum* occurs in central Wisconsin), it seems likely that during the time of zone 1a the landscape around Kotiranta Lake was completely open, except for possible local stands of *Picea* close enough to supply some pollen. Although the high percentages of Cyperaceae and Gramineae pollen might be attributed to local aquatic or marsh plants, the *Artemisia* pollen must have come from the upland. The combination of high counts of herb pollen, presence of macroscopic remains of plants common in tundra regions, and absence of conifer needles is consistent with a picture of open landscape too cold for trees. The same general picture is found at Spider Creek below 890 cm (Baker, 1965) and at Weber Lake in zones 1 and 2 (pl. 6); at both of these latter sites, macrofossils of the same group of tundra herbs occur below the level of the first conifer needles (table 2). The peak of *Betula* pollen at these two latter sites represents the dwarf birch *B. glandulosa,* according to macrofossils; the peak marks the *Betula-Picea* assemblage zone of Cushing (1967).

The only other control on the distance to *Picea* stands comes from the more direct data supplied by contemporaneous sites in Minnesota. Jacobson is apparently not old enough at the base to be a zone 1a, although Anderson may be. Cedar Bog Lake (60 miles south of Kotiranta Lake) is older than 11,500 years at the base, but *Picea* and *Larix* needles already occur in abundance, and tundra-type plants are absent (Cushing, 1963). At nearby Horseshoe Lake, the lowest level contains leaf fragments of *Dryas integrifolia*, as well as a high pollen percentage of Cyperaceae (Cushing, 1967).

The same is found another 50 miles farther southwest at Norwood, where it is interpreted as the reflection of pioneer treeless vegetation rather than as normal tundra (Watts, 1967). Radiocarbon dates of the pollen zone at Madelia and Kirchner Marsh that is correlative with the Norwood horizon indicate that the entire southern area was well forested at the time of zone KL-1a at Kotiranta. Aitkin, 50 miles west of Kotiranta, shows *Betula glandulosa* macrofossils along with *Picea* needles in the basal sediments, dated as 11,635 years old—thus contemporaneous with KL-1a. The Weber Lake area was certainly tundra at this time, as were also the Spider Creek and Glatsch areas (although there are no carbon dates here to demonstrate contemporaneity). At any rate, the tundra/forest border at the time of zone KL-1a must have been located less than 50 miles to the west and south of Kotiranta (fig. 15).

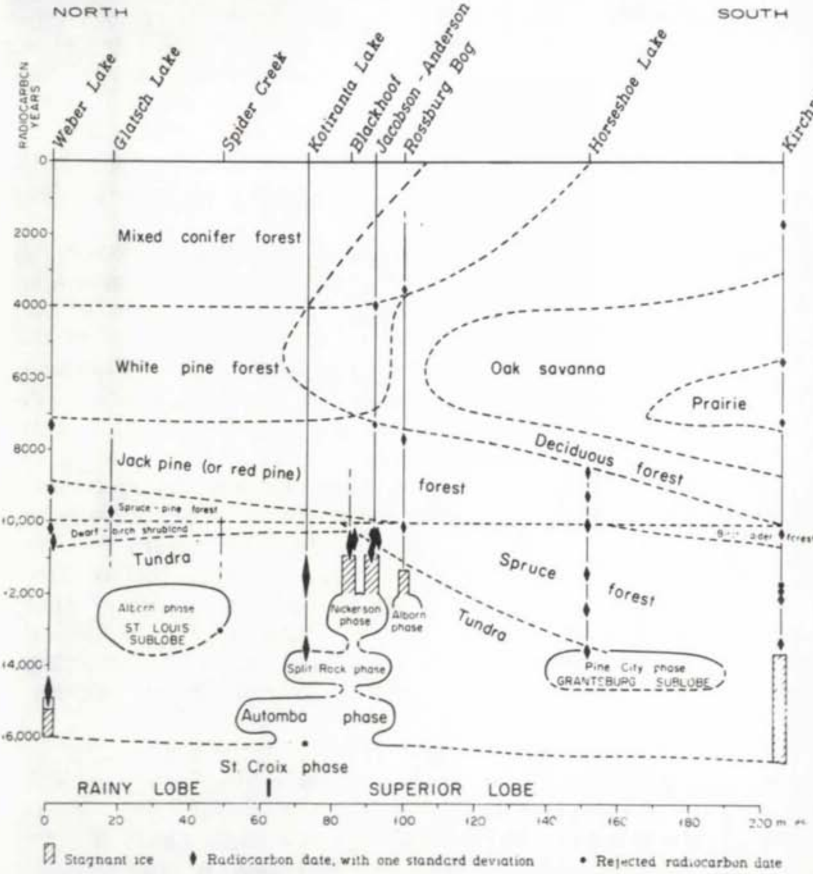

Figure 15. Summary diagram showing the changes in vegetation types from north to south in eastern Minnesota since the time of glaciation, as inferred from pollen diagrams for the sites listed. The times and areas of ice-lobe activity are also shown.

At all northern sites under consideration, the common occurrence of pollen of temperate deciduous trees and of *Ambrosia* type in the Compositae-Cyperaceae zone shows that temperate vegetation was within easy pollen-transporting distance of this region. The total value for these temperate types for each site is 8-16%, compared to <1% in the tundra or the boreal forest of today (table 3). Yet one cannot claim that the continuous deciduous forest was closer to the tundra then than it is now, and thus a closer major source for temperate pollen types, because pollen diagrams throughout the Middle West indicate that the late-glacial boreal forest extended at least as far south as Kansas and Missouri and was thus as broad as it is today (Wright, 1970). Furthermore, the winds then were more northerly than southerly (Wright, 1970). A safer conclusion is that temperate plants must have been distributed throughout much of the boreal forest in fair quantity, to contribute to the pollen rain at nearby tundra sites.

Zone 1b at Kotiranta consists of clayey gyttja grading up into pure gyttja. The pollen content resembles that of Jacobson and Anderson in most details; the zone thus belongs to the *Picea-Larix* assemblage zone. *Picea* (65%) is the dominant tree pollen type, but here (in contrast to Jacobson and Anderson) *Betula* reaches a maximum of 20% at the top of the zone. *Salix* continues its curve from below, but all the other tree types mentioned have very low counts. *Larix* has a continuous curve for the first time. The herb pollen types all show descending curves.

Macrofossils include needles of *Picea* and *Larix*. Trees of these genera must have invaded the region by 11,500 years ago, although they apparently did not reach the Blackhoof site, about midway between Kotiranta and Jacobson, until a thousand years later, at least in any quantity (Wasylikowa and Wright, 1969), nor Weber Lake until as late as 10,000 years ago (Fries, 1962). Perhaps the well-drained character of the sandy outwash plain of Kotiranta Lake encouraged early invasion of *Picea glauca*, in the same manner as it may have encouraged relatively early melting of the buried ice block. White spruce is the pioneer tree on new sandy glacial floodplains in western Canada today, and in fact it even grows extensively on ice-cored moraine until a peat mat of *Sphagnum* and Ericaceae reduces the surface drainage so that black spruce invades (Rampton, 1969).

Zone GL-1: Glatsch Lake. Glatsch Lake is the most northern of the sites for which pollen diagrams are here presented, so its zone GL-1 resembles correlative zones at Spider Creek and Weber Lake more than that at Kotiranta. A clear subdivision is possible (Pl. 5). Zone GL-1a has high values of Cyperaceae, *Artemisia,* and *Salix* at the base (Compositae-Cyperaceae assemblage zone), followed by a *Betula* peak of 35% (*Betula-Picea* zone) that rivals the peak for Weber Lake—*B. glandulosa* is indicated by the catkin scale of this species that was found. This represents tundra vegetation, followed by a burst of dwarf birch as a precursor to boreal forest (Watts, 1967). Zone GL-1b sees a rise in *Picea* and *Larix* pollen, and the first occurrence of their needles. No carbon date is available for the time of arrival of conifer forest in the area.

Table 3. Percentage of total pollen for five major temperate tree pollen types and one herb type in the herb pollen zone at Weber Lake, Spider Creek, and Kotiranta Lake, in comparison with pollen-trap samples from the modern tundra and boreal forest.

	Fries 1962		Baker 1965		Ritchie and Lichti-Fedorovich 1967			LF & R 1965
	Weber C-1	Weber S-1	Spider	Kotiranta	Tundra	Tundra Forest Transition	Northern Boreal Forest	Boreal Forest
No. of analyses	7	6	7	13	6	8	6	4
Quercus	4.	3.7	2.	1.5	. .	. .	. .	. .
Ulmus	.6	.3	.5	.4	. .	<.1	. .	<.1
Fraxinus	1.6	2.2	8.	2.0	. .	. .	. .	.5
Corylus	2.7	1.1	.5	.1	. .	<.1	.2	.2
Ostrya type	.3	2.0	.5	.5	. .	. .	. .	. .
Ambrosia type	7.	6.5	4.	4.0	1.0*	.2	.2	.2
Total	13	16	15	8	1.	.2	.4	.9

*This figure is reduced to .2 if one eliminates the very high value of 4.0% for the far-northern station of Resolute, where the sparse vegetation of the polar desert yields very little local pollen.

Zone RB-1: Rossburg Bog. Zone 1 at Rossburg Bog has a normal *Picea-Larix* assemblage, although the basal spectrum, with high Cyperaceae, *Salix,* and *Populus,* might represent a zone 1a subdivision corresponding to a tundra vegetation (Pl. 5).

Zone JL-2: Jacobson and Anderson Lakes. Pollen zone JL-2 is dominated by *Pinus banksiana/resinosa.* Common throughout are *Abies, Fraxinus nigra, Ulmus, Quercus, Ostrya* type, and *Corylus.* In the lower part (zone JL-2a, *Picea-Pinus* assemblage zone), *Picea* declines to a very few percent, as *Pinus* climbs to 20-30% and *Larix, Juniperus,* and *Salix* reach their maxima. In the upper part (zone JL-2b, *Pinus-Betula-Alnus* zone), *Alnus* rises abruptly, and *Betula* reaches its maximum. Here *Pinus banksiana/resinosa* reaches 40%, whereas *Picea* continues its decline to zero and *Larix* and *Juniperus* likewise decrease. Spores of the bracken fern *Pteridium* are diagnostic, as they are also in the correlative zone at Cedar Bog Lake (Cushing, 1965), Pickerel Lake (Watts and Bright, 1968), and other sites.

The macrofossil diagram for forest types for zone JL-2 confirms the pollen diagram and provides some species identification. *Pinus* is poorly represented, but needles of *P. resinosa* occur near the top of zone JL-2b. Whether or not *P. banksiana* was also present is a question that must be left open. The modern distribution and autecology of the Minnesota pines as they pertain to this problem are summarized elsewhere (Wright, 1964, 1968a). Because *P. banksiana* has a more northerly distribution today than *P. resinosa,* it would be more expected under past conditions of climate transitional from boreal to temperate.

Abies needles are present throughout zone JL-2. *Picea* seeds and needles decline in number. *Larix* seeds and needles are fewer in zone JL-2 than zone JL-1, unlike *Larix* pollen. The *Alnus* so conspicuous in zone JL-2b is *A. rugosa,* and the *Betula* is *B. papyrifera,* for the seed curves closely match the pollen curves.

For the aquatic and marsh plants in zone JL-2, the pollen diagram shows *Potamogeton, Equisetum,* and *Isoëtes* to be conspicuous in zone JL-2a at Jacobson, and *Potamogeton, Typha latifolia, Equisetum,* and *Nuphar* at Anderson. The seed diagram implies that the *Potamogeton* may be *P. amplifolius* and *P. pusillus,* as in zone JL-1. Seeds of *Typha latifolia* type make their first appearance in zone JL-2a of Anderson.

Zone KL-2: Kotiranta Lake. As at Jacobson and Anderson, zone KL-2 at Kotiranta is marked by the rise of *Pinus, Fraxinus, Ulmus,* and *Quercus,* and by the fall of *Picea* and NAP. It is also divisible into two parts at the level of the rise of *Alnus* and *Betula.*

In zone KL-2a *Pinus* (presumably *P. banksiana/resinosa*) already reaches 60%, compared to only 30% at Jacobson-Anderson. In compensation, the curves for deciduous trees rise a smaller amount than at the more southerly sites, and the NAP is less. The *Larix* curve is relatively high throughout.

In zone KL-2b the *Alnus* and *Betula* curves rise to maxima, as the *Picea* curve completes its descent to a very few percent.

Zone 2 at Jacobson, Anderson, and Kotiranta, as well as its correlative zones throughout Minnesota, represents a time of relatively rapid climatic and vegetational change. Warming of the climate about 11,000-10,000 years ago brought about deterioration of the spruce forest, and the gaps created by blowdown or fire were filled by pine and other trees (Wright, 1964, 1968a). This time of change saw different tree species invading from different directions at different rates, producing mixtures that may not be matched by any modern forests.

Pinus, in its rapid migration from the east, extended as far west as Terhell (McAndrews, 1966) but probably not so far west as Qually at the edge of the Lake Agassiz basin (Shay, 1965) nor so far south as Kirchner (Wright and others, 1963). It did not reach so far southwest as Madelia (Jelgersma, 1962) and Pickerel (Watts and Bright, 1968), where the *Picea* was succeeded instead by *Betula papyrifera, Alnus,* and *Abies*. These last three forest trees must have come from the south or southeast; they were already present in eastern Minnesota (Kirchner, Horseshoe Lake) during the fall of *Picea* 10,800-10,200 years ago, before the abrupt rise in *Pinus* (fig. 16), but northward from there (Jacobson, Kotiranta, Weber, and intermediate sites) they arrived later in the succession about 9500-8500 years

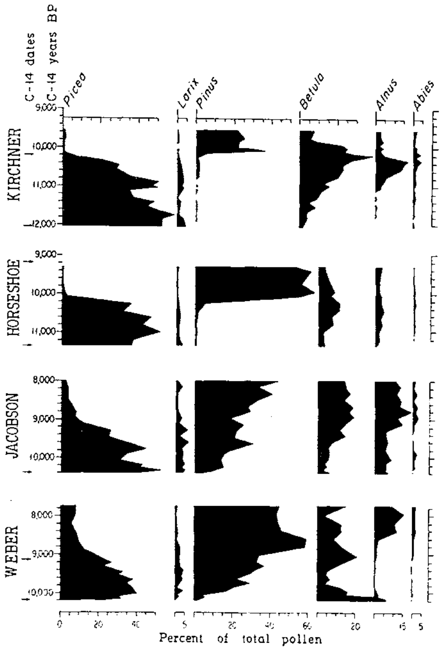

Figure 16. Segments of four eastern Minnesota pollen diagrams showing relation of maxima of BETULA, ALNUS, and ABIES to fall of PICEA. Curves have been replotted on a uniform time scale according to interpolation from available C-14 dates. Original pollen counts from Kirchner Marsh by Winter (1962), Horseshoe Lake by Cushing (1967), Jacobson Lake by Watts (this paper), and Weber Lake by Fries (1962).

ago, well after pine reached its maximum. (The earlier peak of *Betula* pollen, in zone KL-1a and correlative zones of the northern sites, comes from *B. glandulosa*, according to the macrofossils.)

Zone GL-2: Glatsch Lake. In zone GL-2a, *Pinus* pollen rises sharply to replace *Picea* and *Larix* as the dominant types, and *Ulmus, Fraxinus,* and other deciduous tree pollen increases.

In zone GL-2b *Betula* and then *Alnus* rise abruptly, as at other northern sites, as *Pinus* falls from its peak of zone GL-2a.

The pollen sequence thus closely resembles those for other northern sites, especially Weber Lake: of two birch peaks, the lower one (in zone GL-1b) represents dwarf birch, the upper one (in zone GL-2b) paper birch. Paper birch had occurred in the spruce forest of the Jacobson area since zone JL-1, and then it expanded not only there but to the northern sites, probably about 10,200 B.P. The *Alnus* of zone GL-2b, along with *Abies,* which rises at the same level, may represent in part the replacement of *Larix* around certain pond margins.

Zone RB-2: Rossburg Bog. At Rossburg Bog the abrupt *Picea* fall and *Pinus* rise are coincident. This change, which marks the base of zone 2a, is followed by the rise of *Betula* and *Alnus* (zone 2b), as at other northern sites. A radiocarbon date comes from the zone ½ contact—10,100±140 B.P. (Y-2460).

Zone JL-3: Jacobson Lake. Zone JL-3 begins distinctly with a sharp peak in pollen of *Quercus* (duplicated in the two cores) followed immediately by a rise of *Pinus strobus* and an equally sharp fall of *P. banksiana/resinosa,* which reaches a level of about 10%. *Fraxinus nigra* drops from prominence in zone JL-2 to very low values, and *Picea, Larix,* and *Abies* are represented by only a few grains. *Betula, Alnus,* and *Ulmus* continue to decrease from zone JL-2. *Ostrya* type, on the other hand, is slightly higher than in zone JL-2, as is *Tilia.*

The NAP is higher in zone JL-3 than below, largely reflecting the curves for Gramineae, *Ambrosia, Iva xanthifolia* type, Tubuliflorae, and Chenopodiineae. Spores of *Pteridium* are less common.

The macrofossil diagram for zone JL-3 shows low percentages of forest tree types compared to zones below and above. This is true especially for the *Betula papyrifera* curve.

The pollen assemblage for zone JL-3 implies principally an expansion of oak into the region, the approach of prairie openings, and the introduction of *Pinus strobus.* The assemblage resembles the sub-modern assemblage from McCraney Pond at the outer edge of the *Pinus strobus*-Hardwood forest west of Itasca Park in northwestern Minnesota (McAndrews, 1966). The expansion of oak and prairie plants (fig. 15), presumably at the expense of more mesic deciduous forest, implies a drier climate. The oak had reached the Kirchner area in southeastern Minnesota about 10,000 years ago (from the south?), with prairie openings arriving not much later (from the west?). In northwestern Minnesota both reached the Itasca region by 8500 years ago. The oak largely left the Kirchner region by 7200 years ago, leaving the terrain solely to prairie. At this time the oak arrived (with prairie openings) in the Jacobson area, according to a radiocarbon date of 7210±80 B.P. (Y-1690) at the base of zone JL-3. Meanwhile *Pinus banksiana/resinosa,* which had had a brief regime at Kirchner (at least its pollen) until about 9500 years ago, flourished in the Itasca area until the oak invasion 8500 years ago, and in the Jacobson area until the same event 7200 years ago. The new pine pollen identifications for Weber Lake also show the reduction in *P. banksiana/resinosa* and a rise in oak about 7300 years ago, and there even is a small maximum of NAP, along with the virtual end of the *Picea* curve.

The immigration of *Pinus strobus* into the Jacobson area from the east may have been impelled by the same xerothermic climatic trend that brought the oak from the southwest, for of the three pine species involved it has the farthest distribution south and west today. It did not reach the Jacobson area until slightly after the *Quercus,* however, as is shown by the curious peak of *Quercus* at the base of zone JL-3 in both cores.

The macrofossil diagram provides additional climatic information about zone JL-3. The summary curve shows that seeds of weedy annuals characterize this zone, especially *Cyperus engelmanni* and *C. erythrorhizos*—the same "drawdown" species that are so conspicuous at Kirchner Marsh in the correlative zone (Watts and Winter, 1966). These plants can spread over lake floors bared at times of low water level, and their relative abundance in zone JL-3 implies periodic droughts in the Jacobson area. The macrofossils for zone JL-3 also show a steady decrease in the importance of *Typha latifolia* type in the marsh bordering the lake, but otherwise the aquatic and marsh flora show a cosmopolitan character that does not differ much from zones above and below. The lake was apparently bordered by segments of sedge meadow and alder thicket, as well as cattail marsh.

Zone KL-3: Kotiranta Lake. Zone KL-3 at Kotiranta Lake shows some of the elements of the Jacobson diagram, although much subdued. The curves for *Quercus* and NAP are higher than below, and those for *Picea, Larix,* and *Ulmus* are lower. *Pinus* pollen types were not distinguished.

Zone RB-3: Rossburg Bog. Rossburg, being so far west, records the mid-postglacial xerothermic interval much more strongly than the other sites. In the first part the NAP values are high—especially *Ambrosia* and chenopods—as *Pinus, Betula, Alnus,* and *Juniperus* type descend to low levels. In the upper part oak rises to the 30% level, and the NAP percentages are lower. The sequence appears to have percentage values approximately midway between those at Martin Pond, 85 miles to the northwest (McAndrews, 1966), and those of Jacobson Lake, 40 miles to the east. Prairie apparently prevailed from about 8000 to 6000 years ago and then gave way to an oak woodland or to a mixed deciduous forest. In the upper part of the zone a great maximum of grass pollen probably signals the spread of *Zizania* (wild rice) in the shallowing lake, as the sediment changes from gyttja to peat. The zone terminates 3500±180 years ago (Y-2458) with an abrupt increase in *Pinus strobus* pollen.

Zone JL-4: Jacobson Lake. Pinus strobus, which fluctuates between 30 and 60% of total pollen in zone JL-3, jumps to 65-85% in zone JL-4. At the same level several curves are sharply depressed, notably *Quercus, Alnus,* all of the principal herb types, and *Pteridium.* In addition, *Ulmus, Ostrya* type, and *Salix* are slightly less common. The curve for *Betula* decreases at first but then rises. On the other hand, several types show increased percentages, despite the masking effect of the great increase in pine. For example, *Picea, Larix,* and *Abies* resume essentially continuous curves after a near absence in zone JL-3, and *Acer negundo, A. saccharum,* and *A. rubrum* are also more common. *Tsuga* appears for the first time in the upper half of the zone.

The changes in the pollen curves at the base of zone JL-4 imply a reversion to an effectively cooler, more humid climate. The time is indicated as 3920±120 B.P. (Y-1691). The boreal conifers *Picea, Larix,* and *Abies* were re-introduced into the area, and today they occur on the bog forest bounding the lake on the southwest side. The pine/oak woodland was replaced by a more mesic conifer forest with *Acer* and *Tilia.* This forest, however, was probably different from the mesic forest of zone JL-2b, which was characterized more by *Ulmus* and *Ostrya* (or, less probably, *Carpinus*).

The climatic interpretation for the pollen sequence of zones JL-2 to 4 proposes that the rise of the *Pinus strobus* curve at the base of zone JL-3 comes during a time of increased dryness, and that the further rise at the base of zone JL-4 correlates with a return to more humid conditions.

This apparent contradiction can be resolved if the factor of slow migration is taken into account. *Pinus strobus* may have moved into Minnesota from the northeast a thousand years or so after *P. banksiana/resinosa,* which it largely replaced as the climate became warmer and drier. It dominated the forests north of Lake Superior as well, for the Weber Lake diagram shows mostly *Pinus strobus* for this interval. At the same time, oak was advancing from the southwest in response to the same climatic trend, and it reached the Jacobson area just before *Pinus strobus.* During the few thousand years of the mid-postglacial warm period the two tree types held their own in the Jacobson area. Meanwhile the slowly moving *Pinus strobus* may have increased its numbers in Wisconsin, which was far enough east to have escaped the more severe effects of the postglacial warm period, and with the climatic reversal it followed the oak westward and southward.

Of particular interest in zone JL-4 is the macrofossil diagram, which shows the first development of northern wet forest and alder swamp on the margins of Jacobson Lake. A group of bog plants, notably *Chamaedaphne calyculata, Vaccinium* spp., *Scheuchzeria palustris, Larix laricina,* and *Sphagnum* sp. are well represented in the seed counts for zone JL-4. In addition, forest trees such as *Betula papyrifera, Pinus strobus, Abies balsamea,* and *Picea* sp. are again present, after being almost absent in zone JL-3. By contrast the drawdown plants of zone JL-3 are gone from JL-4.

Elsewhere beside the lake was a cattail marsh, which had less cattail (*Typha latifolia* type) in it than in either zones 3 or 2 and more *Eleocharis ovata, E. smallii, Hypericum virginicum,* and *Sagittaria* spp.

Pollen analyses for the top 10 cm of sediment at Jacobson Lake show abrupt increases in *Ambrosia* type to 15%, Chenopodiineae to 5%, and

Gramineae to 10%, all from values of less than 1%. *Rumex* is also conspicuous. On the other hand, *Pinus* drops from 60% to 30%. These changes can be attributed with certainty to the epoch of agriculture and lumbering in northeastern Minnesota during the last hundred years.

Clearing of the adjacent hillslopes for agriculture may have had an effect on the nature of the fringing bog vegetation, which now occurs only on the southwest corner of the lake, above which the slope is still wooded. For example, the decrease in *Picea* pollen and *Chamaedaphne* seeds might be attributed to the destruction of bog habitat by the increase in alkalinity of run-off water when the pine forest on the hillslope was replaced by pasture or cropland (Janssen, 1967). Also, the present-day absence of certain bog species (*Vaccinium macrocarpon, Scheuchzeria palustris*), which are conspicuous in the seed diagram close to the surface, may result from the same factor. On the other hand, the reduction in bog-plant remains seems to have occurred at a time significantly before the rise in *Ambrosia* pollen, which signals the epoch of agriculture, so the changes may rather reflect a natural forestation of the bog area on the southwest.

Although the Kotiranta, Glatsch, and Rossburg diagrams do not reach close enough to the surface to record the changes related to disturbance, the Weber Lake diagrams show the usual rise in *Ambrosia* and chenopods at all three coring sites—the lake center, the edge of the fringing bog, and the center of the bog. Determination of pine pollen types for the uppermost sediment by Junko Ogawa (fig. 17) indicates the severe drop in proportion of *Pinus strobus* compared to *P. banksiana/resinosa* type, a result of the extensive lumbering of the big pines (*P. strobus* and *P. resinosa*) and their replacement by *P. banksiana.* The total percentage of pine in the pollen rain decreases also, at least in the core closest to the upland.

Zone KL-4: Kotiranta Lake. The curve for *Pinus* in zones KL-2b and KL-3 holds uniformly at 50-65%. At zone KL-4 it jumps to 70%, probably representing the renewed expansion of *P. strobus* as at Jacobson. At about the same level the curves for *Picea, Larix, Abies,* and *Acer* all rise. These genera are all from relatively small pollen producers, so the rising curves indicate that these trees immigrated in quantity to produce the mixed coniferous forest evident today. Kotiranta Lake today is surrounded by a fine bog forest of *Picea mariana,* with some *Larix laricina.* Occurrence of *Tsuga* grains at practically every level in zone KL-4 reflects the retarded migration of hemlock into western Wisconsin and barely into Minnesota at the head of Lake Superior, where a few stands occur today.

As the pollen curves for conifers and *Acer* rise, those for *Quercus* and NAP descend, indicating the reduction in the more xeric environments suitable for oak and prairie openings.

Zone RB-4: Rossburg Bog. The abrupt rise of *Pinus strobus* pollen that introduces zone 4 at Rossburg Bog is accompanied by reappearance of *Picea* and *Abies,* marking the climatically-induced westward spread of conifers after the close of the prairie period.

The location of the Rossburg site midway between Jacobson and the Itasca region provides further knowledge of the disposition of the pine spe-

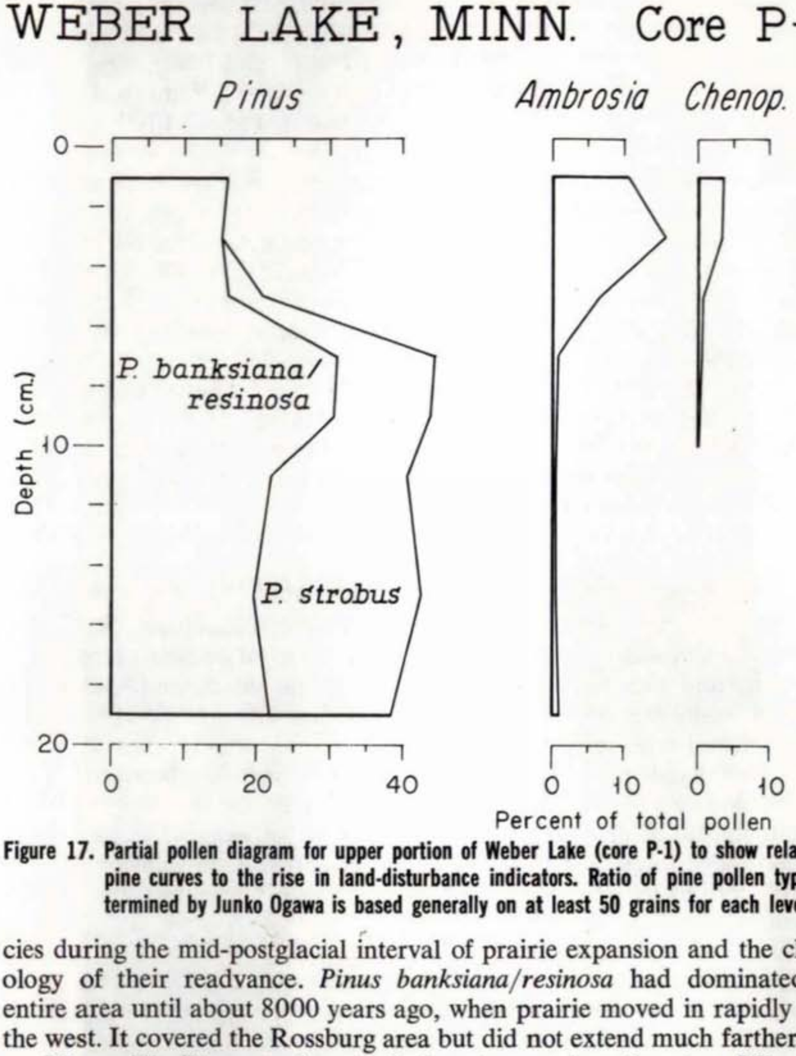

Figure 17. Partial pollen diagram for upper portion of Weber Lake (core P-1) to show relation of pine curves to the rise in land-disturbance indicators. Ratio of pine pollen types determined by Junko Ogawa is based generally on at least 50 grains for each level.

cies during the mid-postglacial interval of prairie expansion and the chronology of their readvance. *Pinus banksiana/resinosa* had dominated the entire area until about 8000 years ago, when prairie moved in rapidly from the west. It covered the Rossburg area but did not extend much farther east.

Meanwhile *Pinus strobus* reached eastern and northeastern Minnesota from Wisconsin about 7200 years ago, and some of the pollen grains were blown to the Rossburg area. After the climax of the xerothermic interval, the prairie retreated to the west, the deciduous forest enlarged, and white pine commenced its great expansion to the west and southwest. This is seen by the rise in the *Pinus strobus* curve at Jacobson about 4000 years ago. It reached Rossburg 3500 years ago, Bog D in Itasca Park 2700 years ago (McAndrews, 1966), and Kirchner Marsh (at least the pollen) about 1700 years ago.

Meanwhile *Pinus banksiana/resinosa* followed a similar pattern. During the xerothermic interval it may have withdrawn into Canada, but about

4000 years ago it increased its representation in the Weber Lake area, along with *Picea*. It increased slowly in this area until about 2500 years ago, when it increased more rapidly, along with *Picea, Abies,* and *Larix*. This expansion is not well recorded in the Rossburg diagram, which terminates 140 cm below the surface of the peat, but at Bog D it is seen about 1700 years ago (McAndrews, 1966).

During this entire period after the xerothermic interval there are other manifestations of vegetational change in northern Minnesota, notably the growth of fringing bogs on lakes and the development of blanket bogs and raised bogs on the vast bed of Glacial Lake Agassiz (Janssen, 1968; Heinselman, 1963). The climate of today has probably returned to that of 8500 years ago, after a long interval of warmer, drier conditions, but the vegetation is not the same—the upland vegetation may differ because the soils are more deeply leached than they were soon after deglaciation, and the lowland vegetation may differ because of filling of lakes and the accumulation of peat. The two may be closely related, for the reduced mineral nutrients in run-off waters from leached upland soils may favor the growth of conifer bogs in lowlands (Janssen, 1967).

Conclusions on Vegetational History

The four sites under principal consideration—Jacobson, Kotiranta, Glatsch, and Rossburg—show a clear pollen zonation that provides a transition from sites to the south (like Kirchner Marsh and Cedar Bog Lake) or west (like the Itasca sites) to those farther north (Weber Lake). A vegetational tension zone of some kind has apparently existed in this region throughout most of late- and postglacial time, first between tundra and boreal spruce forest, later between the spruce forest and forests of jack or red pine, and finally, during the prairie period, between white pine forest and deciduous forest (or even savanna). At present the tension zone is shifting more to the southwest, and the expansion of conifers and bogs is extensive throughout the region.

This is another way of saying that the vegetational belts of Minnesota are narrow, and that only minor climatic changes are sufficient to alter the composition of the forest cover. But such a relatively simple picture of migrating forests is blurred by the evidence that forest dominants, as well as many other plants, migrate independently, at rates determined by their capabilities of seed dispersal and by their edaphic requirements. So even when the climate is fairly stable, the forest composition changes slowly, as the slow migrants catch up, or as soil conditions change through progressive leaching. The original driving force behind the vegetational changes, however, is the shift in climate, which causes the reduction of some forest dominants and provides the space and opportunity for others to invade and start the successional course.

Eastern Minnesota is an area well suited to examine the factors involved in climatic change and forest succession. The climatic gradient is steep, for the area is on the northeast flank of the climatically controlled prairie peninsula (Borchert, 1950; Wright, 1968b), at the southern limit of heavy winter snows and the northern limit of severe summer droughts. Further, the tree flora of the forests is relatively simple, compared to areas farther east and southeast, where *Fagus grandifolia, Tsuga canadensis, Carya* spp., *Betula lutea*, and other trees not common in Minnesota are major components of the forest.

The pollen sequence records predominantly the regional upland vegetation. Supplemental information about environmental history is gained from study of the plant-macrofossil succession. The macrofossils enlarge the list of taxa determined, or they raise the precision of determination from the generic to the specific level. The rather large number of taxa determined by these two techniques (over 100 from Jacobson Lake) provides data of value to biogeography. Where collected and presented in a systematic quantitative manner, the data may provide a basic fund of information from which a type of paleophytosociology may emerge.

The detail of such seed diagrams and the consistency with which seed assemblages can be expected to occur (Watts and Winter, 1966; Watts, 1967) provide the basis for some generalizations. The successive assemblages from *Dryas-Vaccinium-Salix herbacea* to *Picea-Larix*-pioneer aquatics to *Abies-Betula papyrifera-Alnus rugosa* are apparently widespread in Minnesota. At Jacobson Lake, as at Kirchner Marsh and other sites (Watts and Winter, 1966), an assemblage of "drawdown" species, especially in the genera *Cyperus* and *Chenopodium*, mark the dry mid-postglacial "prairie period" throughout the region. This assemblage, like the expression of the "prairie period" in the Jacobson Lake pollen diagram, tends to be reduced in northeastern Minnesota as compared with more southerly parts of the state. The assemblage of *Larix* and bog plants in the upper part of the Jacobson Lake core has as yet no equivalent in other sites studied in Minnesota. It is the stratigraphic correlative of the assemblage of mesic aquatic plants found in zone C-c at Kirchner Marsh (Watts and Winter, 1966). It provides clear stratigraphic evidence for the initiation of bog communities in northeastern Minnesota about 4000 radiocarbon years ago.

The succession of plant-macrofossil assemblages partly records changes in upland vegetation and partly changes in aquatic and marsh vegetation. These changes result ultimately from regional climatic changes that give rise to changes in sedimentation and in the lake environment. Macrofossil studies such as those at Jacobson Lake may prove especially valuable to paleolimnologists in delimiting more exactly than is possible by pollen analysis the points at which changes in limnic fossils and chemistry should be looked for.

Apart from the questions of vegetational succession under the press of climatic change and evolving edaphic controls during the postglacial, there remains the special problem of relating the late-glacial vegetational sequence to the history of ice-margin fluctuations, for radiocarbon dating indicates that the time ranges involved are the same. We must now turn to this special problem.

RELATION OF THE GLACIAL TO THE VEGETATIONAL SEQUENCE

The glacial sequence in northeastern Minnesota shows four phases of advance of the Superior Lobe, all of which can be correlated with movements of adjacent ice lobes in Minnesota through drainage connections or stratigraphic arrangements. They can be given minimal ages in the radiocarbon chronology by dates on the basal organic sediments of lakes located on their surface (table 1). Roughly, the St. Croix phase was at least 16,000, Automba phase 15,000, Split Rock phase 14,000, and Nickerson phase 12,000 years old.

The vegetational sequence may thus go back more than 16,000 years and may cover the time of several glacial fluctuations (Fig. 15). The task is therefore to examine the relations of these two presumed manifestations of climatic change.

The herb zone, as an expression of tundra, is largely confined to the northern sites—Weber, Glatsch, Spider, Kotiranta, and possibly Blackhoof, Anderson, Rossburg, and Aitkin. It is probably absent from Jacobson Lake because late persistence of dead ice prevented formation of the lake until the area had become forested. For a few of the southern-Minnesota sites, such as Kirchner Marsh, Madelia, and Norwood, an herb zone can be recognized, but it does not contain the tundra indicators common in the northern sites; local openings may have occurred in a spruce forest that came up to the very edge of the ice.

The age of the base of the herb zone depends largely on the date at which the buried ice block that localized each site melted out and permitted organic sedimentation. This date is as old as 14,670 B.P. at Weber Lake (perhaps 16,150 at Kotiranta) but as young as 10,400 at Jacobson Lake. The top of the herb zone clearly transgresses time in a northerly direction. It ranges from more than 13,000 years old at Kirchner Marsh in the south to about 10,000 at Weber Lake in the north (Wright, 1968a). Because the ice front was retreating, with fluctuations, during the interval of the herb zone, it seems clear that a periglacial effect existed, at least in the north. The question may now be posed whether the several glacial phases can be matched by subdivisions of the herb zone in the north, or of the spruce zone in the south.

The Weber Lake profile is the best one with which to study the question. The site is located on drift of the St. Croix phase of the Rainy Lobe, and it was open by at least 14,670 years ago for organic sedimentation. Ice of the Automba phase (perhaps 15,000 years ago) came within 15 miles on the southeast, as the Superior Lobe spread out of the Lake Superior basin and onto the North Shore highland to build the Highland Moraine. It also spread westward out of the head of this basin as far west as central Minnesota and thus bounded the area on the south. At the same time, the Rainy Lobe stood at the Vermilion Moraine, only 15 miles to the north. Ice was probably farther away on the west, but the small enclave in which Weber Lake is located may have been almost completely surrounded by ice.

In the Split Rock phase of the Superior Lobe, which followed about 14,000 years ago, ice was largely confined to the Lake Superior basin 25 miles to the southeast of Weber Lake, with a small tongue extending southwest out of the basin, but it should be emphasized that most of southern Minnesota was covered by ice at this time, for the Grantsburg Sublobe of the Des Moines Lobe reached its maximum in its contemporaneous Pine City phase. In the next step, the Nickerson phase of about 12,000 years ago, the Superior Lobe still filled the basin, but it extended only slightly out of the southwest end as far as the Nickerson and Thomson moraines. The Rainy Lobe at this time had withdrawn to some moraine in northwestern Ontario (Zoltai, 1961). Meanwhile, however, the St. Louis Sublobe, in its Alborn phase, invaded from the west to within 30 miles of Weber Lake, so once again the area was practically surrounded by ice.

Subsequent ice-margin fluctuations for the Superior and Rainy lobes have been identified in Ontario north of Minnesota (Zoltai, 1961). One of these may correlate with the Valders phase of the Lake Michigan Lobe about 11,500 years ago.

Thus the Weber Lake area was free of active glacial ice during the Automba, Split Rock, Nickerson, and later phases of Wisconsin glaciation. Radiocarbon dating of the basal lake sediment indicates that the lake was open for sedimentation for almost all of this period. The pollen content of the lake sediments might be expected to reflect the climatic changes that caused the ice-margin fluctuations—or to reflect the local periglacial climatic effects of the fluctuating ice margin. One might therefore expect that pollen zones 1 and 2 at Weber Lake, which end about 10,000 years ago and thus cover most of the time of the three glacial phases, might show changes in the pollen curves that record these presumed climatic changes.

Two almost complete pollen diagrams are available from Weber Lake (Fries, 1962), one from the center of the existing lake (C-1) and one from the shore at the edge of the fringing bog (S-1) (pl. 6). The former has more than 1 m of silty clay assigned to pollen zone 1, and it is marked by a double maximum of herb pollen separated by maxima of *Picea* and *Alnus*. Core S-1 shows only the upper part of this sequence. The principal types involved in the herb maxima are *Artemisia*, Cyperaceae, Gramineae, *Ambrosia*, and *Salix*, along with the temperate deciduous trees *Quercus*, *Corylus*, and *Fraxinus*. The sequence in a sense is like that in Europe, in which the Allerød warm interval is marked by a maximum of *Pinus* between two zones of dominant herb pollen. The double peak of herbs at Weber Lake suggests a tundra landscape (with pollen of temperate trees being blown up from the south), interrupted by a time of more temperate climate marked by the spread of spruce and alder closer to the area. Macrofossil analysis reveals remains of tundra plants but not of spruce or alder, which therefore probably did not grow very close to the lake itself.

The two herb maxima, if they thus represent cold intervals, might correlate with the Split Rock and Nickerson-Alborn phases of glacial activity in the region, but the irregularity of the herb pollen curves, and the lack of close correspondence between the two cores, should encourage caution in considering the pollen profiles to be of more than local significance. Radiocarbon dating does not assist appreciably in the correlation, because the silty sediments are so lean in organic matter that 20 cm of a 4-inch-diameter core were required to obtain a radiocarbon date. Nonetheless, the pollen sequence at Weber Lake is suggestive, and a more detailed analysis at closer intervals would be justified at this or nearby sites (Cushing, 1967).

Kotiranta Lake is located in outwash of the Split Rock phase, and radiocarbon dates indicate that zone KL-1a lasted until 11,500 years ago, thus filling the time of the Nickerson phase as well as the Valders and subsequent glacial phases. The pollen curves permit no subdivision of the zone whatsoever, even after the analysis of 20 spectra.

The Spider Creek pollen site postdates the Nickerson-Alborn phase. Radiocarbon dates of 13,000±400 B.P. (W-1234) and 22,000±600 B.P. (W-1233) from the herb zone are not trusted because of the possibility of contamination by fragments of Cretaceous lignite in the basal sediment. The pollen profiles in the herb zone suggest no reversion sequence that might be related to one or more climatic fluctuations. The same can be said for Glatsch and Rossburg.

Jacobson and Anderson lakes are both too young at the base to cover the time of glacial fluctuations. White Lily Lake and Horseshoe Lake are old enough—they have an herb zone at the base—but they show no reversion (Cushing, 1967).

In southern Minnesota, both Kirchner Marsh and Madelia are old enough to encompass the time of the latest-Wisconsin ice-margin fluctuations, and the pollen sequence has been interpreted as a reflection of a climatic fluctuation correlated with the Two Creeks-Valders cycle (Wright and others, 1963; Jelgersma, 1962). At Kirchner Marsh, zone A-a, assigned to the Two Creeks interval, is marked by relatively high values of *Fraxinus, Quercus,* and *Ambrosia.* The increase in the two tree types is attributed to their greater proportion in the dominantly spruce forest, implying a milder climate than in the preceding zone K, which has maxima of spruce and herbs.

In zone A-b at Kirchner Marsh, the *Fraxinus* and *Quercus* values decrease, and *Artemisia* is somewhat higher. Because *Artemisia* reaches very high levels in the herb zone of the ice-marginal site of Weber Lake, where all evidence points to tundra, it seems reasonable to attribute a rise in *Artemisia* at Kirchner Marsh to local development of tundra openings. On the other hand, zone K at the base of the Kirchner sequence zone K, whose high values of Cyperaceae and Gramineae imply treeless openings, has relatively little *Artemisia,* so comparison with Weber Lake may not be justified. Furthermore, Cushing (1965, 1967) has preferred to refer the *Artemisia* maximum to prairie openings rather than to tundra openings, and thus it may serve as an indicator of a warmer climate rather than cooler. But a similar difficulty exists with this interpretation, for a contemporaneous site to the southwest in the Nebraska Sandhills (Watts and Wright, 1966) has little more *Artemisia* than does Kirchner Marsh, even though it is closer to the presumed prairie of the day and should have more prairie openings.

Prairie openings deep in the boreal forest are known from southwestern Yukon (Raup, 1941), not far south of the permafrost boundary, but these are localized by the low precipitation (12 inches) in the shadow of the high St. Elias Mountains. No such local aridity can be postulated for southern Minnesota, unless it be related to a periglacial climate, in which case we must revert to the hypothesis of cold rather than warm (or dry) to explain the *Artemisia* maximum at Kirchner.

A slight but distinct *Artemisia* maximum occurs at correlative levels at Madelia. It occurs after the major fall in the *Picea* curve but coincident with a slight rise of *Picea* and rise of *Alnus* and *Betula.* These features were attributed to an interruption in the deterioration of the spruce forest by a temporary return of cooler (drier?) climate at the time of the Valders glacial advance (Wright and others, 1963). A similar *Artemisia* maximum can be identified in eastern Wisconsin at Disterhaft Bog 10 miles west of the Valders drift border (West, 1961). It is absent at Seidel Lake, 35 miles inside the Valders drift border and thus post-Valders in age.

The *Artemisia* maximum seems so far to be the best clue for climatic fluctuation within the last-glacial spruce zone, but the nature of the climatic fluctuation must still be considered problematical, as must its correlation with the Valders or any other ice advance. More detailed pollen diagrams, with close-interval analyses and high pollen sums to pick up significant quantities of climatically diagnostic herbs, may ultimately lead to a more convincing picture of the relation of vegetational to climatic and glacial history in the region 100-200 miles from the ice front. In Europe, the Allerød interstadial pollen zone is consistently identified in diagrams south of the Central Swedish Moraine, and now the comparable Bølling zone is noted at a still lower position. They provide examples of the kind of pollen record that perhaps may be expected in Minnesota, although even in Europe the correlation of the pre-Allerød tundra phases with glacial advances is by no means certain. The much more complex glacial system in Minnesota, with four glacial advances in the time from 15,000 to 12,000 years ago and several thereafter in adjacent areas, gives little hope of correlation with the pollen sequence, which may not be sensitive enough to record climatic changes of the magnitude represented by glacial fluctuations. On the other hand, a convincing case can be made that glacial fluctuations are not accurate recorders of contemporaneous climatic changes, because of different lag effects on different ice lobes, or because abrupt ice advances might reflect non-climatic factors, such as ice thickness and thermal gradient, rather than climatic change. The complexities of both the vegetational and glacial systems in this context have been reviewed by Cushing (1967). The complexities of the regional and local climatic systems add more problems. Finally, the limitations of radiocarbon dating will inhibit the development of a highly refined chronology. It must be concluded that an accurate and useful synthesis may never be possible, although such a goal will long serve to delineate some basic problems in environmental reconstructions.

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