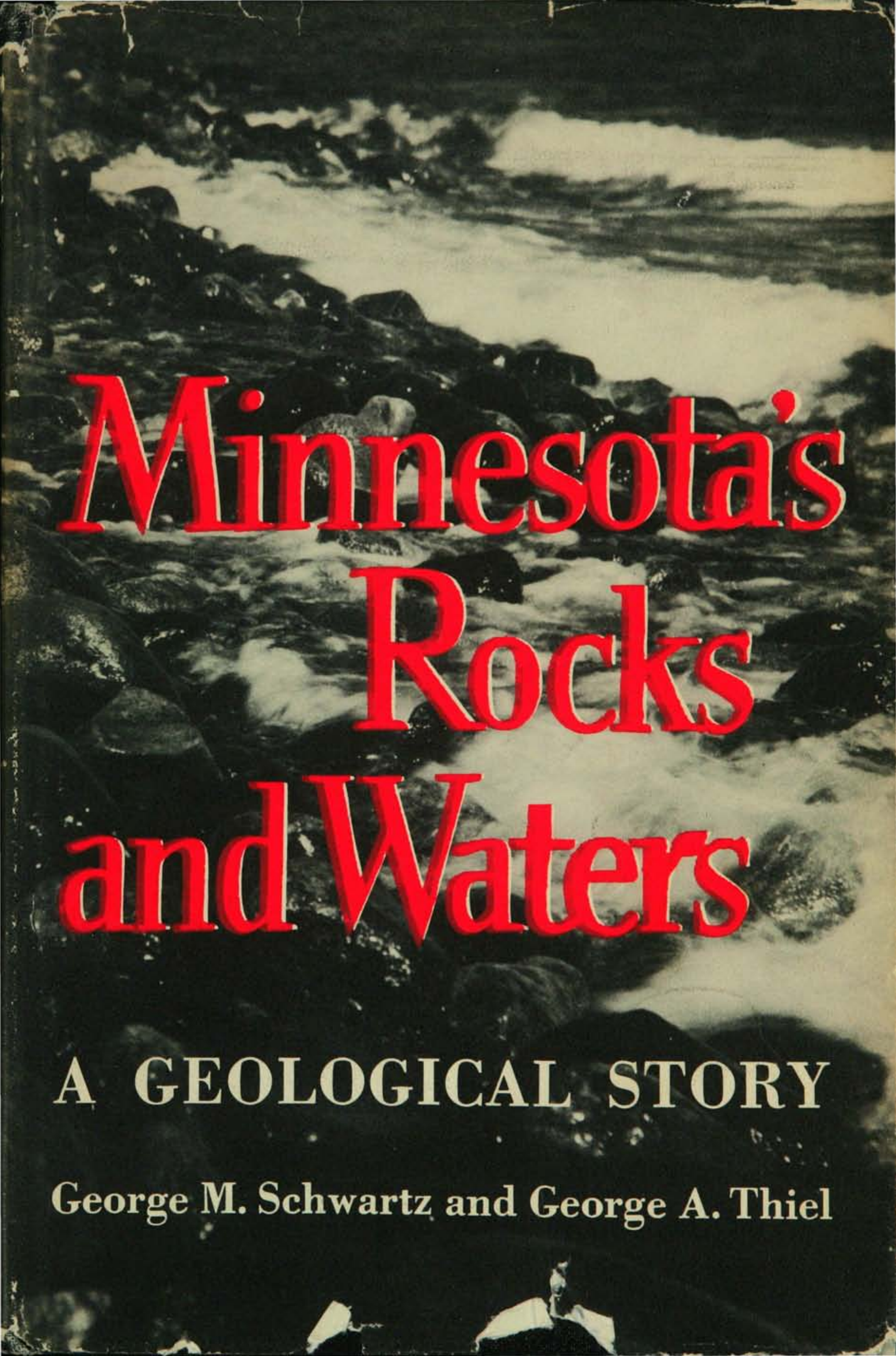
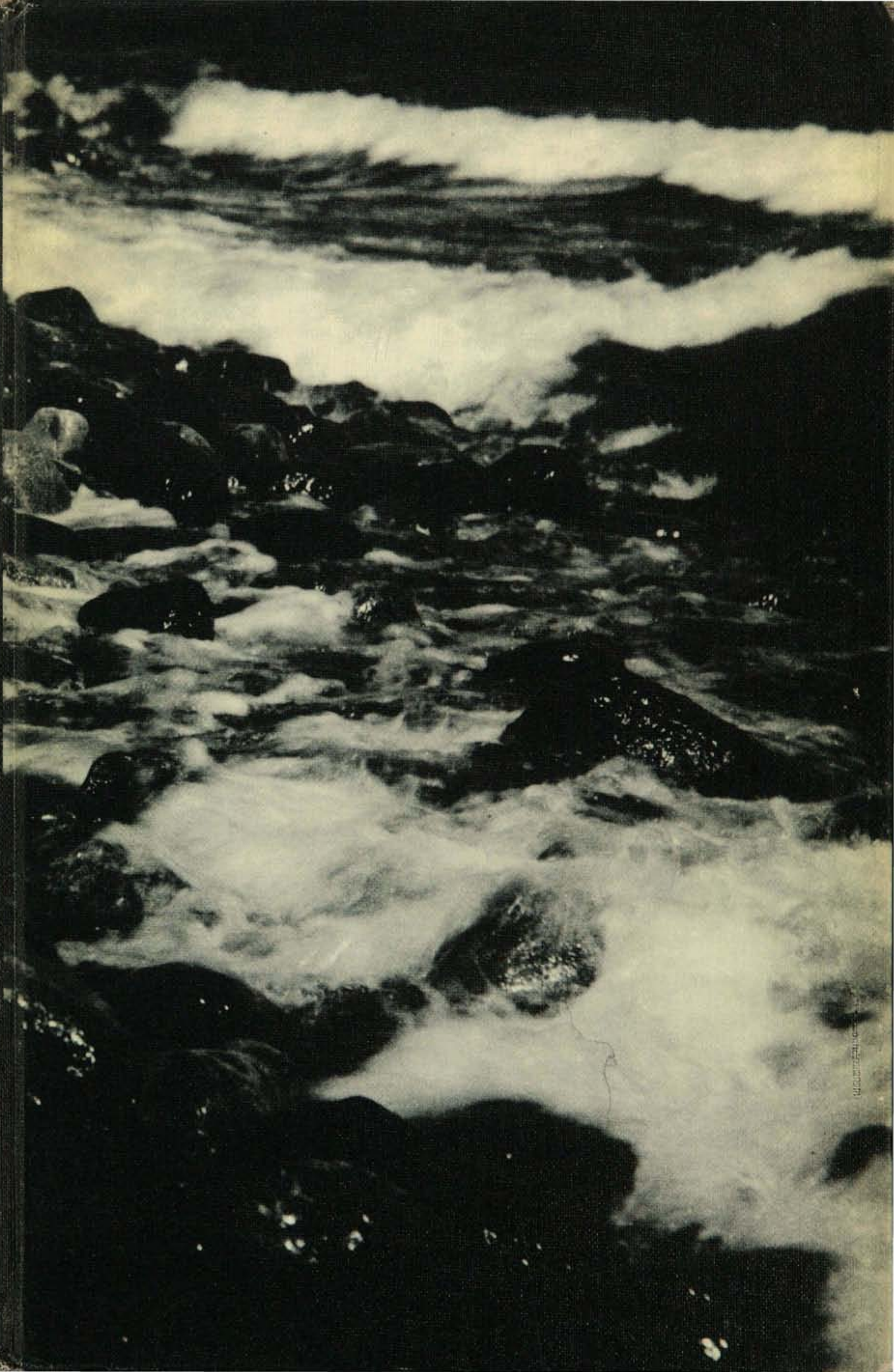
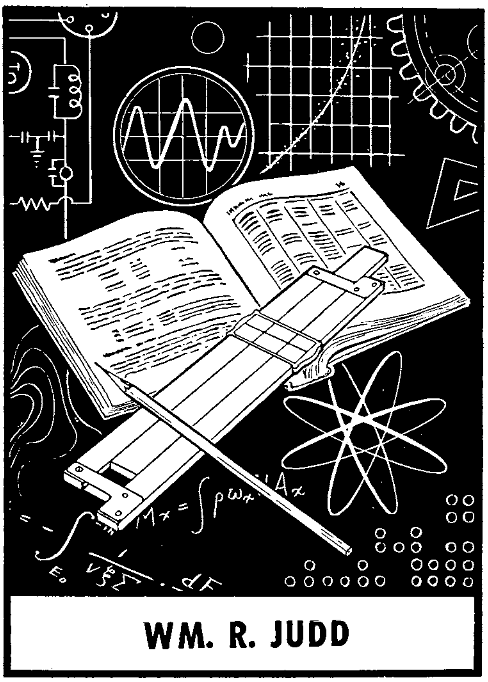


Minnesota's Rocks and Waters

A GEOLOGICAL STORY

George M. Schwartz and George A. Thiel




WM. R. JUDD

UNIVERSITY OF MINNESOTA

Minnesota Geological Survey

GEORGE M. SCHWARTZ, DIRECTOR

BULLETIN 37

PHOTOGRAPH BY KENNETH M. WRIGHT

MINNESOTA'S ROCKS AND WATERS

A Geological Story

by GEORGE M. SCHWARTZ and GEORGE A. THIEL
with the assistance of Peggy Harding Love

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TO THE MEMORY OF

JUNIOR F. HAYDEN

enthusiastic naturalist and benefactor
of the Departments of Botany and Geology of the
University of Minnesota

Preface

THIS volume has been prepared in an attempt to make available to the citizens of Minnesota a general summary of the major geological features of the state and to stimulate a greater interest in, and appreciation of, their natural surroundings. Ability to interpret the landscape requires knowledge of the forces that produced it. One may admire the beauty of a waterfall or marvel at its grandeur, but to appreciate it fully, one must know how it was formed.

Man draws from the earth many materials which are necessary for life and happiness, and he deals with geological conditions in many of his daily activities. For example, he plows the soil, which is composed largely of weathered rock materials, and cuts the surface rocks as he grades roads and railroads and excavates foundation places for his skyscrapers and his great plants in which to exploit the earth's resources. Yet how many of the thousands of citizens of Minnesota employed in these enterprises understand the geological relationships of the materials with which they labor? How much greater would be their interest in their assigned tasks if they knew more about the formation of the materials which occupy their attention? An understanding of geological processes guides us in the search for mineral resources and aids us in understanding the forces which produced them. Soil erosion, one of our most important problems, is closely related to the geology of the area involved.

The resources of any region determine to a marked degree the activity of its inhabitants. They are the foundation of our well-being, the hope of our future. Minnesota, though known as an agricultural state, has great mineral wealth, and many of its citizens are engaged in mineral industries. All of the mineral substances produced from the rocks of the state may be classified as industrial minerals even though some are metals and others nonmetals. Metal mining is restricted to the iron ranges, but the nonmetals include a great variety of materials—such as limestone for agricultural lime, marl, sand and gravel, clays and shales, wool rock, and structural and architectural stone—which are excavated and processed at many places in the state.

The authors of this book have had many years of experience in educational work in Minnesota. It is their opinion, based upon observation and experience, that in the curriculums in our schools not enough time is devoted to a study of our own state and its resources. It is hoped that this volume will furnish science teachers with accurate information which they can in turn pass on to their students at the appropriate time, and that citizens at large will find it a source of information regarding their state. Technical terms have been held to a minimum in order to make the text intelligible to those unfamiliar with detailed geological terminology. The authors know that this method inevitably results in generalities that may not always take into account all detailed scientific information available to the geologist. We hope, however, that geologists will recommend the book to their friends and that they will not hesitate to explain some of the exceptions that are bound to appear where such broad generalizations are employed for the sake of simplicity. Geology is the science that weaves all the other natural sciences together into a comprehensive whole and this results in great complexity. The authors, with full awareness of the magnitude of the task, have attempted to resolve complex geological details by employing a nonscientific assistant who screened out much of the detail and obtained a residue that is sufficiently free of technicalities to be comprehensible to the general reader.

George M. Schwartz
George A. Thiel

Acknowledgments

THIS bulletin is an attempt to summarize the most important aspects of the geology of Minnesota. It follows, therefore, that the authors have called on every available source of information, together with their own knowledge gained in over thirty years of geological work and teaching within the state. Because this is a nontechnical publication it was decided to omit footnote references to sources of information. All sources published before 1951 will be found in the Bibliography of Minnesota Geology, which appeared as Bulletin 34 of the Minnesota Geological Survey. A complete list of the publications of the Geological and Natural History Survey of Minnesota and its successor, the Minnesota Geological Survey, is reproduced as Appendix 2 of this bulletin. Other principal sources of data are the following:

C. W. Hall. The geography and geology of Minnesota. Minneapolis 1903.

C. K. Leith. The Mesabi iron-bearing district of Minnesota: U.S.G.S. Mon. 43, 1903.

J. M. Clements. The Vermilion iron-bearing district of Minnesota. U.S.G.S. Mon. 45, 1903.

C. R. Van Hise and C. K. Leith. The geology of the Lake Superior region. U.S.G.S. Mon. 52, 1911.

D. E. Willard. The story of the North Star State. St. Paul. 1922.

J. W. Gruner. The mineralogy and geology of the taconites and iron ores of the Mesabi range, Minnesota. St. Paul, Office of the Commissioner of Iron Range Resources and Rehabilitation. 1946.

F. F. Grout. The titaniferous magnetites of Minnesota. St. Paul, Office of the Commissioner of Iron Range Resources and Rehabilitation. 1949–1950.

The authors acknowledge their debt to these sources. They also owe much to their colleagues past and present in the Department of Geology at the University of Minnesota. We are indebted to Dr. N. Prokopovich for many of the line drawings.

Many of the illustrations have been taken from previous publications of the Minnesota Geological Survey; others originated through the activity of the survey personnel. These have not been separately acknowledged. Illustrations from outside the Survey have been credited to the proper source.

The book is illustrated profusely, and the cost of the illustrations was covered by funds from the generous bequest of Junior F. Hayden to the Department of Geology. It was Mr. Hayden's hope to join with the authors in preparing the illustrations, but his untimely death deprived him of that pleasure. It is, therefore, with a deep sense of gratitude that we have dedicated this volume to his memory.

Contents

Illustrations

PART I • THE STORY OF THE ROCKS

GEOLOGY *is the science that studies the history of the earth, its composition and structure, the various stages through which it has passed, the development of life upon it, and the natural processes that are constantly working to alter it. Records of these events and processes are preserved in the rocks of the outer crust of the earth. The various masses and layers of rock may be compared with the pages of a great and ancient book, some containing a wealth of detailed information, while others seem almost blank or illegible. In Part I of this book we will discuss the ways in which the rocks and land forms of Minnesota reveal their long, dramatic story.*

CHAPTER

1

The Face of the Land

THE Minnesota we know today, with its thousands of lakes, fertile farm lands, rolling southern hills, and rocky northland, started its development millions of years ago when the earth was a new planet. The soil we now till and the stone we now quarry are composed of the same elements, though much altered, that made up that original globe. The iron ore of our iron ranges and the clay for our potteries are products of complex geological processes that began long before man arrived on earth. Almost all aspects of our landscape, in fact — hills, valleys, rivers, lakes, peat bogs and marshes, rocks and waterfalls — bear secret clues to their history that we can learn to decipher.

During those prehistoric eons the face of Minnesota went through many drastic changes. In the earliest days molten lava often spilled out in great lava flows from the hot interior of the earth. High mountain ranges were uplifted. For millions of years these Minnesota mountains towered over the landscape until wind and frost and rain eroded them away, leaving only the ancient granite hills we see today west of Lake Superior's North Shore. Time and again vast seas submerged the land and then retreated. The earliest forms of life appeared, then fishes, birds, reptiles, and mammals, each leaving their remains preserved for all time in the rocks of their eras.

During some periods Minnesota's climate was one of arctic cold;

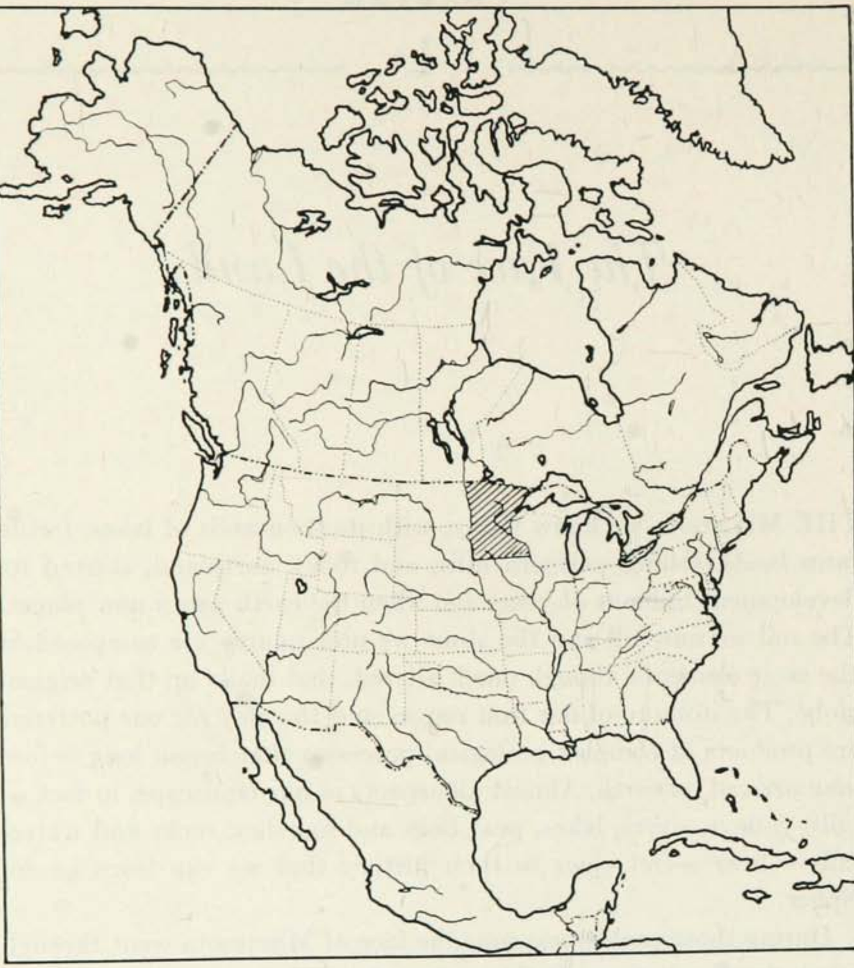


Figure 1. Map showing location of Minnesota near the center of North America.

during others it was mild or almost tropical. Finally the Great Ice Age came — about a million years ago, but only yesterday by geological time. Four great glaciers advanced and retreated across Minnesota, and when the ice had finally melted, the face of the land looked very much as it does today.

The state of Minnesota lies near the center of North America (Figure 1). It occupies a crest of the continent and includes the sources of three of the great river systems of North America. Even though its height above sea level is not as great as the divides in the Appalachian and Rocky Mountains, nevertheless Minnesota has within its boundaries several continental divides of its own. These important geographical turning points, also called watersheds, are elevations of land that separate one large drainage or water-collecting basin from another. Minnesota's major divides separate the water that flows northward in the Red River of the North from that which flows southward in the Minnesota and Mississippi rivers. Minnesota also has the headwaters of the eastward-flowing St. Lawrence drainage system, since the small tributary streams that flow into the St. Louis River flow down into Lake Superior at Duluth and eventually on to the St. Lawrence River. Thus the rains and snows that fall on Minnesota may ultimately travel either north into Hudson Bay, south into the Gulf of Mexico, or east through the Great Lakes to the Atlantic Ocean (Figure 2).

Much of the boundary of Minnesota is outlined by natural waterways. Most of the north and northeast is bounded by Lake of the Woods, Rainy River, Pigeon River, Lake Superior, and the beautiful Minnesota "Border Lakes" that stretch in an almost unbroken chain from Rainy Lake to Lake Superior, forming a canoeists' highway through the roadless wilderness of coniferous forest. The St. Louis, St. Croix, and Mississippi rivers form most of the eastern boundary, and along the west side of the state the Red River of the North and Big Stone and Traverse lakes separate Minnesota from North Dakota and part of South Dakota.

By international agreement the boundary between the United States and Canada was to follow the natural waterways into the "most northwestern point of the Lake of the Woods." Minnesota thus acquired an area of land northwest of that lake which has no land connection with the remainder of the state. This area, commonly referred to as the "Northwest Angle," extends to 49° 23′ 50.28″ north latitude, the northernmost point in the United States.

The state of Minnesota received its name from the largest river that lies wholly within its area. The Dakota Indians called that river the Minnesota, meaning "tinted or turbid water," because of

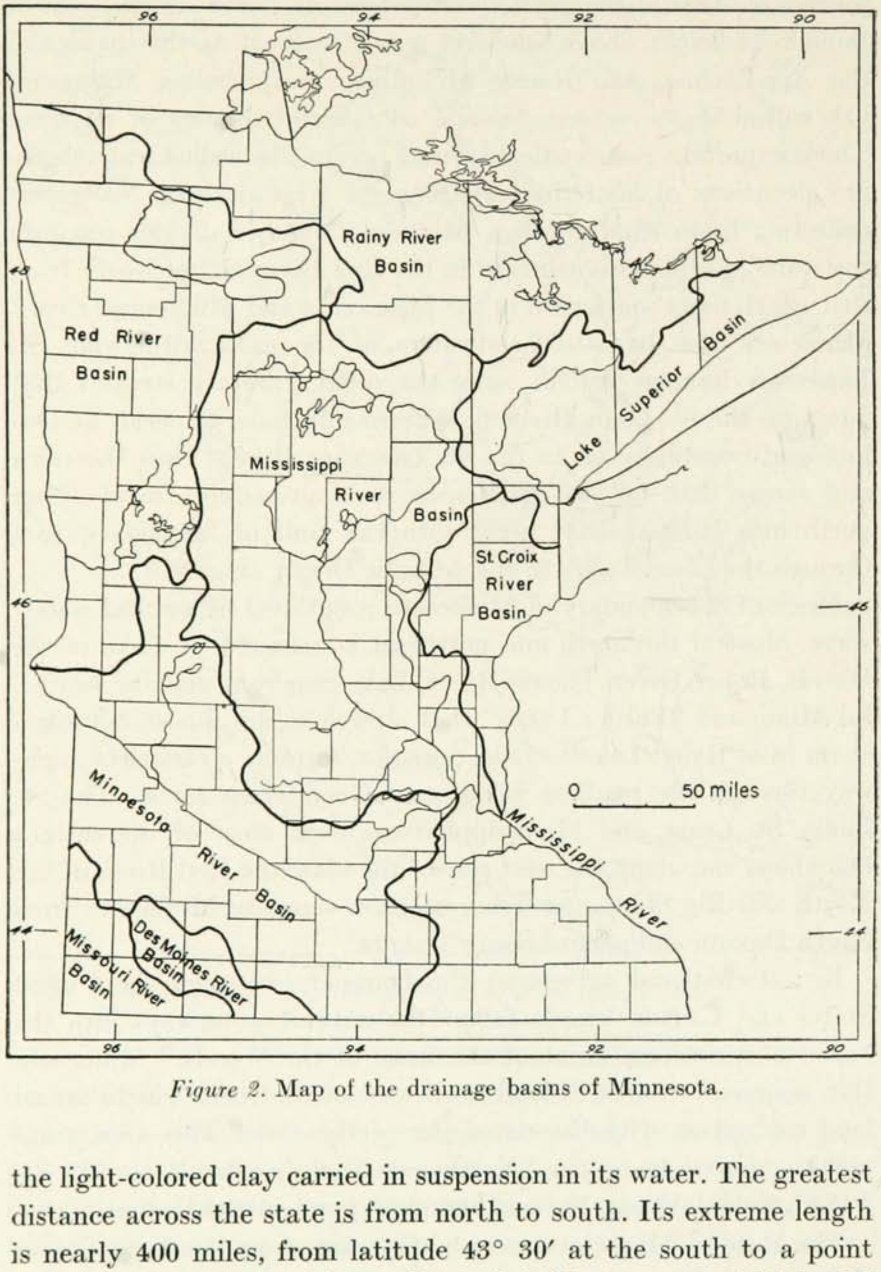


Figure 2. Map of the drainage basins of Minnesota.

the light-colored clay carried in suspension in its water. The greatest distance across the state is from north to south. Its extreme length is nearly 400 miles, from latitude 43° 30′ at the south to a point about 23 miles north of the 49th parallel. The greatest width is 367 miles, but the average width is only about 225 miles. It is narrowest between the south tip of Big Stone Lake on the west and the mouth of Goose Creek, north of Taylors Falls, on the eastern boundary. The state embraces an area of 84,068 square miles, of which about 80,009 are land. The remaining 4059 square miles are covered by water — more water area than in any other state. The state is divided into 87 counties, which are shown in Figure 3.

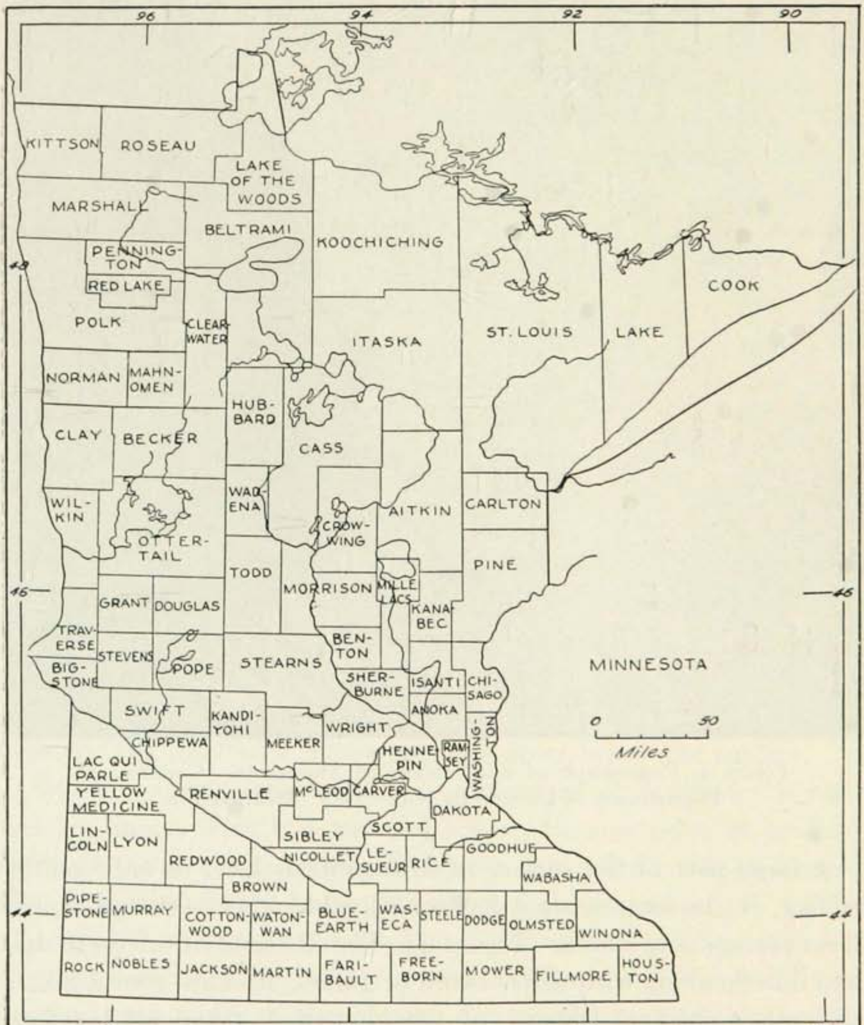


Figure 3. Map showing the counties of Minnesota.

Figure 4. Photograph of relief model of Minnesota. (Courtesy of Department of Geography, University of Minnesota.)

A large part of the surface of Minnesota is level or only gently rolling, yet in some areas it has considerable relief — the geological term for ups and downs (Figure 4). The distribution of these ups and downs, along with the network of gullies, streams, rivers, lakes, and other physical features of the landscape, taken all together make up what is called the topography of a region. In Minnesota both the highest and lowest points are in the northeastern part of the state. There the surface of Lake Superior, which is the lowest area, is 602 feet above sea level, whereas a few miles inland from the lake the Misquah Hills in western Cook County reach an altitude of 2230 feet, the highest point in the state. The highest town, however, is in the opposite corner of the state — the village of Holland in Pipestone County, where the altitude at the railway station is 1780 feet.

Most of the state lies between 1000 and 1500 feet above the sea and is nearly level. The portions above 1500 feet are chiefly in the two areas mentioned, the northeast and the southwest corners of the state, but a fairly large area around the headwaters of the Mississippi River as well as the Leaf Hills region in the southern part of Otter Tail County are also above 1500 feet. The portions below 1000 feet fall into two areas widely separated but connected by a narrow zone along the Minnesota River Valley. They are the Red River Valley region on the west and the Mississippi Valley on the east. There is also a narrow, low-lying strip bordering Lake Superior.

Topographically the most rugged parts of the state are in the so-called Sawtooth Range region that lies north of Lake Superior (Figure 110) and in portions of Houston, Fillmore, and Winona counties in the southeast corner of the state. Some of the prominent rock ridges along the North Shore of Lake Superior rise abruptly from 500 to 900 feet above the lake. In the southeastern counties the ruggedness is due to an intricate natural drainage system (Figures 5, 6, and 7), the streams and rivers of which have cut innumerable steep valleys and ravines several hundred feet deep into the bedrock, the solid rock masses that lie at or below the surface.

Another conspicuous feature in Minnesota's topography is the Giant's Range. This is a more or less continuous ridge of granite nearly 100 miles long, extending from a few miles north of Grand Rapids northeastward to beyond Birch Lake in eastern St. Louis County and western Lake County. South of the granite ridge lie the iron-bearing rocks that are mined in Minnesota's widely known open-pit iron mines of the Mesabi Range. The granite ridge itself rises from 50 to 500 feet above the general level of the region, which

Figure 5. Aerial photograph, in area with mature topography, of fields partly dissected by gullies, Winona County, southeastern Minnesota. Such erosion is characteristic of the area not invaded by the later ice sheets and where most of the drift of earlier invasions has been removed by erosion.
(Photograph by Mark Hurd Air Mapping Co.)

Figure 6. Tributary valley of the Mississippi River near Dakota, Winona County.

Figure 7. View of Mississippi Valley near Red Wing, Goodhue County. Bluff is Oneota dolomite.
(Photograph by Kenneth M. Wright.)

is part of the great Laurentian peneplain. This peneplain (literally "almost a plain") is a vast, nearly level rocky platform that extends from northeastern Minnesota up through central Canada. It was the first large part of North America to be more or less permanently elevated above the level of the sea, and during the eons of geological time it has been eroded very deeply to expose large areas of the earth's oldest rocks — granites, gneisses, and schists that were probably formed during the earth's earliest era, the Archeozoic, some two billion years B.C. The Giant's Range granite is somewhat younger though still very ancient; but around Saganaga Lake on the Minnesota border we can see some of the very oldest granite on earth.

This northeastern corner of Minnesota has many descriptive labels. Geologically it is part of the Laurentian peneplain; popularly it is called the Arrowhead region, from its somewhat triangular shape; and physiographically — that is, from the standpoint of its physical geography — it is said to occupy the western part of the Superior Upland. Minnesota can be subdivided into several such physiographic units, each with its own topographic characteristics (Figure 8). All except the northeastern part of the state belongs to the geographical province of the United States commonly referred to as the Central Lowland, but there is no sharp topographic boundary separating the Central Lowland from the Superior Upland.

Southern Minnesota, though all within the Central Lowland, is characterized by three distinct elevated regions. The most prominent of these is in the southwestern counties. This plateau, extending from Minnesota far into the Dakotas and into Iowa, has long been known as the Coteau des Prairies, a name the early French explorers gave it, meaning "highland of the prairies." Physiographically this plateau is part of what is called the Dissected Till Plains of the Central Lowland. These are plains of "till," a name for the miscellaneous rock and soil debris spread out underneath a glacier, that are "dissected," or divided by ridges and valleys. The upper surface of the Coteau is 700 to 800 feet above the smoother glacial plains of the central part of the state, and in isolated areas the Coteau reaches elevations of more than 1900 feet above sea level. The southern part of this plateau stands high because it has a core of re-

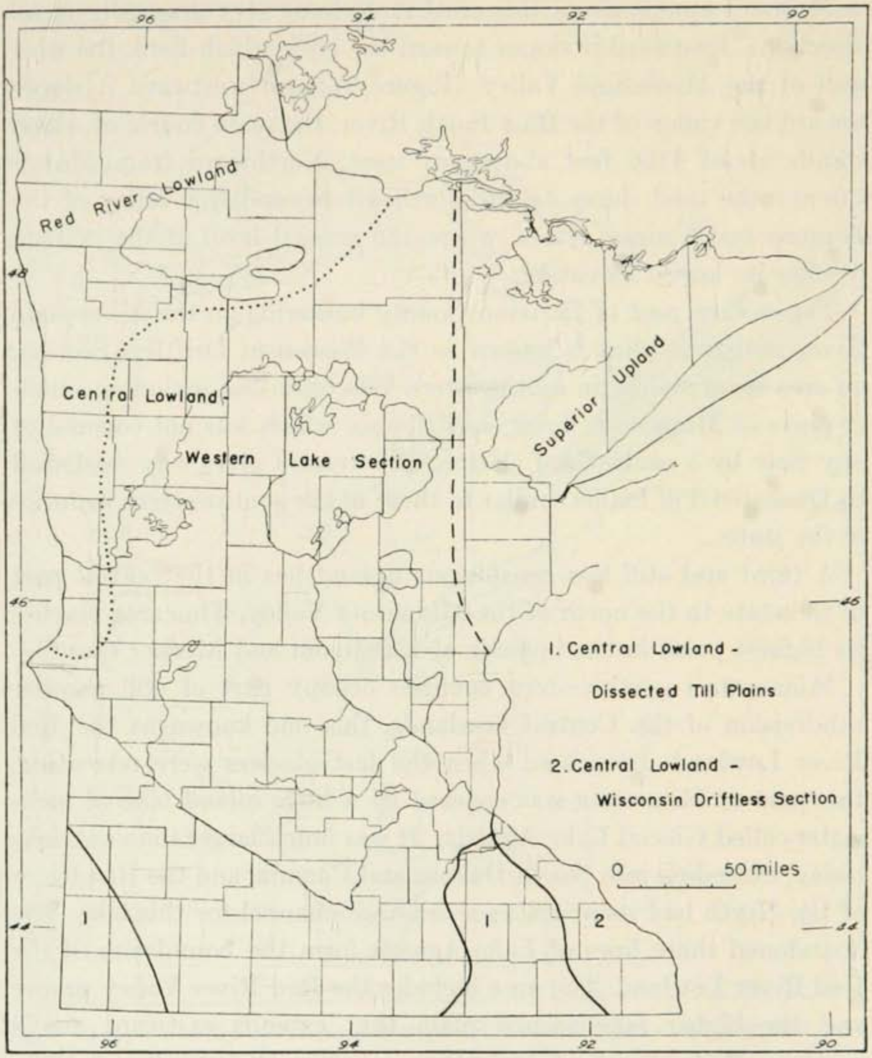


Figure 8. Map of major physiographic divisions of Minnesota. (After Fenneman.)

sistant quartzitic rock that has withstood erosion, but most of the Coteau is a moraine, a series of hills of rock and mineral debris piled up by the glacier that once covered the region.

A second but much lower elevated area occurs in the southeastern counties of Minnesota and reaches its summit of 1400 feet in Mower County. From this crest it declines very gradually in all directions. Eastward it slopes toward the cliffs which flank the west wall of the Mississippi Valley (Figure 7), and westward it slopes toward the valley of the Blue Earth River, the main course of which stands about 1100 feet above sea level. Northward from Mower County the land slopes to the northeast beyond the valley of the Zumbro and Cannon rivers, where the general level of the plateau reaches its lowest elevation.

The eastern part of Houston County bordering on the Mississippi River is within what is known as the Wisconsin Driftless Section, an area lying mainly in southwestern Wisconsin but including smaller parts of Minnesota, Iowa, and Illinois, which was not covered at any time by a continental glacier. This terrain gives way westward to Dissected Till Plains similar to those of the southwestern counties of the state.

A third and still less conspicuous upland lies in the central part of the state to the north of the Minnesota Valley. This area reaches its highest point in the uplands of Kandiyohi and Meeker counties.

Minnesota's northwestern counties occupy part of still another subdivision of the Central Lowlands, this one known as the Red River Lowland. Long ago, when the last glaciers were retreating, this part of Minnesota was covered by a huge inland lake of meltwater called Glacial Lake Agassiz. It was much larger than any lake today, extending into North Dakota and Canada, and the Red River of the North had its origin as a drainage channel for this lake. The abandoned shore lines of Lake Agassiz form the boundaries of the Red River Lowland. The area includes the Red River Valley proper and the higher lake-washed plain that extends eastward across northern Beltrami and Koochiching counties (Figures 9 and 123). The lowest points within the area are about 760 feet above sea level.

These major upland and lowland areas of Minnesota, like all land regions, are the result of many different and sometimes very ancient geological processes — mountain building, tiltings and warpings, and eons of erosion. Our landscape looks secure and permanent to us, but deep in the earth stresses are being applied very slowly

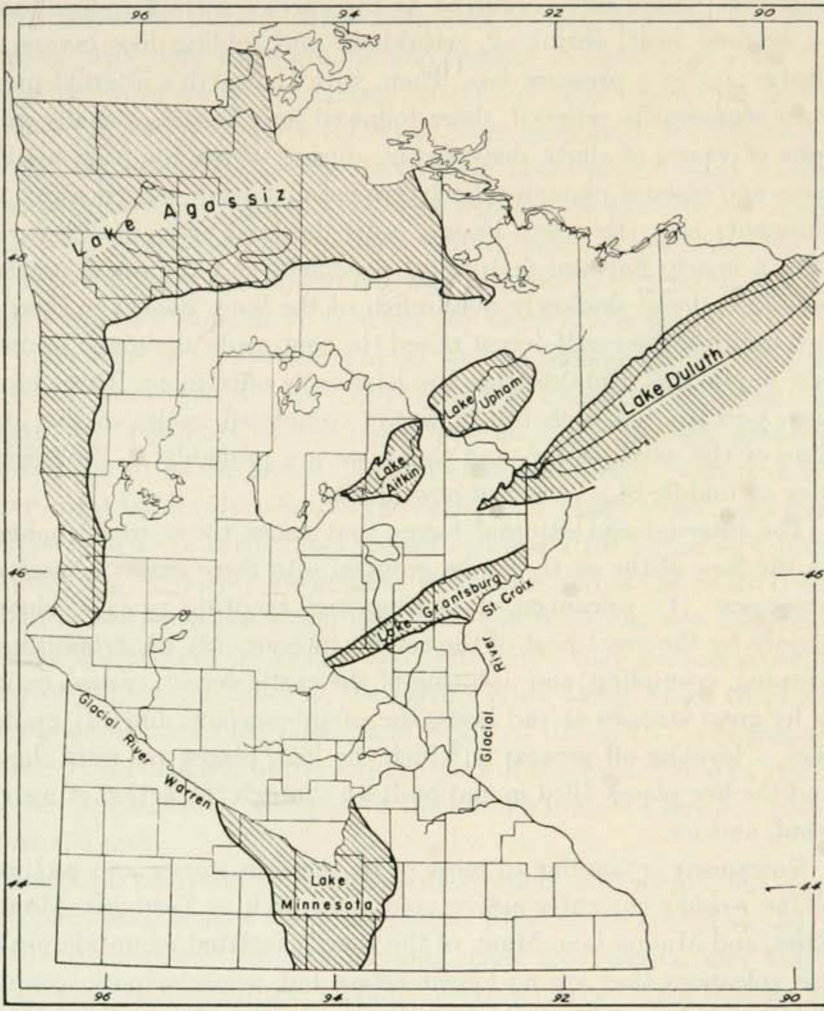


Figure 9. Map of former major glacial lakes and rivers of Minnesota.

but ceaselessly to change it from below, and year after year water and wind work to alter it from above.

Ever since the earth was formed these processes have been going on continuously. Geologists have learned from their study of land and rock formations that from the beginning the surface of the earth has undergone slow, recurrent cycles of great change. Periods of violent volcanic eruptions and vast uplifts of the continents and mountain ranges have occurred as the earth's surface cooled from its original heat, shrinking, wrinkling, and folding like layers of plastic wax in a pressure box. Then, with the earth's internal pressures temporarily relieved, there followed long periods, usually millions of years, of slight disturbance, during which the high mountains and upland plateaus slowly eroded and were carried away as sediments into the ocean basins, until the land areas of the earth were a nearly flat and featureless peneplain and the ocean waters rose and spread shallowly over much of the land. Sooner or later a new uplift of the earth's crust raised the continents again and formed new mountains, thus starting the long cycle once more. There have been perhaps ten such full or partly completed cycles in the lifetime of the earth so far, and today we are probably at the beginning or middle of a period of new uplift.

The internal and external forces that cause these great changes on the face of the earth can be grouped into three major geological processes: (1) volcanism, a melting and erupting process caused mainly by the great heat of the earth's interior; (2) diastrophism, a warping, crumpling, and uplifting of the earth's crust, caused mainly by great stresses at and below the earth's surface; and (3) gradation, a leveling-off process in which the high places are worn down and the low places filled in and built up through the action of water, wind, and ice.

Volcanism is familiar to most of us through stories and pictures of the world's currently active volcanoes, such as Vesuvius, Mount Etna, and Mauna Loa. Many of the world's isolated mountain peaks are volcanoes that are no longer active but whose smooth, conical shape and slopes of hardened lava or volcanic cinders indicate their origin. We know that Minnesota, too, had active volcanoes among its long-ago mountains, for today in some parts of the state we find beds of volcanic tuff, a porous, fine-grained type of rock formed from molten material thrown into the air by volcanic explosion.

Not all volcanism occurs in the form of erupting volcanoes, however. Volcanism refers to any movement of molten rock material, whether it is forced from a volcanic vent, flows out of cracks and fissures on the earth's surface, or forces its way among older rocks deep below the surface. Most volcanism, in fact, is of the last type, taking place deep underground and coming to light only when erosion has worn away the surface to expose great masses of molten mineral matter that have cooled to form igneous rocks. Minnesota is one of several states that have large areas where these ancient rocks, formed underground, are now exposed on the surface. Along the North Shore of Lake Superior we can also see hardened sheets of lava that long ago flowed out from fissures on the surface of the earth and now slope down beneath the water of the lake.

Volcanism is often accompanied by the second great geological process, diastrophism, for along with the intense heat inside the earth that produces molten rock there may also be high pressure, enough to lift whole mountain chains and continents. Such pressure may build up slowly beneath the surface for many years, and then at last, when the earth's rocky crust can stand the strain no longer, it may yield suddenly along some weak zone across the rock layers. High-velocity waves are thus generated and travel through the rocks. Where these waves are violent and destructive, they are called earthquakes. The weak zones in the earth's crust along which displacements occur are called faults, and many of the earth's topographic features, particularly in the western part of the United States, result from a sinking or an upthrust of the earth's surface along the plane of such a fault.

Earthquakes result from sudden diastrophic movements, but diastrophism may be slow and gradual, too. Most of the continents have been raised above the seas by long, slow movements, and many mountain ranges also take millions of years to rise. Most mountains are formed by a slow folding and crumpling process in response to vertical stresses from below and horizontal stresses near the margins of the continents. It is probably the latter type of stress that has produced North America's general topographic pattern, with mountain ranges near and parallel to the coasts, and in between a much more level continental basin, of which southern Minnesota is now a part.

In the distant past Minnesota, too, had giant mountain ranges. We know that many types of rocks, those called sedimentary rocks, are originally laid down in horizontal layers; so when we find these layers folded and tilted (Figure 113), or crumpled into wavy lines, we know that diastrophism has taken place, pressing the originally flat layers up into ridges and mountains. By measuring the angle and thickness — sometimes hundreds of feet — of these layers, or strata, and by studying the places where still-hidden underground strata appear as outcrops on the surface, geologists can determine the height and extent of former mountains that have long since been eroded away.

The eroding away of mountains is part of the third great geological process, gradation. Gradation is a leveling process that includes both erosion, or wearing away, and deposition, or building up. All rocks exposed on the surface of the earth are subject to constant weathering, which tends to break rocks down into small fragments. This may be chemical weathering, in which the chemical elements of the air and water combine with the elements of the exposed rock, making the rock surfaces pitted and crumbly.

There is usually physical weathering, too — alternate freezing and thawing of water in the pores and cracks of the rock, or a slow abrasive scouring by running water and wind-carried sand. Biological weathering may hasten the process if lichens cling to the rock surface and dissolve out plant food, or if plant roots or burrowing animals widen small cracks already started. Eventually, after many centuries, all exposed rocks are broken down into rock debris of various sizes, and when such material accumulates at the surface it is called mantle rock. This debris is then gradually carried away to lower resting places, eventually buried and compressed there into new kinds of rock; and perhaps millions of years later, in a new diastrophic uplift, the remains of those early rocks may be raised into mountains or plateaus to start the long gradational cycle once more.

These erosional and depositional processes are carried on by what are called the geological agents — wind, running water, waves and currents, ground water, and ice. All of these are essentially means of transportation for the rock debris broken down by weathering. All of them obey the law of gravity in their movements, so that the patterns of erosion and deposition that each forms are easily recognizable. Wind, for example, can carry fairly sizable particles if it has a high velocity, but as its speed is checked the heavier particles are dropped first. Thus wind tends to sort out the debris it carries and deposit it according to size. Sands are usually too coarse to be transported very far, and for that reason the characteristic forms of sand dunes develop. The wind continually picks up sand on the windward side of the dune and drops it on the leeward side, so that the dunes are forever moving without changing their form appreciably (Figure 93).

The running water of streams and rivers operates according to the same laws, carrying pebbles, sand, and silt as long as it has a rapid flow, but dropping them in characteristic patterns wherever the slope of the river bed levels off suddenly or wherever the velocity of the stream is retarded because of other factors. When a hillside stream reaches a flatter, broader plain, its rate of flow is lowered at once and the debris dropped by the water forms an alluvial fan, a sloping, fan-shaped deposit under the slower-moving water. A similiar deposit called a delta is formed at the mouth of most rivers, where the flow of water is retarded as it enters a large, quiet body of water — the Mississippi delta, for example, in the Gulf of Mexico, or the smaller deltas where the rapid North Shore rivers enter the broad expanse of Lake Superior.

The waves and currents of standing bodies of water are also erosional and depositional agents. Large waves pounding against rocky cliffs may very quickly erode and break off great masses of rock, while smaller waves and currents pick up or roll away the debris to form beaches (Figure 96), spits, and sand bars somewhere else (Figure 92). Ground water, too, both erodes and deposits elsewhere, but unlike the other geological agents it carries its erosional products dissolved in solution. Ground water is water that moves through the pore spaces of rocks and soil instead of being carried away in streams and rivers. It sinks underground, percolating very gradually through soil particles and rock pores, and though it moves too slowly to transport any debris, it often dissolves out some of the rock elements as it circulates.

Some rocks, such as limestone, are especially susceptible to the dissolving action of ground water, and as a result underground caverns and caves like Mystery Cave near Spring Valley (Figure 148), are often formed in beds of limestone. The ground water dissolves away a mineral called calcite from the limestone, causing the rock to crumble and collapse; and later, other ground water bearing calcium bicarbonate in solution may trickle into these limestone caverns and deposit calcite there in a new form, the "rock icicles" called stalactites and stalagmites.

We have left till last the most impressive geological agent of all, the glacial ice that has played such a great part in shaping the face of Minnesota. Running water is probably the most widespread and effective agent for leveling the land, but the glaciers, limited in extent and time though they have been, are the most overwhelming and powerful. Much of North America (Figure 66) and Europe has been covered by continental glaciers several times during the long history of the earth. The last glacier retreated from Minnesota as recently as 11,000 years ago, and many of the most familiar details of the state's landscape — its lakes, streams, and rolling farm lands — are the result of glacial action.

The advance of a glacier was caused in each case by a long period of cold climate in the earth's history, during which the snow that fell in northeastern North America and northwestern Europe did not melt but accumulated in snowfields that reached a depth of many thousand feet. The weight of the snow compacted the bottom layers into ice, and gradually under the increasing pressure of the snow the ice spread out in all directions over the land. As the thick ice sheets moved southward over hills and valleys, mountains and plains, they scraped off great quantities of rock and soil. They carried along everything from huge boulders to fine dust, freezing everything they touched into their vast, icy bases. As the glaciers advanced, the rocks over which the ice moved were scoured and striated (Figures 67 and 68), and the larger boulders incorporated in the ice often gouged large grooves in the bedrock. The rocky basins of many of Minnesota's lakes near the Canadian border were scraped out by this process.

The rock and soil debris carried by the glaciers was heterogeneous and unsorted, unlike the particles carried by other geological agents.

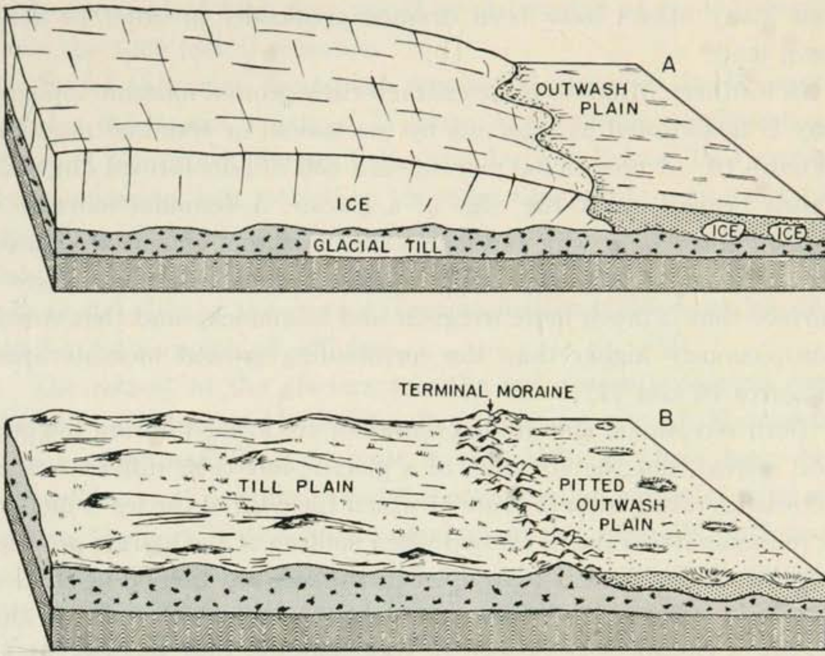


Figure 10. Diagram showing formation of an outwash plain (*A*) and a terminal moraine (*B*).

This unsorted glacial debris of all sizes and shapes is called "drift"; and when the ice began to melt, this drift was deposited in various ways. Some of the larger boulders were left standing as isolated "erratics" on the glacial plain (Figure 70) . Some of the drift was spread out thinly over the land, forming till plains (Figure 79), or filled old preglacial hollows and valleys. Some of it was piled up higher at the edges of the glacier, forming belts of hills, called moraines, of various types and sizes (Figure 10) .

Almost all of midwestern United States and much of Canada were covered by ice sheets at one time or another, but nowhere in North America is there a more typical example of ground moraine left in the wake of a glacier than is exhibited by the extensive, slightly undulating expanses of south central Minnesota (Figure 79) . This ground moraine is a widely distributed mass of rock and mineral debris deposited underneath and at the edge of the glacier as the ice melted. Its surface is dotted with numerous shallow lakes and ponds.

and many others have been drained artificially in order to make farm land.

In southern Minnesota the characteristic ground moraine topography is interrupted at intervals by recessional or terminal moraines (Figure 10). A recessional moraine is a belt of hills formed of glacial debris heaped up at the edge of a glacier. A terminal moraine is formed in the same way and marks the maximum extent of a glacier during a major advance. Both of these types of moraines have a surface that is much more irregular and hummocky and that stands conspicuously higher than the surrounding ground moraine areas (Figures 76 and 77).

Both recessional and ground moraines are formed during the general retreat, not the advance, of a glacier, but their different characteristics result from the *rate* at which the edge of the ice is melted. A recessional moraine is formed when melting at the margin or outer edge of the glacier is about equal to the forward motion of the ice. The front margin thus remains stationary for a long time. When this occurs, a considerable deposit of rock material that was caught up in the ice will accumulate at the edge of the melting glacier. The height of such a moraine depends to a considerable extent upon the length of time during which the front of the glacier remained stationary, for a rapid retreat of the ice would not allow much material to be piled up at the same place. If the ice of a glacier moved forward 1000 feet a year for a period of 50 years but melted at the outer edge as fast as the ice moved, the front of the glacier would remain stationary, and during the whole 50 years all the debris from the melted ice would be deposited in one ridge along the edge of the glacier. In other words, during those 50 years nearly 10 miles of solid ice would have moved forward to the margin, where it melted and dropped its load of debris to form a recessional moraine.

Suppose, however, that the front of the glacier had receded — that is, melted back — more quickly, say 1000 feet a year, while the main ice mass remained stationary. In that case very little debris would be piled up at any one spot, and consequently no pronounced morainic ridge would be formed. The rock debris of the whole 1000 feet of ice melted each year would be distributed as ground moraine over the 1000 feet of recession.

One of the most prominent recessional moraines in Minnesota crosses the region north of Willmar and extends northwestward through Glenwood, Fergus Falls, and Detroit Lakes, This moraine is a hummocky belt more than ten miles wide, containing many hills and basins in a disorderly and irregular manner. Such patternless landscape has many rounded hills, lakes, ponds, and bogs. Its height above the plain of the ground moraine surface varies from less than 50 feet to as much as 400 feet.

The retreat of the glaciers was the last major geological event before our time in Minnesota, but other aspects of Minnesota's topography may be even more recent. Most of these have been caused by local peculiarities of the never-ending action of wind and water. On part of the Anoka sand plain, for example, just north of Minneapolis, local wind action has superimposed sand dunes on top of the glacial moraine. This sand plain extends from Minneapolis to Elk River, northward to Princeton, and eastward to the St. Croix Valley. Other excellent examples of small dunes can be seen on Minnesota Point at Duluth (Figure 93).

Here and there about the state we find other local curiosities — flat areas that once lay at the bottom of glacial lakes like Lake Agassiz; rock ridges of some hard rock such as quartzite that rise abruptly above the smooth surface of the glacial drift; or low mesas of horizontal rock layers, limestone or sandstone, left by erosion to stand as isolated towers in regions where the glacial drift is thin or entirely absent. In the southeastern counties we find regions where there are many sinkholes (hollow cavities in the ground where the tops of limestone caverns have fallen in), where the drift is thin and the underlying limestone is near the surface. In other parts of southeastern Minnesota the wind has deposited a mantle of fine-grained loess, or siltlike dust, from one to fifteen feet thick, obscuring surface irregularities like a heavy fall of snow.

These are all local phenomena, fascinating in their own right but not typical of large parts of Minnesota. On an even smaller scale we can see year by year the geological changes occurring in our own home territories — the widening or drying up of a creek bed, the crumbling away of a lake-shore cliff, or the growth of gullies on a hillside. Many such minor changes of topography we can watch with our own eyes throughout our lifetimes; but many other much greater changes are also occurring, slowly and imperceptibly, on too vast a scale for us to see.

For example, geologists know that diastrophic forces are still raising our western mountain ranges; that in some regions quantities of molten lava still make their way up from deep within the earth; and that our climate is growing perceptibly warmer, enough so that in a few hundred thousand years the melting polar ice caps may raise the oceans to spread again over parts of the continents. And when the seas retreat, a drop of a few degrees in temperature could bring new glaciers in their wake. Like land surfaces everywhere, the face of Minnesota will always be changing, a massive sculpture that is never finished.

CHAPTER

2

Rivers and Lakes

THE advance and retreat of the continental glaciers was one of the most crucial events in shaping Minnesota's present landscape. We have already learned how the ice sheets were responsible for the rolling, morainic topography of southern Minnesota. Even more spectacular, however, is the way they turned Minnesota into a "Land of 10,000 Lakes" (actually, more than 11,000). When the climate grew warmer and the glacial ice began to melt, lakes of many kinds and sizes were left in the uneven surface of the land. Streams and rivers cut their way through the drift and underlying rock to drain some of these bodies of water, but as rain and snow and underground springs constantly replenished them, many lakes remained. Slowly the network of drainage systems in the state formed into its present pattern.

Because of the work of the glaciers, Minnesota's water area is greater than that of any other state, even without including any part of Lake Superior. There is one square mile of water to every twenty of land for the entire state. The water from the numerous lakes flows out of the state in the valleys of seven different rivers — the Mississippi, the St. Louis, the Rainy, the Red River of the North, the Des Moines, the Cedar, and the Rock. There are many other rivers, too, that do not leave the boundaries of the state, ranging in character from the placid, winding Minnesota River, which joins the Mississippi, to the short, turbulent streams along the North Shore that race down rocky gorges and over beautiful waterfalls to end in Lake Superior (Figures 11, 101, 103, and 115).

Of all these rivers, the Mississippi is by far the largest and has the most extensive drainage basin (Figure 2). A river's drainage basin includes all the surrounding area that drains toward it and supplies it with water. Every drop of water that falls on Minnesota must fall in one drainage basin or another, and we have already seen how ultimately that water, unless it evaporates or is used by animals and plants, must join one of three great drainage systems of North America, flowing north to Hudson Bay, east to the Atlantic Ocean, or south to the Gulf of Mexico.

In the large Mississippi drainage basin, the river's valleys extend nearly across the state from north to south, and its major tributary, the Minnesota River, crosses the state from west to east. Upstream from St. Anthony Falls in Minneapolis, the river flows almost exclusively on glacial drift, and in the area north of Aitkin it meanders over the bed of Glacial Lake Aitkin, an ancient, long-vanished lake like Lake Agassiz, though much smaller (Figure 9). Downstream below the Falls of St. Anthony the river and all of its major tributaries have cut deep gorges into the bedrock formations. Where the river leaves the state in Houston County, its gorge, carved out of solid rock, is four miles wide and 500 feet deep. The valley was once nearly 200 feet deeper, for the river now flows over a thick deposit of alluvium — the sediments of sand and gravel dropped over the years by the flowing water.

The St. Louis River and Lake Superior jointly constitute one of the state's smaller but most rugged drainage areas. The streams flowing directly into Lake Superior from the northwest descend with frequent cascades from over 2200 feet above sea level to 602 feet, the level of Lake Superior. Most of this drop occurs within five to ten miles from the lake shore. In such high-gradient valleys numerous waterfalls are to be expected. The double falls of the Gooseberry River and the falls of the Manitou, Arrowhead, and Baptism rivers are typical examples (Figures 11, 101, and 103).

In contrast to the steep, rapidly falling streams that descend

Figure 11. Manitou Falls, Manitou River, North Shore of Lake Superior, Lake County. Falls formed by erosion of soft amygdaloidal top of a lava flow below massive rock of the overlying flow.

from the high escarpment that parallels the North Shore of Lake Superior, there are the leisurely flowing streams on the plateau to the northwest of the lake. The headwaters of the St. Louis River, including the Cloquet and Whiteface rivers, have an average slope of no more than eight to ten feet to the mile. A study of the history of the St. Louis River reveals that its present headwaters once flowed into the Mississippi River. A large valley extending southwestward from the town of Floodwood, where the St. Louis River turns abruptly to the southeast, indicates that this bend is an "elbow of capture" where the St. Louis was able to divert the water from the Whiteface River to itself (Figure 12).

The "capture" of one river by another is an interesting phenomenon. During the process of valley development, each stream continues to extend itself by slow erosion toward its head, or source, until it meets high ground, or divides, separating its drainage basin from that of another stream. During this process it frequently happens that one stream finds conditions for growth and headward extension more favorable than does another stream on the opposite side of the divide. The first stream, by the extension of its tributaries, cuts back until it steals some of the headwaters of the less favorably situated stream and diverts them to its own channel. The marked slope of the lower part of the St. Louis River favored such stream capture. Thus today all of its headwaters start to flow southwestward toward the Mississippi River, but change their course abruptly at Floodwood to join the St. Louis, leaving only a dry, abandoned valley to continue toward the Mississippi. The Cloquet River undoubtedly had a similar history.

Another of Minnesota's large drainage basins is the Rainy River system, with an area of slightly more than 10,000 square miles in Minnesota (Figure 2). Part of this river system is in reality a chain of lakes, including the many beautiful wilderness lakes along the Canadian border — Gunflint, Saganaga, Lac La Croix, Rainy, and many more. Much of its water comes from tributaries to the north of the international boundary. The river system, flowing west and north, extends from a divide at North Lake on the boundary in Cook County to Lake of the Woods; but Rainy River proper flows

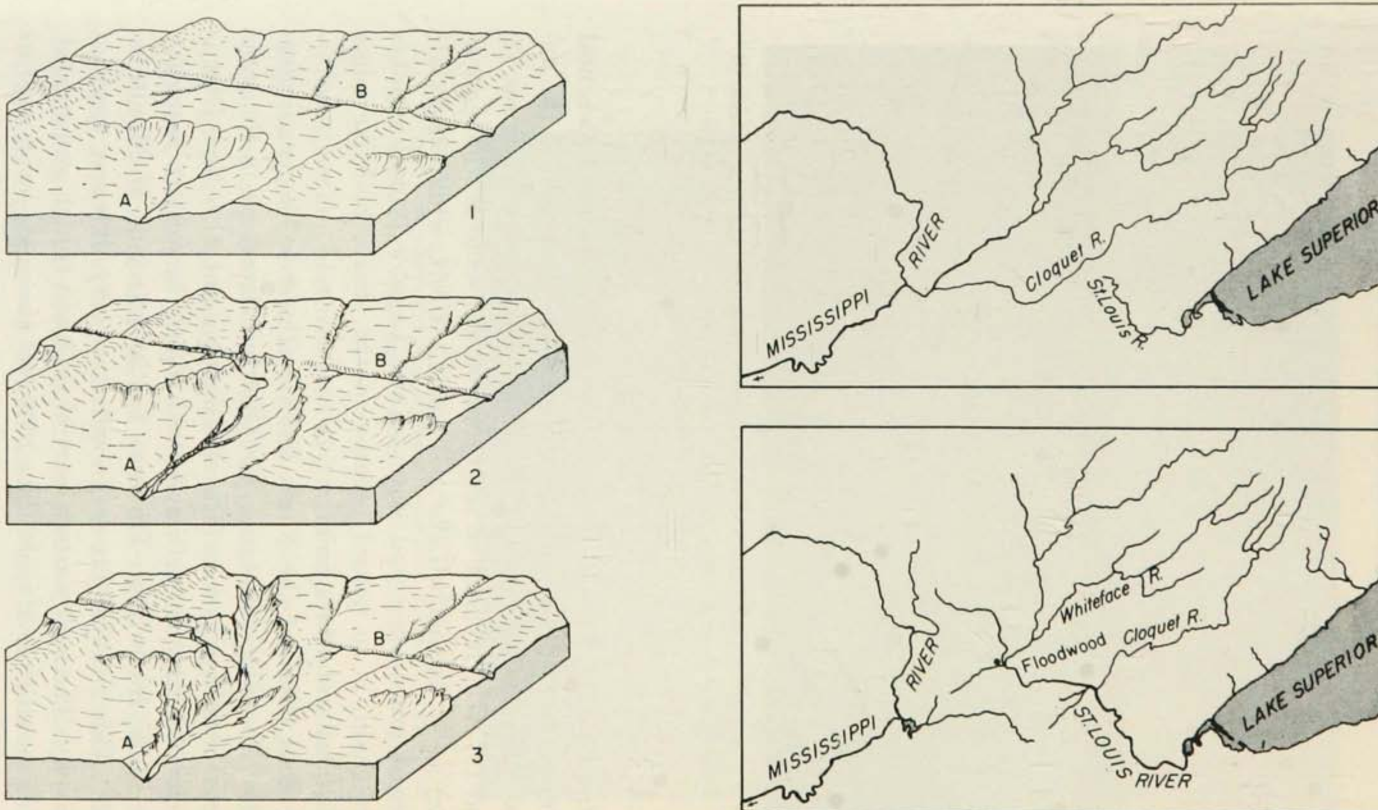


Figure 12. LEFT. Diagrams illustrating stream piracy: (1) The tributaries at *A* are advancing by headward erosion toward the valley of the stream *B*; (2) The stream *B* has been beheaded or captured and its headwaters are diverted to the pirate stream *A*; (3) The valley of *A* is extended and deepened. (Based on a drawing by Davis.) RIGHT. Maps showing the drainage changes of the St. Louis and Mississippi rivers: ABOVE, before stream capture; BELOW, after capture and diversion.
(After Lawrence Martin, U.S. Geological Survey, Monograph 52.)

Figure 13. Aerial view of Lac La Croix, a typical northern Minnesota lake, St. Louis County. (Courtesy of Minnesota Department of Business Research and Development.)

only from Rainy Lake to Lake of the Woods. Some of the most picturesque topography in the state occurs in the region of the numerous lakes that are part of the Rainy Lake system (Figures 13, 14, and 15). The lakes lie in solid rock basins, some of which are in granite, as at Saganaga Lake and Lac La Croix, while others are in ancient greenstones and slates. Knife Lake, a typical member of this chain, is so named because of the sharp, knifelike edges of the slates around its basin.

The Red River of the North flows northward. The headwaters of one of its major tributaries, the Ottertail River, are in the same rolling morainic region as the Mississippi, but the Red River's main channel extends north and south along the western boundary of the state from Lake Traverse to the province of Manitoba, Canada. This river drains areas with two very different types of topography. The southeastern part of its basin is high and rugged, reaching an altitude of more than 1600 feet above sea level, whereas

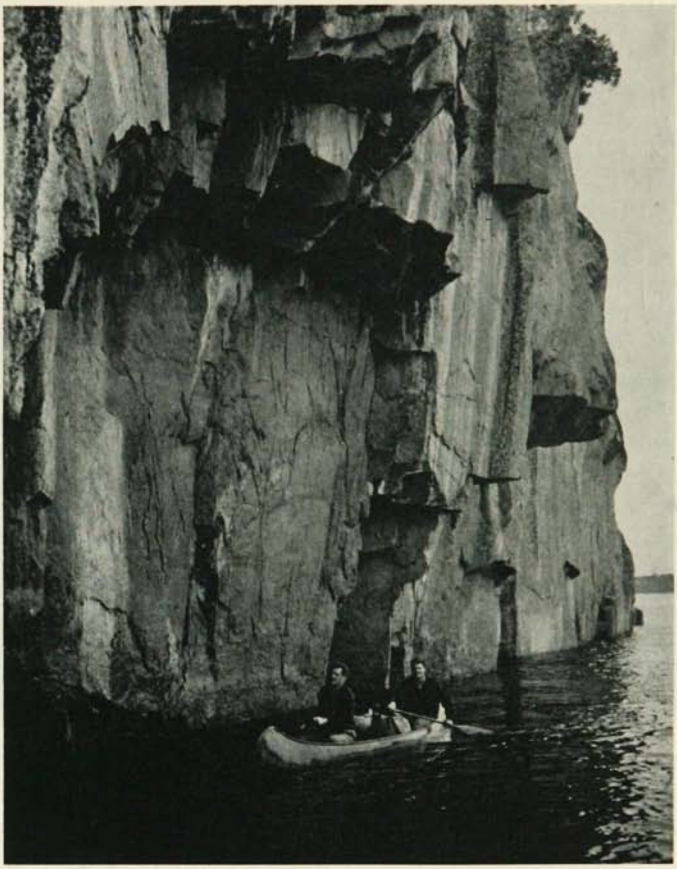


Figure 14. Painted Rocks, Lac La Croix. Rock bluffs of this type are characteristic of many northern lakes. (Courtesy of Minnesota Department of Business Research and Development.)

the western and northern part of its drainage area is a flat plain that lies less than 800 feet above the sea. This expansive plain is part of the bed of the ancient Glacial Lake Agassiz, the beaches of which may be traced for many miles across Pennington, Red Lake, Polk, Norman, Clay, and Wilkin counties (Figures 9 and 125).

Way back when the glaciers were retreating, leaving Lake Agassiz in their stead, that lake was forced to establish a drainage channel. At first the water rushed southward across the normal continental divide, in a great river we call the Glacial River Warren. It carved

Figure 15. Mica Bay, Lake Namekan, in northwestern St. Louis County.

out the wide valley that is now the Minnesota River Valley. As the ice retreated farther into Canada, however, lower-lying channels were uncovered, and the waters of Lake Agassiz then drained northward into Hudson Bay. When most of the lake was drained, the Red River of the North was formed on the floor of the lake, in a sense by capturing Lake Agassiz from the Glacial River Warren. This glacial river then subsided, leaving only the much smaller Minnesota River to flow through its wide valley. But for some time afterward, when lake levels were higher than they are at present, the water in the Red River of the North was continuous with that of the Mississippi River drainage area through the valley-like basins of Lake Traverse and Big Stone Lake, which were once part of the Glacial River Warren. The topography around the village of Browns Valley shows many signs of the former existence of a river that flowed through a valley between the two large lakes and drained the water of the Red River of the North and Lake Winnipeg through the Minnesota River to the Mississippi (Figure 132).

The southwestern counties of Minnesota lie in the Missouri River drainage basin. In all of Rock County and parts of Pipestone, Murray, and Nobles counties the drainage is southwestward to the Big Sioux River, the main tributaries of which are the Rock River and Beaver Creek. The Rock River, the largest stream in the area, flows southward across the eastern portion of Rock County, where it occupies a wide valley and receives many tributaries which enter it through narrow, gorgelike valleys.

The valley of the Des Moines River developed along the northeast margin of the Coteau des Prairies, from which it receives numerous small tributaries that have cut shallow channels in the prairie-like topography of that part of the state. Farther south, in Iowa, the river discharges into the Mississippi, so it is in reality part of that drainage system. The Cedar and Rock rivers are also part of the Mississippi drainage system.

River systems are constantly draining water away from Minnesota, yet much remains in her thousands of lakes. The lakes, indeed, are probably the most interesting and striking feature of Minnesota's scenery. They occur in many sizes and shapes and in a great variety of landscapes, but whatever their setting, they represent natural beauty of the highest order.

The lakes are not evenly distributed throughout the state. In some parts of Minnesota they are so numerous that when one stands on a high point of land it is possible to see literally scores of lakes lying in different directions (Figure 16). But other parts of the state, notably the southeastern counties and parts of many northwestern counties, show a remarkably sparse distribution. The reason for their absence in the southeast is the fact that the last ice sheet did not cover that area. Therefore no moraines, with their lake-forming hollows and hummocks, were left here, and the previously developed, preglacial river valleys were not filled in by glacial drift. These well-established rivers continued to drain water away from the last glacier in large quantities, providing this part of the state with what is called a mature drainage system — that is,

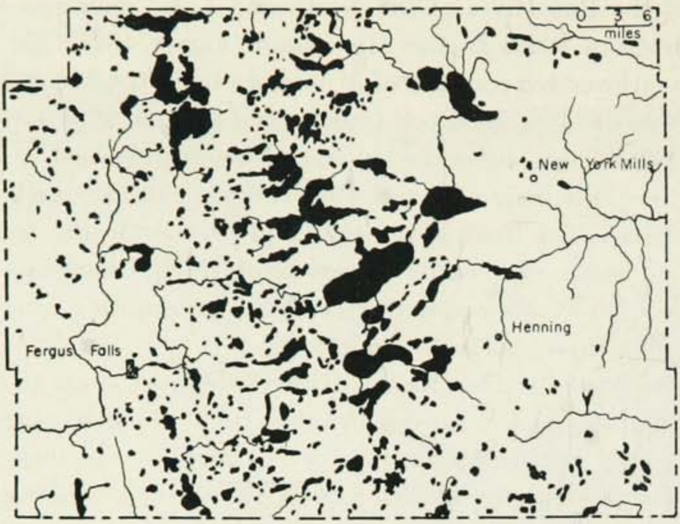


Figure 16. Map showing many irregular lakes in a terminal moraine area, Otter Tail County, west central Minnesota.

one that is old and deeply cut and does not allow much water to stand in surface basins like lakes. The reason for the absence of lakes in the Red River Valley region is that the valley itself is the bottom of the former Glacial Lake Agassiz and has no depressions to hold surface water.

If we planned to view the greatest number of Minnesota lakes in the shortest period of time, we should travel by airplane, entering the state from Wisconsin at Taylors Falls and flying southwestward toward Lake Minnetonka. Having crossed Minnetonka, the flight should turn almost at right angles to a northwesterly direction across Wright, Meeker, Kandiyohi, Pope, Douglas, and Otter Tail counties. Along this route, on a clear day, scores of lakes would always be in sight. If after crossing Detroit Lakes the flight turned northeastward toward the headwater lakes of the Mississippi, and thence onward across Itasca and St. Louis counties to include Vermilion and Burntside lakes and those of the international boundary region, we would see literally thousands of lakes along the route. Few other places in the world offer such a remarkable diversity of land, water, and winding streams.

Minnesota lakes may be shallow and sandy or rocky and deep; mucky and weed-fringed or clear as crystal; big, little, wide, narrow, round, long, sun-warmed, ice-cold, with or without islands, inlets, bays, sand bars, beaches, and cliffs. A lake may be defined as a natural inland depression or reservoir containing an appreciable amount of water. A pond is a very small, very shallow lake, with quiet water and much aquatic plant life. Any geological process that produces a depression on the surface or obstructs drainage channels may produce a lake.

Almost all the lake basins in Minnesota are directly or indirectly a result of glacial action. Some glacial lakes are due to erosion — for example, the Canadian border lakes, the basins of which were scoured out of solid rock by the ice sheet. These northeastern Minnesota lakes will be discussed in a later chapter. Other lakes are the result of deposition, the depositing of glacial debris to form hollows where water collects; and still others result from a combination of erosion and deposition. In the unusually rugged surface of the moraines, small lakes formed by depressions in the glacial drift may exceed a score to a square mile. These are often called kettle lakes from a fancied resemblance to a kettle partly full of water. Very deep and irregular basins are found in the recessional or terminal moraine zones. Lake Minnetonka is an outstanding example of an exceedingly irregular basin in terminal moraine topography. Its numerous bays, points, and islands are the product of partially submerged "knobs and kettles." In such terminal moraines it is difficult, if not impossible, to distinguish lakes formed by irregular deposition of drift from those formed by the melting of stagnant ice blocks. The latter type of lake we shall discuss a little later.

A lake in ground moraine is always shallow. This is because its depth is determined by the relief of the local topography, which in ground moraine rarely exceeds 20 or 30 feet. Heron Lake in northwestern Jackson County is an excellent example of this type of lake. It is located entirely within the ground moraine of glacial drift and has a maximum depth of 5 or 6 feet. The topography of the immediate vicinity is level and undistinguished, typical of ground moraine and with a maximum variation of about 20 feet.

If a terminal or recessional moraine is sufficiently irregular, and if the land surface near its margin slopes toward the moraine, then conditions are favorable for the formation of a moraine-dam lake. Mille Lacs Lake in northern Mille Lacs County is one of the best examples of a moraine-dam lake in Minnesota (Figure 129). This lake, nearly 200 square miles in area, is impounded, or dammed up, behind the rugged Mille Lacs moraine, which rises abruptly 130 feet above the lake south of Garrison. In some places the dammed-up water of the lake reaches a depth of 35 feet. Unlike the western and southern shores of the lake, the northern and eastern shores are marked by swamps, indicating that at one time the lake level was about 15 feet above the present level and covered the area that now is swamp.

Another way in which glaciers form lakes is by leaving behind stagnant ice blocks as the main ice mass starts to retreat. Usually these ice blocks are partially or completely buried by the lighter debris, mostly gravel and sand, that is carried away from the melting glacier by streams of "meltwater." This lighter glacial debris is sorted and stratified by the process of being carried by the meltwater, the heavier particles being dropped before the lighter ones. We call this sorted, water-borne glacial debris "outwash," in contrast to the unsorted, heterogeneous debris of glacial drift and moraines, much of which is carried frozen into the ice.

If the front margin of a glacier remains stationary for some time, the meltwater streams issuing from its surface are apt to build an extensive "outwash plain," provided the land uncovered by the glacier in its previous retreat slopes away from the ice margin. Sometimes a large mass of ice at the margin of the glacier becomes buried by outwash. When this ice melts it leaves an ice-block basin, or pit, which when filled or partially filled with water becomes a lake. Some of the lakes formed in this manner, such as Lake Edward north of Merrifield, have depths up to 70 feet, but the average is closer to 20 or 30 feet.

When an outwash plain has many ice-block basins, it is called a pitted outwash plain (Figure 17). One of the best examples of a pitted outwash plain in Minnesota is in Crow Wing County near

Brainerd. There the retreating glacier left an outwash plain dotted with kettle lakes, as these ice-block lakes are often called, some of which do not entirely fill their basins.

Sometimes an ice-block basin may lie partially within the drift of a recessional moraine and partially in the outwash plain. That portion of the basin that has its rim in the outwash will be a steep ice-contact slope (see Figure 17, B), which may be partially submerged below the level of the lake now occupying the basin. Lake Minnewaska is a typical example of such a lake. It is located in west central Minnesota, near the town of Glenwood. Glenwood lies at the base of a steep ice-contact slope which forms the northeastern shore of the lake and rises 230 feet above the present lake level to an extensive outwash plain. The major part of the Lake Minnewaska basin is situated within the moraine itself, and thus

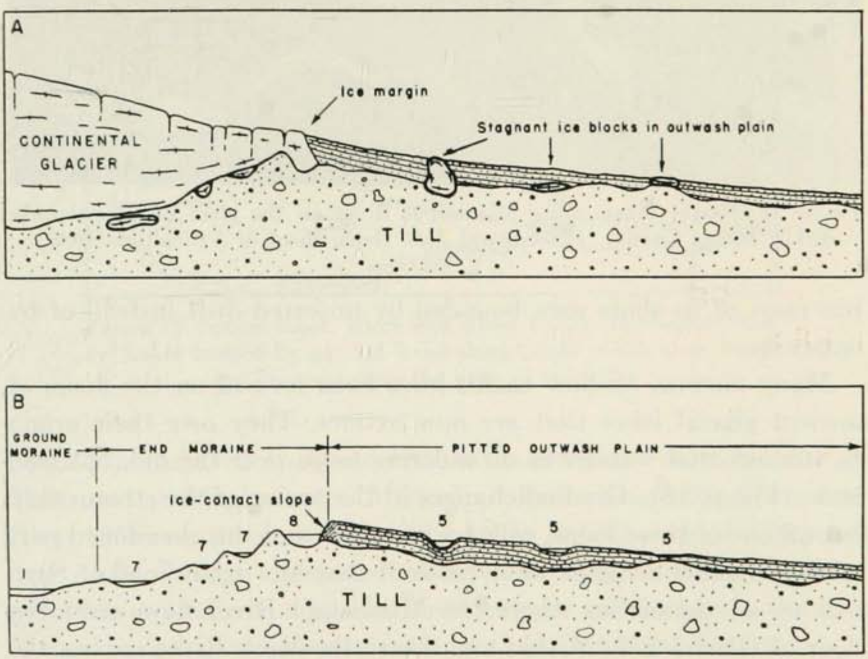


Figure 17. Diagrams showing origin of several different kinds of glacial lakes. The numbers indicate the lake type: (1) basin formed by the irregular deposition of till; (5) ice-block basins in an outwash plain; (7) ice-block basins in till; (8) ice-block basin in till and outwash.

Figure 18. Oxbow lakes, along Mississippi River on the plain of Glacial Lake Aitkin, Aitkin County. (Photograph U.S. Department of Agriculture, 1939.)

has most of its shore area bounded by unsorted drift instead of by outwash.

Many narrow, shallow basins have been formed on the floors of ancient glacial lakes that are now extinct. They owe their origin to streams that wander in meandering loops over the old, flat lake beds (Figure 18). Gradual changes in the course of the stream may cut off one of these loops, called a meander, and the abandoned part of the channel remains as a crescent-shaped "oxbow" lake. Such oxbows are numerous where the Mississippi River flows over the floor of Glacial Lake Aitkin and where the Rum River crosses the sandy plain north of Anoka. Another type of lake may be formed by a stream at places where floods have left natural levees or ridges along its banks. These ridges prevent the drainage of parts of the flood plain after the flood is over, and shallow lakes are left like those along the Minnesota River between Shakopee and Fort Snelling (Figure 19).

Rivers may form lakes by still another method. Where a tributary stream brings to the main stream an excess of sediment, it is deposited as a delta, forming an obstruction or dam in the channel of the main stream. The water of the main stream that is thus

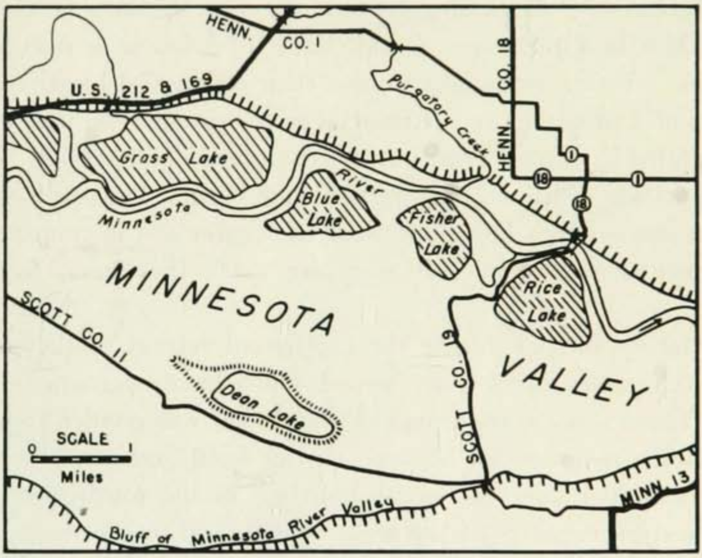


Figure 19. Saucer lakes, Minnesota River Valley, Hennepin County. Lakes formed by natural levee along banks of the river blocking drainage from the sides of the valley.

ponded or dammed up forms what is known as a river lake. This is illustrated strikingly in the Mississippi River where the Chippewa River of Wisconsin empties into it, causing the Mississippi to expand over its flood plain and form Lake Pepin (Figure 146). The Chippewa has a gradient of nearly three feet per mile, whereas the bed of the Mississippi slopes no more than three inches per mile. Because of this difference in gradient, the Chippewa flows much faster than the Mississippi (several miles per hour) and carries with it much coarse sand and gravel. Where the two rivers meet, this material is dumped into the channel of the Mississippi, since the latter is too slow moving to transport the heavy load of sediment. The Mississippi is thus forced to back up, spread out, rise, and flow over the barrier. The backwater or backing-up caused by this natural dam of sediment extends 30 miles upstream to the mouth of the Cannon River. A somewhat similar example is Lake St. Croix in the St. Croix River, which was formed by sediment deposited by the Mississippi across the mouth of the St. Croix (Figure 20).

Former river valleys may become the sites of lakes or chains of lakes. Martin County has three chains of lakes in a north–south direction which are thought to owe their origin and location to old valleys of a preglacial or interglacial river system. The valleys were partly filled by glacial drift, but not completely obliterated. The unfilled portions of the valleys are now lake basins. The chain of lakes that passes through Fairmont, near the center of the county, has a very regular alignment and may also mark the line of a former valley.

As the ice melted during the northward retreat of the glaciers, many temporary lakes were formed which have long since drained away. These lakes were formed by water that was ponded temporarily between moraines, or between the ice front and morainic ridges. The northward slope of the land surface in the south central and northwestern counties of the state contributed to the formation of such lakes. The normal flow of the meltwater would be northward because of this slope, so the water was ponded by the south margin of the ice. In a number of regions the drainage of such glacial lakes led to the formation of valleys, the waters of which flowed in one direction until the lakes were drained but now flow the opposite way. We have already seen how Glacial Lake Agassiz and the southern part of the Red River Valley are an example of this change in the direction of flow.

Of the glacial lakes that are now extinct, Lake Agassiz was by far the largest formed on this continent. It occupied the entire Red River Valley region and extended northward to include North and South Red lakes, Lake of the Woods, and Lake Winnipeg (Figure 9). Another of the larger glacial lakes was Lake Minnesota, which

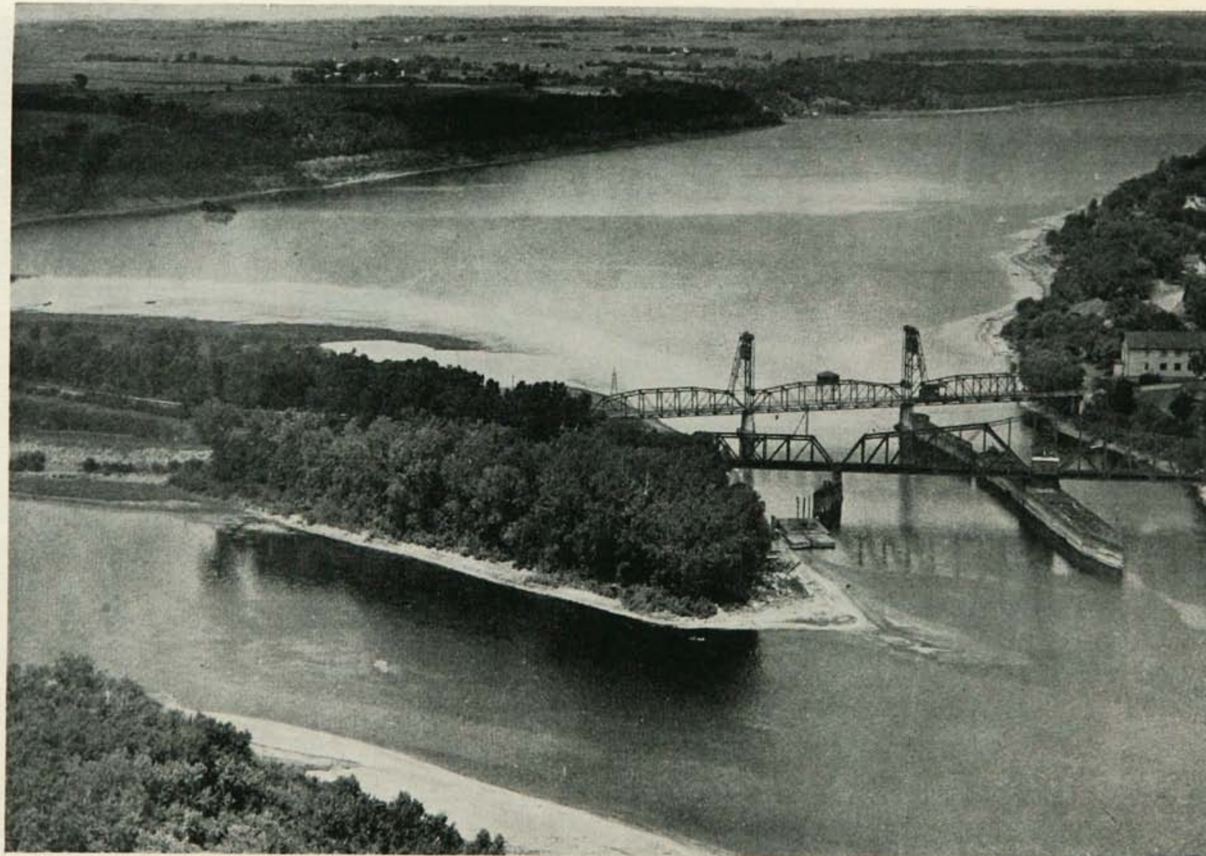


Figure 20. Junction of the St. Croix and Mississippi rivers. Point Douglas, Minnesota, on the left; Prescott, Wisconsin, on the right. Lake St. Croix extends above the junction. (Photograph by Harry Poague.)

once covered most of the area of Brown, Blue Earth, and Watonwan counties and parts of Waseca, Faribault, and Martin counties. This lake drained southward into the Des Moines River, but the area it occupied now drains northward through the Blue Earth River. Glacial Lake Upham covered the great level tract lying to the south of the Mesabi Range and extended southward to beyond Floodwood. Lake Grantsburg occupied a large area from the southeast corner of Benton County northeastward to Pine City and thence southeastward to the vicinity of Grantsburg, Wisconsin. The Lake Superior basin was occupied by a glacial lake whose most important stage is known as Glacial Lake Duluth.

After a lake is formed and is well supplied with water to maintain itself, from rainfall, streams, springs, or other underground sources, many natural processes still work hard to change its appearance. Its area, depth, shore line, vegetation, and many underwater features may all be changed. The action of its own waves is one of these natural evolutionary processes. If an original lake shore is very irregular and marked by several bays, arms, and indentations, a wave-built terrace of sand or pebbles is gradually deposited across the mouths of such irregularities and eventually isolates them from the main body of water. The tendency then is for the lake to become more regular in outline as these underwater terraces develop. This tendency is more pronounced in lakes that lie in sandy material than in those formed in clay or bedrock, but eventually even the latter will be changed in form by the development of underwater bars and terraces.

On Pelican Lake north of Brainerd especially good examples of isolated bays can be found (Figure 21). The small pond on the southeastern shore of the lake was obviously part of the original lake basin but now is completely cut off from the main body of water. The depression behind the bar is nearly filled with vegetation and contains little open water. On the opposite side of the lake the isolation of a bay of similar size has not yet been completed, but the expansion of the underwater terrace across its mouth necessitates the dredging of a channel from the bay to the main body of water in order to facilitate passage by small boats harbored in the bay.

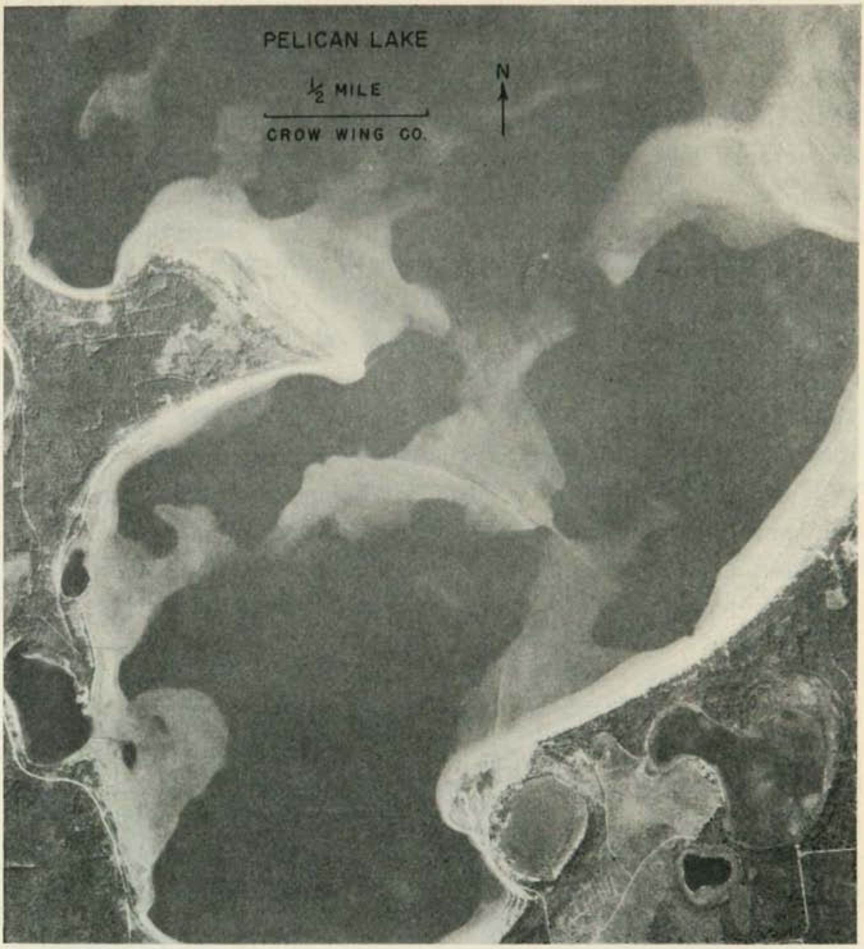


Figure 21. Underwater sand bars (white), Pelican Lake, Crow Wing County. Such deposits tend eventually to form isolated bays. (Photograph U.S. Department of Agriculture.)

The action of ice also modifies the shore zone of a lake. After the first ice cover forms on a lake in late fall, the thickness increases slowly and may reach several feet in extremely cold winters. Water expands when it freezes, but once frozen, the ice reacts to temperature changes like any other solid; that is, it contracts when its temperature is lowered and expands when the temperature is raised.

Lake ice attaches itself to the shore and may even freeze to the bottom of a very shallow area. A rapid fall in air temperature causes the ice on the lake to contract. Since it cannot pull away from the shore area to which it is firmly frozen, it develops tension cracks in the main ice cover. Water rises into these cracks from below and freezes, thus increasing the total mass of the ice cover. A subsequent rise in air temperature will cause the ice to expand again, and the area of the ice will be greater than it was before contraction.

This increase in area of the ice cover results in the ice exerting a "push" against the shore. If the shore material is unconsolidated — loose and yielding, like sand or pebbles — and if the slope of the shore is not exceptionally steep, the ice will push the shore material into an ice rampart, a ridge of debris lying more or less parallel to the shore line (Figure 22). The size of an ice rampart depends on the number of times the temperature has fluctuated enough to produce a new push while the lake remained at the same level.

Figure 22. Ice rampart, Leech Lake, Cass County. Formed of sand and gravel pushed up by ice.

Ice ramparts may develop at the mouth of a shallow bay of a lake and isolate the bay from the main body of water. Such a condition can be seen at the east end of Rose Lake in Otter Tail County. There a small pond called Pug Lake was originally a bay of Rose Lake, but an ice rampart was pushed up across the mouth of the bay and now is so well established that trees and other vegetation grow on its surface.

The accumulation of sediments of all types tends to reduce the volume of a lake basin. These sediments are derived from erosion of the lake shore by waves and also from streams carrying silt and sand into the lake basin. If the supply of sediment is too great to be redistributed by the waves onto the beaches, a delta is formed at the mouth of the incoming stream. Eventually such sediments tend to fill a lake basin to approximately the level of the regional water table, the level below the surface at which the ground is always saturated with ground water. Once that level is reached, the lake is converted into a swamp, which sooner or later develops a thick bed of peat.

Many swamps, bogs, and marshes are successors to lakes and sluggish streams, but this is not the mode of origin of all of them. Wherever there is a wide stretch of relatively flat-lying, poorly drained land and an abundant supply of water, a swamp is very likely to occur. Such conditions are often found on the poorly drained till plains and along the flood plains of major streams. A few relatively small swamps occur on high ground or on hillsides. Swampy areas of this type usually result from an impervious subsoil and the seepage of ground water from still higher ground.

Minnesota is reputed to have a larger area of swamps and marshes than any other state. They cover several thousand square miles in the northern part of the state in Roseau, Marshall, Beltrami, and Koochiching counties, mostly in the poorly drained area once occupied by Lake Agassiz. Much of this area is overgrown by sphagnum moss, low bushes and evergreens, or numerous aquatic plants which in many places are so thickly set and tangled that they are almost impenetrable, and the ground is so wet that it is almost impossible to traverse. Such is the character of much of the

Figure 23. Muskeg swamp, east of Grand Rapids, Itasca County. Typical of peat swamps with black spruce trees.

so-called "muskeg" country north of Red Lake and eastward toward Vermilion Lake. Large areas of muskeg occur also in the southwestern part of St. Louis County from Meadowlands southwestward toward Aitkin and elsewhere (Figure 23). These swamps have their own very particular assemblage of plants and animals and have played an important part in providing a suitable habitat for Minnesota's wild life.

Typical sphagnum moss and muskeg swamps do not occur in the southern part of the state. In that area most of the marshes or bogs contain sedges and grasses that grew up around the shallow portions of lakes which became partially filled by the deposition of sediments carried into the basin or by the accumulation of peat derived from decaying vegetation (Figure 24). Such swamps commonly encroach on the shallow lakes and eventually convert the whole area into swampland. At some lakes the mat of vegetation surrounding the open water develops so fast that it may be floating on eight or ten feet of water for a number of yards out from the completely filled-in shore area (Figure 25). One must be cautious when walking over such boggy areas, for if the layer of peaty sod over the water is not sufficiently thick to support one's weight, there is danger of breaking through into the water below.

In central Minnesota there are many swamps with open grassy marshes or even clear lakes or ponds at their centers. In fact, every degree of growth can be seen, from small, open lakes or ponds to those completely overgrown by vegetation. A heavy growth of spruce or tamarack trees characterizes the outer margins of such encroaching swamps. Thousands of what were once shallow lakes in Minnesota have become swamps in this way, and many others have been drained artificially and are now productive meadows.

Along with rivers, lakes, and swamps, springs are an important part of Minnesota's water systems. The bluffs of the St. Croix, Min-

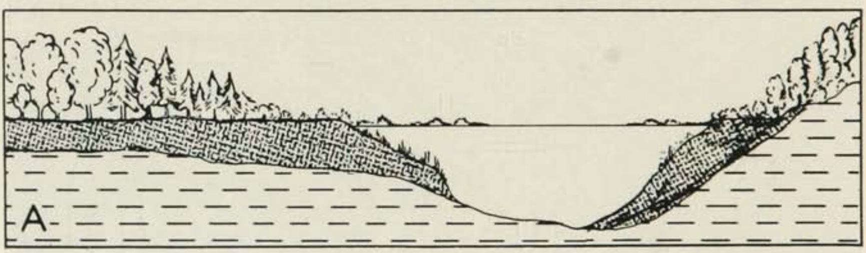


Figure 24. Diagrams showing the successive stages in the filling of a lake basin by peat.

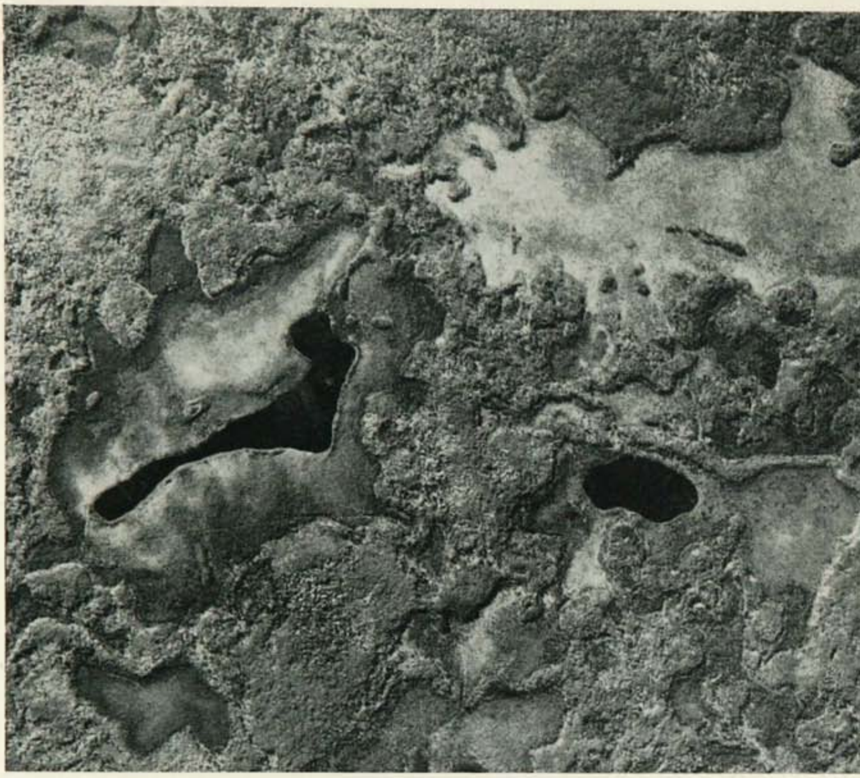


Figure 25. Bog succession zones, spruce and muskeg encroaching on open water, Aitkin County. (Photograph U.S. Department of Agriculture.)

nesota, and Mississippi rivers and their many tributaries afford almost perfect conditions for the occurrence of springs. A spring is formed wherever underground water flows to the surface through natural openings (Figure 26). The rate and manner of flow are regulated by the geological structure of the mantle rock — the fragmentary surface rock — and of the underlying rock formations. When rain water falls on the land, most of it percolates downward and seeps slowly through the rocks. It always flows along planes or channels of least resistance, and in time some of it wears well-defined courses. If porous sand or sandstone rests upon tight, impervious clay or shale, the outlet of the percolating waters will be where the lowest point of contact between the two comes to the surface of the

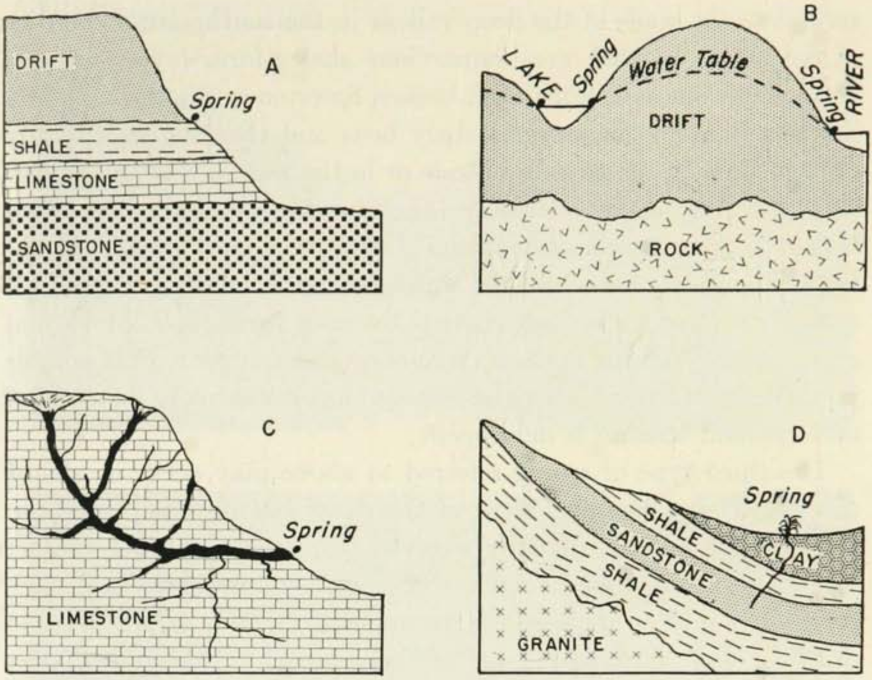


Figure 26. Diagrams showing some structures favorable for the formation of springs.

ground. This lowest point of contact is usually on a hillside or in a valley wall.

In general, springs may be classified as follows:

Springs in unconsolidated material
- Impervious layers emerging at low points
- Emergence of water table at low points

Springs in solid rocks
- Porous rocks underlain by impervious beds
- Porous rocks outcropping near stream or lake levels

Springs at contact of unconsolidated material with solid rock

Springs of the first type are very common around the basins of the lakes in the "knob and kettle" topography of the terminal moraine zones. This is especially true in the sandy moraines, where there is rather free underground percolation toward the low points in the topography. The second type is represented by scores of springs in the walls of the deep valleys in the southeastern counties of the state. In that area impervious shales form layers or beds between porous sandstones and broken limestones. Water percolates downward to the impervious shaly beds and then moves laterally until it finds an outlet on a hillside or in the wall of a gorgelike valley. A number of very large springs issue from underground channels in the limestone in the regions of Preston, Lanesboro, and Rushford (Figure 27). Much of the water issuing from these channels is actually surface water that entered the rock through sinkholes and other cavities at the surface. Since limestone is somewhat soluble in water, such channels may be enlarged until eventually a system of underground streams is developed.

The third type of spring referred to above may occur in almost any county in the state. Most of the state was glaciated, and consequently there are virtually everywhere sharp planes of contact where unconsolidated glacial material lies over solid rock. A high percentage of the springs along the gorge of the Mississippi River in St. Paul and Minneapolis are of this type. The water percolates downward through the glacial drift onto the top of a type of sedimentary rock called Platteville limestone, which lies in nearly horizontal layers, thus causing the water to flow laterally until it issues at the gorge. This underground seepage continues during the winter months, and as the water reaches the surface of the valley wall it freezes to form large columns of ice. During the cold season these columns are very characteristic of the Mississippi bluffs at many places between St. Anthony Falls and Hastings.

Another region famous for springs lies along the foothills of the Coteau des Prairies. Much of the rain that falls on the high quartzite plateau soaks into the earth until it reaches the bedrock surface, which slopes gently toward the northeast. The water seeps down the bedrock slope and reappears in hundreds of springs along a zone five to ten miles wide in Cottonwood, Redwood, Lyon, and Lincoln counties. This spring water feeds the tributaries of the Yellow Medicine, Redwood, and Cottonwood rivers.

We have seen now how springs, swamps, lakes, rivers, glacial moraines and plains, and ridges and plateaus of ancient rock all fit

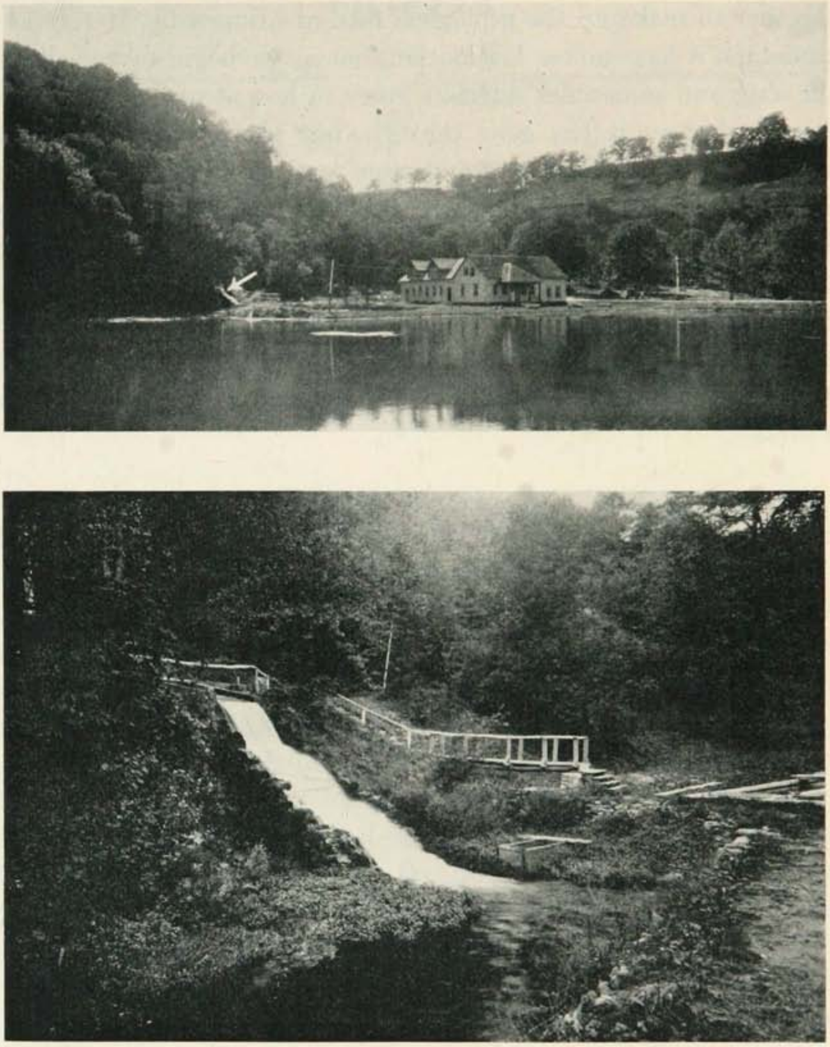


Figure 27. A large spring, Lanesboro, Fillmore County. ABOVE: spring pool in valley ponded by a low dam and used by State Fish Hatchery. Arrow indicates position of spring. BELOW: spring discharging from valley wall. (Photographs by Yorklane Studio, Lanesboro, Minnesota.)

together to make up the geological face of Minnesota. Merely as a landscape it has endless fascination, but as we begin to understand the long and sometimes intricate story of how it came to be, what drastic changes it has gone through, our pleasure in the natural scene becomes much deeper and more lasting. As yet we have, literally, hardly scratched the surface of Minnesota's geological story. What *are* these rocks and soils we depend on for our life? What are they made of? Why are there so many different kinds? Where did they come from and how long ago? And what goes on in the depths of the earth beneath us to produce this familiar surface we see? In the chapters to come we will delve into some of these underground secrets.

CHAPTER

3

Minerals and Rocks

THE earth on which we live is essentially a huge, bulging ball of rock. This rock and everything else on the earth, and in the entire universe, is made up of 92 different elements, though there are a few more that are man-made. Rocks, water, soil, air, plants, and animals — all are composed of different combinations of these natural building blocks. Most of the earth is made up not of pure elements but of chemical compounds of two or more different kinds of elements. The many inorganic chemical compounds — those that are not derived from any plant or animal substance — are called minerals, and the minerals in turn make up the different kinds of rocks. Thus from inconceivably small atoms of the chemical elements, all the vast, rocky substance of the earth is built.

Geologists often use the term "earth's crust" when speaking of the outer few miles of the earth's surface about which we know something by direct observation. It is a very thin crust indeed compared to the earth's average diameter of nearly 8000 miles, and man's immediate experience of that crust is limited to a little over 4 miles, for there are no canyons, wells, mines, or explored sea bottoms deeper than that. Nevertheless there are many kinds of evidence from which geologists can deduce what lies deeper below the surface.

It is quite generally agreed that the composition of the earth's rock changes with depth and that the earth has a dense central core about 4000 miles in diameter that is composed largely of metallic iron alloyed with a small amount of nickel. The metallic meteorites that have fallen to the earth from interplanetary space are made up of somewhat similar material, a fact that reminds us that the earth has many relatives in the universe. The outer part of the globe is much more complex than this dense iron core and consists largely of elements lighter in weight than iron. The three most abundant elements in the earth's crust are oxygen, silicon, and aluminum. We therefore find that rocks that occur near the earth's surface contain a high proportion of these elements, which along with smaller quantities of iron, calcium, sodium, potassium, and magnesium make up more than 98 per cent, by weight, of all the surface minerals and rocks. All the other 84 natural elements form less than 2 per cent of the total crust.

Minerals

Of these eight most abundant elements, only iron is found in the earth in a pure, uncombined form, and even this occurrence is rare. All the others are combined in one way or another into chemical compounds, and most of these chemical compounds are minerals. A mineral is usually defined as a naturally occurring inorganic substance of more or less definite chemical composition. Gold and silver that occur free in nature are minerals; so are table salt and asbestos. A more modern definition might state that a mineral is a natural inorganic substance usually occurring in a crystalline state; that is, the atoms are arranged in a regular form. However, this definition would rule out water and mercury, which are liquid and noncrystalline at ordinary temperatures but are nevertheless considered to be minerals. On the other hand, there are natural glasses, like obsidian, which are not called minerals even though under proper conditions they may crystallize to form one or more minerals. Thus we see that minerals, though they surround us on all sides, are nonetheless difficult to define.

According to most definitions, however, minerals are either pure elements or chemical compounds. Native copper is a naturally occurring element and is a mineral. So are diamonds and graphite, both being crystalline forms of the single element, carbon. Minerals may also be simple compounds of two elements, such as pyrite, which consists of iron and sulphur, or halite (common salt), which is a compound with a ratio of one atom of sodium to one of chlorine (Figures 28 and 29). Many minerals are compounds of several elements and may have an exceedingly complicated chemical structure. But regardless of how many elements a mineral contains, it is always a homogeneous chemical material, unlike the rocks, which are heterogeneous physical aggregates of one or more minerals.

These minerals are so important that our whole civilization depends on them. They are the raw materials from which are obtained practically all the metals, acids, salts, and other chemicals except the organic chemicals; all glass, porcelain, pottery, and bricks; and many pigments, writing materials, fertilizers, mineral fuels, and gems. Few industries could exist without them, and they are certainly one of the world's greatest sources of wealth. In Minnesota the great iron mines on the Mesabi Range and the scores of quarries and gravel pits give profit and employment to thousands of people. New uses are constantly being found for minerals once thought to be worthless, and there is no known limit to the possibilities for their future development.

But there are other reasons for studying the fascinating world of minerals. An understanding of this world gives us the answers to innumerable questions that otherwise are veiled in mystery. If we understand the properties of minerals, we know why flint arrowheads have sharp edges, why some types of clay are so sticky, why a diamond shows such brilliant rainbow colors, why ice floats on water. When we stop at that roadside quarry we formerly regarded as just a hole in the ground, we will find that the rocks in the quarry are composed of grains and crystals of a number of minerals, some of which we can easily identify. When we go to the beach of one of our thousands of lakes, we may really look at the sands for the very first time. We notice that the sand grains are not all colorless or white. Some are pink or red and others are yellow, green, or black. We will realize that the sand is composed of small pieces of many different kinds of minerals, tiny grains that may have been formed eons ago from molten lava, fused and weathered and carried about by centuries of ice and wind and water until they have washed up on our particular beach.

We learn to identify minerals by means of their physical and chemical properties. Their chemical composition is not easy to determine and requires special equipment, but for everyday determination in the field, the physical properties of color, luster, hardness, specific gravity, crystal form, and cleavage or fracture are usually sufficient. There are also many other physical properties that are not so easily determined but are useful in precise work — for example, the index of refraction of light passing through the minerals.

Minerals vary widely in color, from the black of magnetite crystals, to the red of hematite, the yellow of limonite, and the familiar colors of turquoise, copper, gold, and garnet. Sometimes the identical mineral will appear in several different colors, depending on how large or small a sample we look at, or on the presence of minute amounts of impurities. Thus diamonds come in several different colors, and in quartz the range of color and translucency is almost endless. For these minerals color is too arbitrary to be a satisfactory identifying property. Some minerals are always one color, however; for example, graphite, the "lead" in our writing pencils (really a soft, lustrous form of carbon) is always black.

The luster of minerals also varies greatly. This quality, too, may depend on the size of the mineral sample, but certain minerals have very characteristic lusters. Thus the pyrites are said to have a metallic luster, quartz is glassy or vitreous or may have a greasy luster, talc is pearly, and so on with many other descriptive terms. The hardness of minerals is another identifying property, tested by scratching one mineral with another of known hardness or with a steel knife blade. Mineral hardness varies all the way from talc, so soft it is used in babies' talcum powder, to diamond, the hardest known naturally occurring substance.

Minerals and all other crystalline substances crystallize in one of six systems or patterns (Figures 28, 29, and 30). Some of these systems are simple, forming cubes or prisms; others are quite complex.

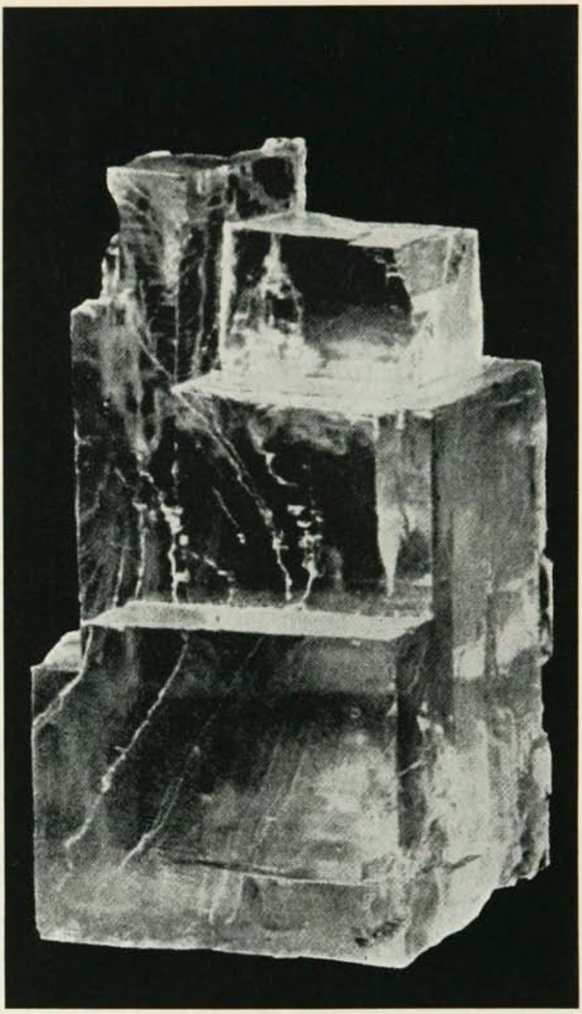


Figure 28. A crystal of halite (common salt) showing cubic cleavage. (Courtesy of Ward's Natural Science Establishment.)

Some minerals occur fairly commonly as "good" crystals, meaning with precise external forms. An example is pyrite, which frequently occurs as perfect cubes. Most minerals, however, do not exhibit good external crystal form, but the grains nevertheless have just as good and unvarying an internal arrangement of the atoms as does a perfect crystal. Such a substance is said to be crystalline.

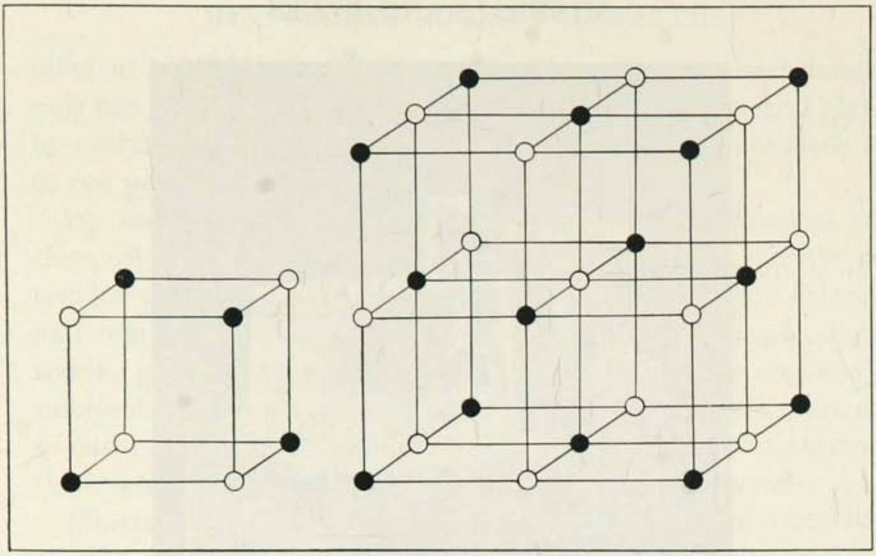


Figure 29. Diagram showing the arrangement of sodium and chlorine ions in a single unit and eight units of the lattice of sodium chloride (common salt).

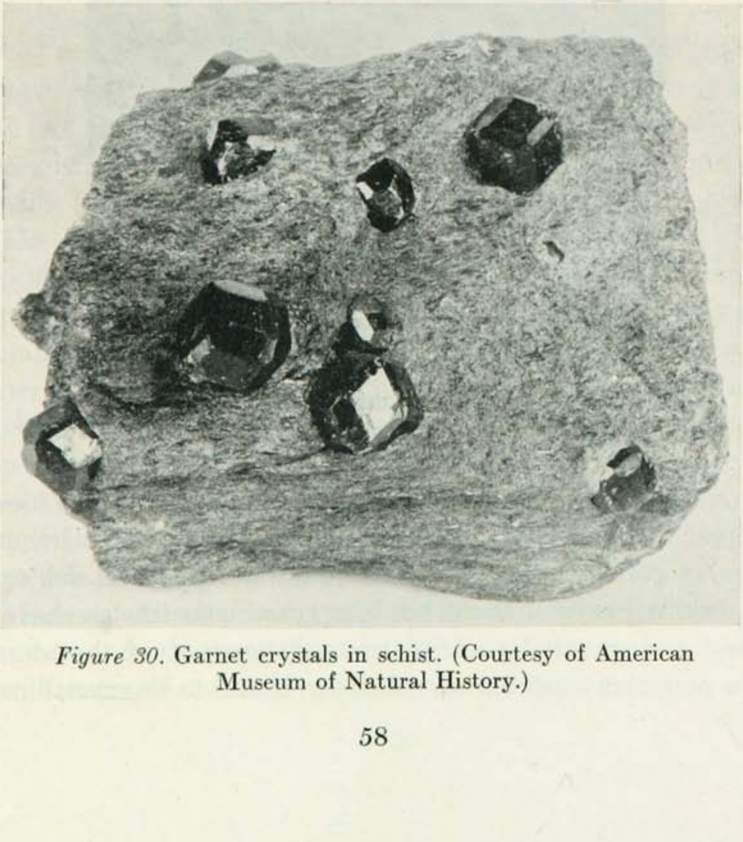


Figure 30. Garnet crystals in schist. (Courtesy of American Museum of Natural History.)

Mineral crystals occur in a wide range of sizes, from the microscopic crystals of quartz, feldspar, and many other minerals in dense lava flows, to crystals of calcite and quartz that are fairly commonly an inch or more in length, and less commonly to crystals of rarer minerals which may be measured in feet. In the Black Hills of South Dakota probably the largest crystal on record occurred in a lithium mine. Its length was 42 feet and its weight 37 tons. When crystals form from molten material their size is roughly proportional to the speed of cooling. The quick-cooling material that poured out at the earth's surface usually produced small crystals, and the slower cooling material deep in the earth produced larger crystals or grains.

Closely allied to a mineral's crystal form is the property known as mineral cleavage. This is defined as a tendency to split or break along a plane which is always parallel to a possible crystal face (Figure 28). Some minerals have one perfect cleavage; for example, mica always splits along one parallel plane. Other minerals have two, three, four, or, rarely, six or more cleavages. These may vary in the degree of perfection of the parting. Minerals that lack cleavage usually break with a characteristic fracture surface, which may be described as conchoidal (curved like a clamshell), hackly (with short, sharp points), or fibrous.

The specific gravity of a mineral, or of any substance, is the relative weight of the substance compared to the weight of an equal volume of pure water. One cubic centimeter of pure water under standard conditions weighs one gram. By comparison 1 cubic centimeter of quartz weighs 2.65 grams, pyrite 4.95 grams, galena 7.4 grams, and pure gold 17 grams. The specific gravity of a mineral is determined by the weight of the atoms of which it is composed and by the spacing of the atoms in the crystals. The atoms of such metals as uranium and lead are very heavy. Other things being equal, the compounds of these metals would also be heavy; however, if the atoms are widely separated in the compound, the compound itself may be light even though composed of heavy atoms. Likewise if the atoms in a crystal are light but densely crowded, the resulting mineral will be heavy. This is well illustrated by corundum, a comparatively heavy mineral, which is composed of two light atoms, aluminum and oxygen. Its atoms are so closely spaced that the mineral is heavy and exceedingly hard.

Among Minnesota's minerals native elements are comparatively rare, although native copper has been found in the glacial drift at many places. Some of the most important minerals, in Minnesota and elsewhere, are simple oxides, that is, simple compounds of oxygen and one other element. Quartz, which is composed of silicon and oxygen, is the most abundant mineral with which we come in contact in everyday life. Its crystalline nature is usually easy to recognize, and it is so hard it cannot be scratched by a steel knife blade. Quartz is a common constituent of many varieties of rocks, such as granite and iron formations, and is the principal mineral in sand, sandstone, and quartzite. It often occurs as veins in other rocks, sometimes in massive form — which means its crystal faces are not apparent — and sometimes as good crystals along the walls of rock fractures. It comes in many varieties, including milky, smoky, rose, amythystine, and chalcedonic quartz. Jasper, flint, chert, and agate are still other varieties of quartz, distinguished by their grain or color or both.

Quartz occurs in many forms throughout Minnesota, but a few occurrences are of special interest. Of the many varieties, agate is particularly common in the hardened lava flows and on the beaches of Lake Superior, as well as in gravels of the glacial drift throughout the state. Agate collecting is an absorbing hobby for many amateur geologists, and the striped and colored patterns revealed when the agate is cut and polished make handsome native gems. Jasper, an opaque, compact, noncrystalline variety of quartz, is conspicuous in the Soudan iron formation of the Vermilion district. The white sandstones of southeastern Minnesota are another example, for they are composed almost entirely of rounded grains of quartz.

The other common oxide minerals are oxides of iron. They are particularly important in Minnesota because they make up the bulk of the iron ores. Magnetite, which is a combination of ferrous and ferric oxide, is unique among minerals in being strongly magnetic. It is often present in many igneous rocks, which are formed from cooled lava, and some metamorphic rocks, the rocks that have been altered from their original structure by great pressure or heat. Magnetite is a hard, black, heavy mineral and is easily identified by a test for magnetism with a magnet or a compass.

In Minnesota, magnetite is one of the chief iron minerals in the low-grade taconite ore of the Mesabi district. It occurs in lesser amounts in the iron-bearing rocks of the Vermilion and Cuyuna districts. Rock areas high in magnetite are also abundant in the Duluth Gabbro (a large mass of granular igneous rock), particularly in Cook County. Magnetite is an accessory constituent of the lava flows and rock sills and dikes of the North Shore of Lake Superior and elsewhere in the state. The black sands of some of Superior's beaches also contain much magnetite. Some magnetite contains ilmenite, an oxide of iron and titanium, intergrown along the octahedral planes and is called titaniferous magnetite (Figure 31).

The presence of magnetite in rocks results in variations in the direction and intensity of the magnetic field of force at the earth's surface. This variation is an aid in locating iron-bearing formations, but it should be understood that many rocks that contain magnetite have too little iron to be of commercial interest. A considerable amount of magnetite in rocks renders an ordinary compass unreliable — a good thing for campers and woodsmen to remember in regions like northeastern Minnesota where magnetite is known to be abundant.

Hematite, which is simple ferric oxide, is a common constituent of weathered rocks and soils. It is the most important mineral of iron ore, although not necessarily present in all iron ores. It occurs in a variety of forms, called specularite or specular iron, micaceous, fibrous, oölitic, and earthy hematite. The soft, earthy variety is known also as red ocher and is used as a pigment in paints. The hard, crystalline varieties of hematite often appear almost black, but the powdered mineral reveals the true red color. Most of the hard iron ore of the Vermilion district consists of hematite. It is abundant also in the ore of the Mesabi and Cuyuna districts, though by no means constituting all of that ore. It occurs, too, as a cement or coloring matter in the red sandstone at Fond du Lac and along the North Shore of Lake Superior. Most red rocks and soils, in fact,

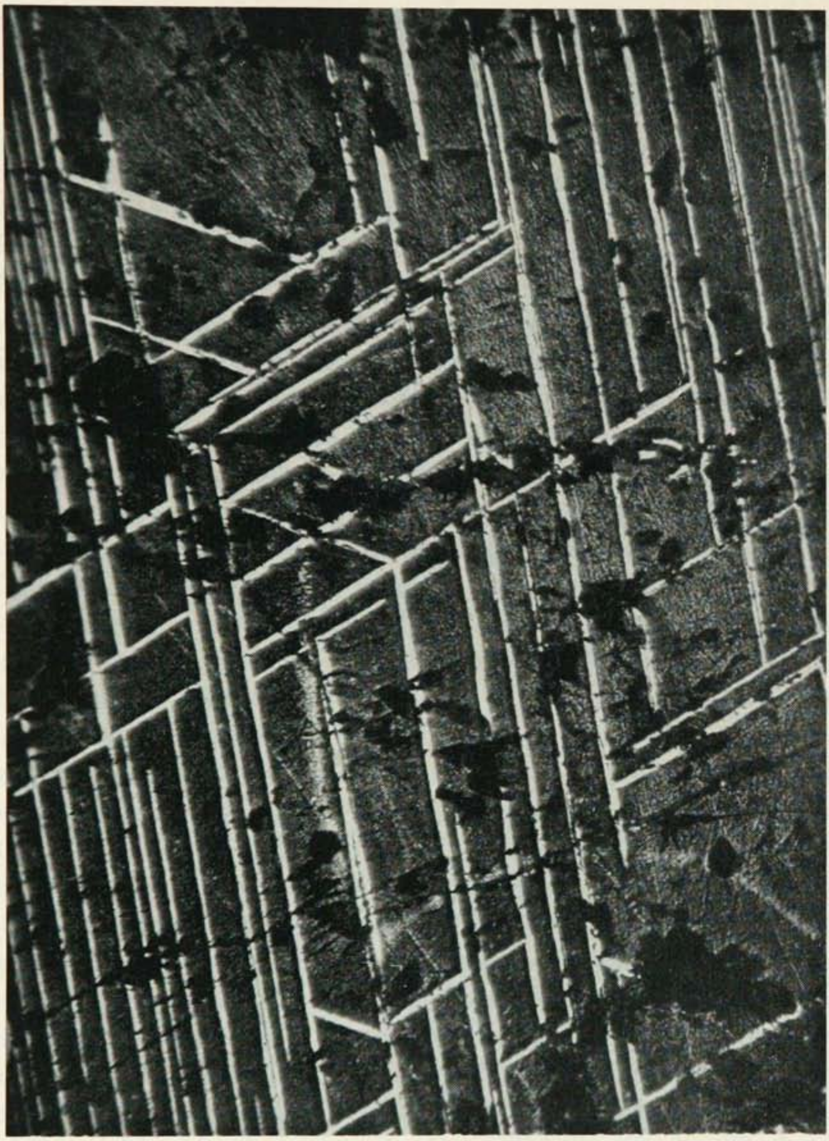


Figure 31. Microphotograph of a polished surface of titaniferous magnetite. The oriented blades are ilmenite (white) and the black is magnetite. Cook County, Minnesota. Magnification 160×.

owe their color to minute amounts of very finely distributed hematite.

Limonite consists of hydrous ferric oxide, the same oxide that hematite contains but with one or more molecules of water attached to each molecule of the oxide. Limonite has been the common name for this substance, but in modern mineralogy the name "goethite" is used for the definitely crystalline form of the mineral, the

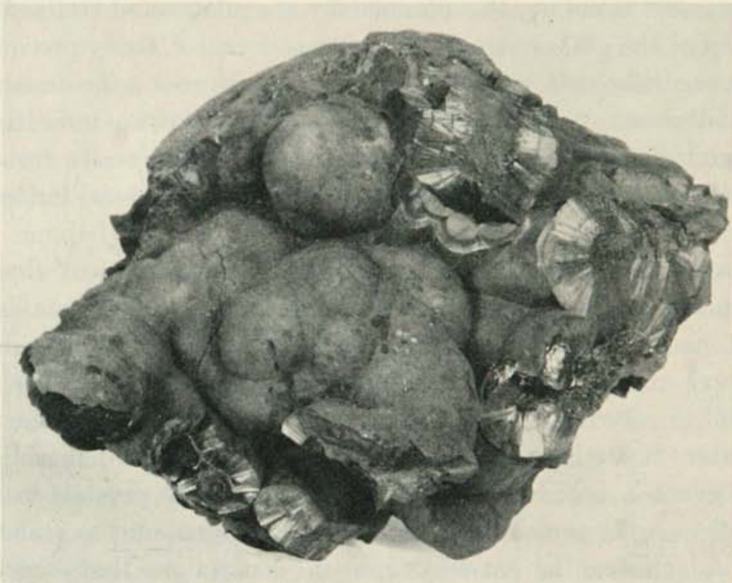


Figure 32. Crystals of goethite (hydrated iron oxide) showing botryoidal structure. (Courtesy of American Museum of Natural History.)

term "limonite" being reserved for the earthy variety, which has a somewhat indefinite structure (Figure 32). When limonite is very soft and powdery, it is called yellow ocher and, like red ocher, is used as a pigment in paint. The ordinary powdery orange iron rust we see so often is essentially the same material. Limonite is an abundant mineral in iron ores and occurs as a constituent of many weathered rocks, soils, and sands, to which it imparts its characteristic yellow or brown color.

Limonite occurs in Minnesota in all these different forms. It is very abundant in the ores of the Mesabi and Cuyuna iron districts, much more so than many people realize. It is frequently found as so-called "bog iron ore" in swamps or where springs and seeps issue from the ground. This kind of iron oxide frequently precipitates in well water after it is pumped to the surface and exposed to the air. When first formed, this precipitate often looks like an oily film, which misleads many into suspecting the presence of oil; but if the water is left standing, this film usually coagulates and settles to the bottom of the pail or jar, where it forms a yellow, fluffy precipitate. Since iron in some form is present in nearly all rocks, the occurrence of small amounts of iron in ground water is not an indication of commercial iron ore. An unpleasant taste often results from the presence of iron in drinking water, but it is not harmful for human use.

Among the common minerals formed of *three* different elements we find the carbonates, which are combinations of a metallic element, carbon, and oxygen. Calcite (calcium carbonate) is one of the most abundant minerals found on the earth's surface. The presence of dissolved calcium carbonate is the major cause of hardness in water. It is the chief constituent of limestone and marble and also occurs in a wide variety of other forms — as crystals in veins of rocks, as the cementing material in sandstone, and as stalactites and stalagmites, the icicle-like mineral concretions that sometimes form in caves. Sometimes calcite is deposited by springs or rivers as travertine, a rock that often has beautiful bands and colors, produced by impurities, and is used in decorative building. Chalk, too, is a form of calcite, laid down long ago under prehistoric oceans and composed chiefly of the calcium carbonate from the shells of minute sea creatures.

In Minnesota, calcite makes up much of the limestone of the southeastern part of the state. It also forms large deposits of marl, a crumbly mixture of calcite and clay used as fertilizer, beneath many of the state's lakes and swamps. As a vein mineral, calcite is particularly common in the lava flows along the North Shore of Lake Superior and also along fractures and other openings in sedimentary rocks. Most of the calcite we ordinarily see is a fine-grained aggregate, or unstructured mass, but good crystals ranging up to a foot in length occur in favorable locations. Smaller crystals are far more common, however. Calcite often resembles quartz but, unlike it, is relatively soft so that it can easily be scratched with a knife. Its softness and the fact that it effervesces freely when placed in a dilute weak acid, like vinegar, are its most characteristic properties.

Dolomite is a carbonate mineral that very closely resembles calcite except that it has about equal parts of calcium and magnesium. Dolomite is a common constituent of limestones, which vary from practically pure calcite to pure dolomite. In the latter case the rock itself, although it looks much like limestone, is called dolomite— a rather confusing bit of terminology. Slightly weathered dolomite is commonly buff colored, because of the presence of small amounts of iron carbonate which has been oxidized (combined with oxygen from the air or water) to form yellow iron oxides. The usual test to distinguish dolomite from calcite is to try its effervescence in a dilute, cold acid. If it does not effervesce when cold, but does when warmed gently, the mineral is probably dolomite. The presence of magnesium is often of practical importance in the utilization of rocks. For example, limestone containing more than 5 per cent dolomite cannot be used in making Portland cement because the magnesium interferes with the cement's setting properties.

Another carbonate of importance is siderite, or iron carbonate. This mineral varies from light grayish-yellow to brown in surface color, but its "streak" is always white. By "streak" we mean the color of a mineral's powder, revealed when the substance is scratched or crushed. The color of a mineral's streak is usually more constant and a truer clue to its identity than is its color in the mass. Siderite is by no means as common or abundant as calcite and dolomite, but it is of considerable importance in the iron formations of the iron ranges. There it occurs as a fine-grained mineral in the so-called carbonate slates. Weathering may cause the iron carbonate of siderite to be altered chemically to form limonite.

A mineral made up of only two elements, iron and sulphur, is pyrite, a very widely distributed mineral but usually not abundant at the surface because it is easily destroyed by weathering, especially in a warm, moist climate. Pyrite has a brassy yellow color that is much lighter than gold or chalcopyrite (copper pyrite), which is the reason for its nickname, "fool's gold." Its streak, however, is greenish-black. It often crystallizes as cubes, but it also occurs as granular masses and, less commonly, as fibrous, kidney-shaped, and globular aggregates. Because of its yellow color it is often mistaken for gold, but unlike gold, which is soft and malleable, pyrite is harder than steel. Its most abundant occurrence in Minnesota is near the Cuyuna Range, where drilling has shown that a body of slate has been partly replaced, through complicated chemical alterations, by pyrite and closely related minerals. Pyrite occurs in small amounts in many other rocks as well, particularly in the limestones of southeastern Minnesota.

A less abundant Minnesota mineral is gypsum, a colorless to white mineral composed of hydrous calcium sulphate. It occurs in some places in the state as crystals in shales or clays of the Cretaceous geological period, a fairly recent time, geologically speaking, when reptiles of all kinds ruled Minnesota. A massive form of gypsum, of delicate color and texture, is known as alabaster, but its most familiar everyday use is in plaster of Paris, a fine, white powder made by heating gypsum to expel its water.

In this brief introduction to Minnesota's common minerals, we have left to the last the most complex, most numerous, and most abundant group of all — the silicates. The two unvarying constituents in all the many silicate minerals are oxygen and silicon, those two ubiquitous elements that together make up about three quarters of the earth's crust. They form a very widespread compound, silicon oxide, which we met earlier in the form of quartz. Most of the silicates are combinations of silicon oxide with one or two or often more of the six next-most-common elements — aluminum, iron, calcium, sodium, potassium, and magnesium. These elements may be combined in many slightly different ways, but the silicon oxide is always there to maintain some family resemblance among all the relatives. These silicate minerals are so complex that it is difficult to describe them briefly, but they are so important in rocks that some understanding of them is practically essential.

First of all, we can divide the silicates into two groups, depending on whether or not water is combined with the silicate. The anhydrous group (without water) is much the largest, so we will start with it. In this group of silicates the feldspar family is outstanding. We already know that silicates constitute most of the earth's crust, but the feldspars alone are estimated to make up about 60 per cent. The members of this family are orthoclase, microcline, albite, and anorthite. The last two often unite to form still another variety. We may not remember these names too easily, but the feldspars will crop up again and again as constituents of Minnesota's rocks.

Feldspars are generally light in color, varying from white to gray to red, and they are somewhat harder than a knife blade. They are mostly combinations of the oxides of aluminum, calcium, sodium, and potassium with silicon oxide, with practically no iron or magnesium. Feldspar occurs almost everywhere in Minnesota as a rock constituent, either in gravels in the glacial drift or as the most abundant mineral in granite and similar rocks. Along the North Shore of Lake Superior there are huge masses of nearly pure feldspar in the anorthosite rocks — a type of rock we will hear more of later, formed deep in the earth by the cooling of molten rock material or magma (Figure 98).

Three other complex groups of silicates are moderately abundant in many rocks: the mica, amphibole, and pyroxene groups. They consist of a chemical complex of calcium, magnesium, iron, and potassium, with silicon oxide, of course, and in some members other elements. The micas are best known because of their perfect cleavage. Nearly everyone at some time or other has played with a chunk of mica, splitting it with the greatest of ease into transparent, gleaming, paper-thin layers. Of the two main varieties, one is colorless and the other brown or black. The color difference illustrates the interesting fact that the silicates that lack iron are often colorless, whereas those containing iron are green, brown, or black. Mica is often a constituent of granite and also occurs in loose sand, where the colorless variety attracts attention because of its silvery sheen. Biotite, another of the mica group, frequently tarnishes to a beautiful golden color and may be mistaken for gold.

The most common varieties of the amphiboles and pyroxenes are iron-bearing, and unlike the feldspars, their colors are therefore dark, from green to black. Although these silicates also have cleavage, it is much less perfect than that of mica and occurs along two planes rather than one. Hornblende, the principal member of the amphibole group, is a common constituent of the granites and allied types of rocks. Augite is the most common member of the pyroxene group. It is an important mineral in the lava flows of basalt and the dark-colored intrusive rocks that occur abundantly in northeastern Minnesota, and in the gravels of the state. We will learn something about these basalts and other rocks and how they were formed in just a few pages.

The garnet group is another interesting example of complex silicate minerals (Figure 30). Garnets have a strong crystallizing power and frequently form good crystals of the cubic system. Garnet is not abundant in Minnesota but occurs in the rocks exposed in the Mississippi Valley near Little Falls and at various scattered places in northern Minnesota and along the Minnesota River Valley. Another mineral that forms good crystals is staurolite, a complex silicate that often forms crossed twin crystals (Figure 33).

Some silicates contain water crystallized with the other materials —the hydrous silicates that make up the second of our two general silicate groups. The most important of these is kaolinite, the principal constituent of clay. Another hydrous silicate is chlorite, a very soft, dark green mineral that is the principal constituent of the ancient greenstones of northern Minnesota, which some geologists think to be the oldest rocks exposed on the earth's surface. Glauconite, essentially a hydrous silicate of iron and potassium, is a common green mineral that occurs abundantly in some Minnesota sandstones.

We have had a quick survey of some of the most important minerals, both in Minnesota and in the total make-up of the earth's crust. We have seen that they are composed almost entirely of a few very abundant elements, and that they are formed naturally on

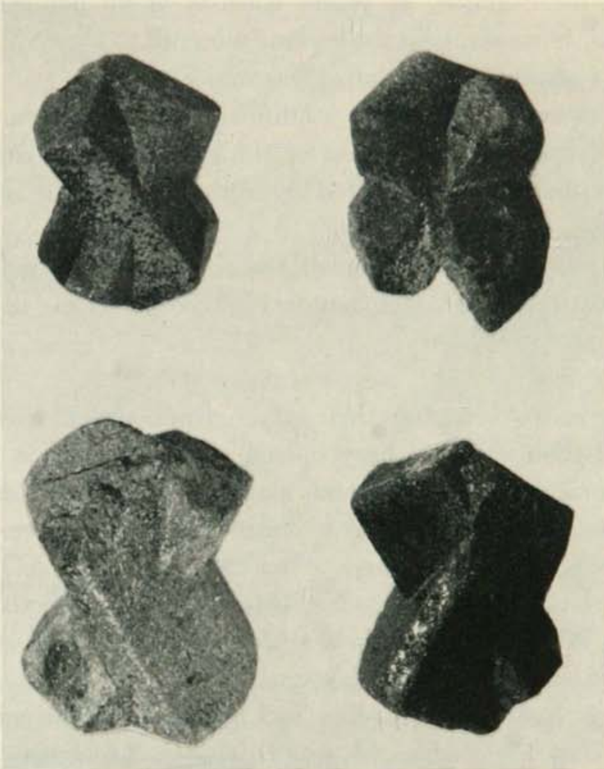


Figure 33. Photograph of twin crystals of staurolite. (Courtesy of Ward's Natural Science Establishment.)

or below the surface by various simple and complicated chemical reactions. They are formed, usually in a crystalline state, as integral parts of different kinds of rock. We will go on now to talk a bit about these rocks — old and young rocks, deeply formed or surface-built, hard or soft, coarse- or fine-grained, crystalline and fragmental — all the many rocks that make up Minnesota.

Rocks

A rock is defined broadly as any material that forms an essential part of the earth's crust. Most rocks can be defined somewhat more definitely as aggregates of one or more minerals or organic remains. Some rocks consist almost entirely of one mineral; the St. Peter sandstone, for example, at places consists of 99 per cent quartz. Most rocks, however, contain several minerals.

All rocks are subdivided into three major groups:

1. *Igneous rocks,* formed by solidification of molten material.

2. *Sedimentary rocks,* formed at the surface of the earth by deposition of material transported by water, wind, and ice, and by organisms.

3. *Metamorphic rocks,* formed from pre-existing rocks by the action of heat, pressure, and chemical solutions at some depth in the earth's crust.

IGNEOUS ROCKS

Igneous rocks acquired their name from the Latin word for "fire," and their origin is fiery indeed. All rocks of this type were formed from superheated liquid masses of material deep in the earth, called "magma" when it remains below the surface, or "lava" when it spills out aboveground. When the earth was younger, much of its interior was superheated in this way and subjected to great pressures. When this magma was forced to the surface through cracks or fissures in the earth's crust, it poured out in great lava flows which cooled into igneous rock. Sometimes the magma was trapped below the surface by pre-existing rocks above, and there it also cooled, though more slowly, to form another type of igneous rock. Even today the center of the earth is many thousand degrees hotter than the surface and compressed by the weight of surface rock. As its heat is conducted outward it may be great enough to melt large quantities of rock. When these molten masses find an outlet to the surface we have a volcanic eruption or a flow of lava. Lava flows are probably much less common on the earth today than in the distant past, and there are doubtless many other masses of magma within the earth that did not reach the surface and that we therefore know little about.

The igneous rocks formed by the cooling of molten material are divided into two broad groups. Extrusive igneous rocks are formed from lava that pours out of fissures on the surface of the earth or is blown out of volcanoes. Intrusive igneous rocks are formed below the surface from magma that has been forced — or intruded, as the

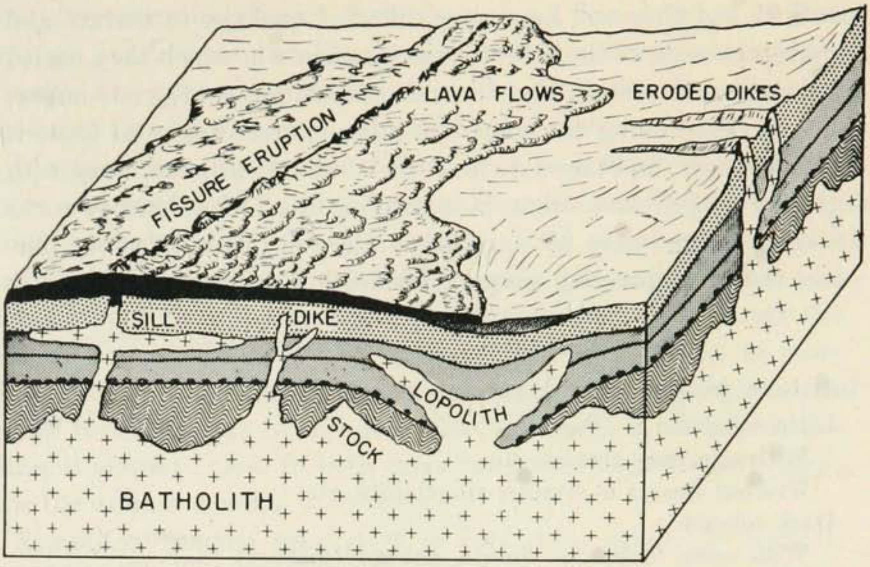


Figure 34. Diagram showing the structural relations of igneous rock masses.

name "intrusive" reminds us — into older, pre-existing rocks of the earth's crust. These intrusions of magma below the surface occur in several characteristic patterns (Figure 34).

When a great mass of magma moves upward, lifting or engulfing the older rocks above it, we call that mass a batholith. Such batholiths often form the cores of mountain ranges. Smaller intrusions of magma are called sills and dikes. A sill is a thin sheet of magma that has penetrated between beds of previously formed rock and lies parallel to them. A dike is formed when the magma cuts upward through the rock beds either vertically or at an angle, forming a narrow wall through the other rocks. Sometimes dikes extend for many miles, often projecting above the earth's surface where erosion has worn away the beds of intruded rock and left the harder rock of the dike still standing.

In general, extrusive rocks are fine-grained, with very small, frequently microscopic, crystals, while intrusive rocks are granular and coarse-grained, with large, easily visible crystals. The mineral composition of an intrusive and an extrusive rock may be almost identical, but they will have very different qualities of texture and hardness because of the different environments in which they cooled from magma into rock. The mineral composition is of prime importance in determining the color and other characteristics of igneous rocks, however, and therefore must be taken into account along with intrusive or extrusive origin in classifying the rocks. Igneous rocks are complex and may be classified in many ways, but for our purposes the accompanying simple classification suffices.

Simple Classification of Igneous Rocks

Intrusive (coarse-grained; crystals recognizable):
- Light colored:
  - With quartz — granite, etc.
  - Without quartz — syenite, anorthosite, etc.
- Dark colored:
  - With some feldspar — diorite, gabbro (diabase)
  - With no feldspar — peridotite, etc.

Intrusive or Extrusive (dense, fine-grained; crystals recognizable only by magnification):
- Light colored — felsite, etc.
- Dark colored — basalt, etc.

Extrusive (composed wholly or partly of glass; no crystals):
- Obsidian, pumice, etc.
- Fragmental extrusive rocks — tuff, volcanic breccia, volcanic ash

The character of igneous rocks is determined mainly by their mineral composition and texture. The mineral composition, to a large extent, results from the chemical elements present in the magma from which the rocks solidify. Pressure and temperature also have a bearing on what specific minerals are formed. The texture of an igneous rock is largely determined by the speed with which the molten material cooled, and this in turn depends on its depth below the surface and the volume of magma involved. Lavas that pour out on the earth's surface cool quickly in the air, and the minerals usually crystallize as small, often microscopic, grains. The middle of very thick flows of lava may be coarser grained, however, since that part of the flow cools more slowly. Some lavas cool so quickly that crystallization cannot take place at all, and a volcanic glass with no crystals results. Thus we see that the extrusive rocks are usually fine-grained, with tiny crystals, or glassy, because they cooled so rapidly that large crystals had no chance to grow.

Magmas that intrude the earth's crust at a depth of a mile or more cool very slowly, and the mineral crystals have a long time to grow. Such intrusive rocks are granular and coarse-grained, with easily visible crystals. Granite is probably the most typical and familiar example of this type of rock. Other magmas that intrude the pre-existing rocks nearer the earth's surface are subject to more rapid cooling, especially along the planes of contact with the older, cooler rocks. Magma in sills and dikes also cools more quickly because it is spread thin. In both cases fine-grained rocks result, much like the extrusive rocks.

Sometimes magma may start to cool deep below the surface, forming a number of typical large crystals. A renewal of activity may then suddenly force the magma to, or near, the surface, where the remaining material cools quickly in small grains. Such a rock is called a porphyry (Figure 35), and the large crystals embedded in the finer grained matrix are called phenocrysts. Other influences, such as the presence of water and other volatile liquids, also promote crystallization, so depth of intrusion and consequent rate of cooling are not the only factors involved in the size of the grains.

If any one form of rock is most typical of Minnesota, it is granite. Some of Minnesota's granites are among the very oldest rocks on the earth's surface, pushed up from deep below along the centers of ancient mountain chains and now exposed after millions of years of erosion. Granites are intrusive rocks, relatively coarse-grained and composed mainly of quartz and feldspar with, as a rule, considerable amounts of hornblende or mica (Figure 36). Lesser amounts of several other minerals may be present. Because the granites were formed only at considerable depths in the earth, where crystallization is slow, the grains are large enough to be recognized with the naked eye or with the aid of a hand lens. The color of granite is always fairly light but varies with its constituent minerals from light to dark gray or red. Pink granite contains pink or reddish feldspar. In

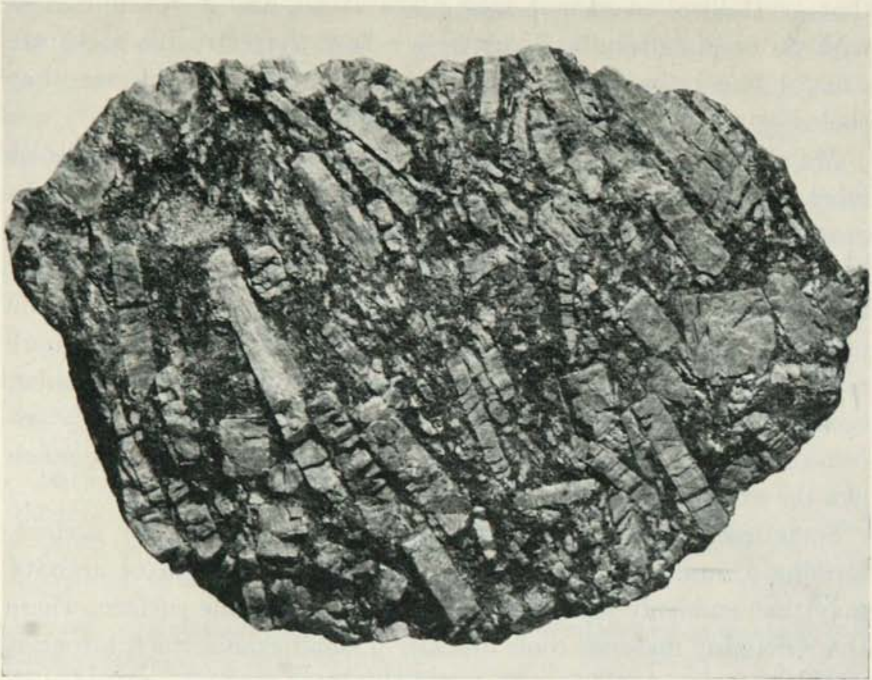


Figure 35. Porphyritic texture in syenite. Crystals of feldspar in a fine-grained matrix. St. Louis County. Approximately natural scale.

gray granite the feldspar is white or gray, allowing the dark minerals that are present to show plainly.

There are many varieties of granites classified according to the minerals that are present. Other variety names are based on texture, such as porphyritic granite. Minnesota's abundant granites have been the basis of an important quarrying industry, particularly at St. Cloud and nearby at Melrose, Sauk Centre, Rockville, and Cold Springs. The most extensive outcrops of granite, places where erosion has exposed the deep granite masses at the surface, occur in the northeastern part of the state. The Giant's Range, Vermilion, Basswood, Kekequabic, Snowbank, and Saganaga granites are examples. Other granites crop out at other places in the state, especially near Milaca, Mille Lacs Lake, and Denham. In the Minnesota River Valley, granite is exposed at places from Franklin to Ortonville.

Syenites are similar to granites except that they contain no quartz

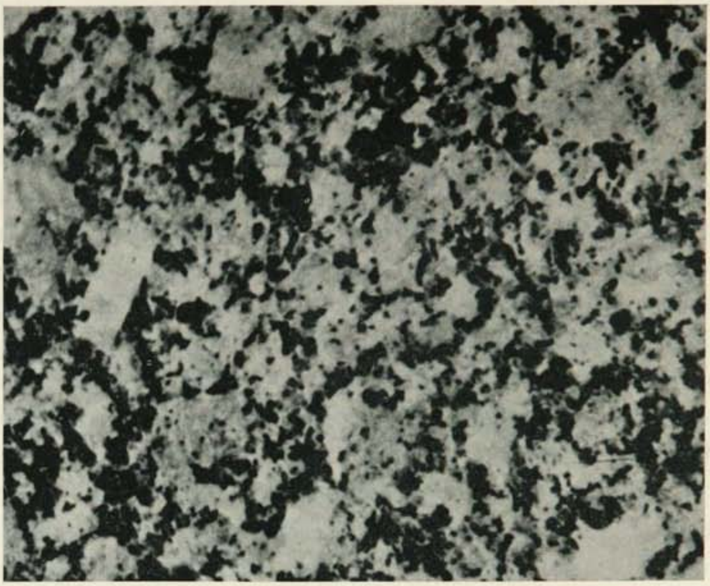


Figure 36. Granite. An aggregate of light and dark mineral grains. Rockville, Stearns County. Approximately natural scale.

They are much less common than granite but occur in small masses in northern Minnesota.

Felsites include all the fine-grained, light-colored igneous rocks that are equivalent in mineral content to the coarse-grained granites and syenites, but that cooled quickly at or near the earth's surface, usually in lava flows. They vary from light to dark gray, with many colored pink or red. Felsites are abundant along the North Shore of Lake Superior between Duluth and the Reservation River.

Diorite is a coarse-grained intrusive rock intermediate in mineral composition between granite and gabbro. Most diorites contain more light-colored feldspar than dark minerals, and although they contain no quartz, they closely resemble gray granite. Diorites occur sporadically in Minnesota, particularly between the Cuyuna district and Duluth, but they are not widespread.

Gabbro is an abundant rock in Minnesota because of the occurrence of what is called the Duluth Gabbro, one of the largest gabbro masses in the world. Gabbro is another of the coarse-grained subterranean rocks that has been exposed at the surface long after cooling. It is darker in color than granite, usually dark gray to black, and on its weathered surface it appears brown. Chemically, a gabbro is higher in lime, magnesium oxide, and iron than granite and lower in silicon oxide. It also has a higher proportion of the dark, iron-bearing minerals than granite has. Gabbro is common in sills and dikes, particularly north of Lake Superior in St. Louis, Lake, and Cook counties. It is sometimes called diabase, particularly when the gabbro is somewhat finer grained than usual and has a texture where lath-shaped crystals of feldspar are embedded in a matrix of pyroxene, one of the dark-colored silicate minerals.

A somewhat unusual rock consisting largely of coarse-grained plagioclase feldspar is called anorthosite. In its deep, underground origin it is related to the gabbros and other varieties of coarse-grained, dark-colored igneous rocks; but because of its high proportion of feldspar it is unusually light in color. Anorthosites are abundant in northern Minnesota. Large parts of the Duluth Gabbro intrusion consist of anorthosite. In the sills and dikes of diabase gabbro along the North Shore of Lake Superior (Figures 98 and 102), islands of anorthosite are enclosed in the gabbro, ranging from small fragments of crystals up to masses measured in hundreds of feet. These masses are distinguished by the white color of their exposed surfaces and by a very light, transparent, green feldspar that can be seen in the fresh rock.

Basalts are the most common extrusive rocks in Minnesota. They are fine-grained igneous rocks whose mineral grains are too small to be recognized with the eye but can be readily identified with a microscope. Basalt is dark gray to black in color when freshly exposed, or brown or reddish when weathered. In mineral content it corresponds in a general way to gabbro and diabase. Basalt, also known as "trap," is formed most commonly as surface lava flows, but it may also be found as small dikes and sills intrusive into preexisting rocks. All these occurrences are common in Minnesota, particularly in the rocks that are found from Taylors Falls on the St. Croix River up to the North Shore of Lake Superior and Grand Portage at the northeast tip of the state. Old basalt lava flows have also been encountered in a deep well at Stillwater and southwest of Minneapolis in Le Sueur County.

Some extrusive rocks are formed from lava pouring out so rapidly that no crystals at all have time to form, and a glasslike material results. Obsidian is a general term used for such massive volcanic glasses of variable composition. These glasses are not important in Minnesota, but another type of volcanic rock, volcanic tuff, does occur. During explosive activity in volcanoes, large amounts of of molten and solidified material may be thrown into the air and settle over wide areas as fragmental volcanic rocks. When solidified, deposits of this sort may consist of coarse fragments cemented with finer volcanic material. Such a rock is called volcanic breccia. Tuff, or volcanic ash, however, is a fine-grained aggregate of smaller fragments, often light in weight because of high porosity. Its color varies from light gray to brown, yellow, and dark gray. Very compact tuff may be confused with felsite, which is also fine-grained and light colored, and a microscope is needed to distinguish them. Tuffs contain the minerals of the lava rocks plus volcanic glass, but rock fragments are likely to be more abundant than individual minerals.

Tuffs are not very widespread in Minnesota because most of the early lavas presumably poured out slowly from great fissures, rather than being violently expelled from volcanoes. Some tuff beds do occur sandwiched between layers of lava flows, and metamorphosed tuffs — that is, tuffs baked and altered by the heat of later magma intrusions nearby — are very abundant in the Knife Lake group of rocks of the Vermilion district.

We have learned enough of the different igneous rocks and their origins to realize that in Minnesota the great majority were formed a very long time ago. We can see now that the earth's first solidified rocks were necessarily of igneous origin, and that the earth's rocky crust began with hardened lavas. Once these igneous rocks were formed, however, they were exposed on the surface to water and air, or, if they remained underground, to more heat, pressure, and nearby flows of magma. These different forces, working over the centuries, wrought many changes in the old igneous rocks, and gradually new kinds of rocks began to appear.

The rocks that we call metamorphic, from the Greek word for "change," resulted from underground heat and pressure exerted on the pre-existing rocks. The rocks we call sedimentary were formed very slowly from tiny particles dissolved or chipped away from the surface rocks and carried by the geological agents to new places, until millions of such particles — the "sediment" for which these rocks are named — eventually formed new, sedimentary rocks.

SEDIMENTARY ROCKS

The common phrase "solid as a rock" is quite misleading, for as we have already seen, the processes of weathering are constantly working to produce the mechanical and chemical breakdown of rocks at and near the earth's surface. As a result, rock particles accumulate at the surface and are carried away by water, wind, and ice to be deposited elsewhere. Some of this material is dissolved and carried away in solution, most of it to be deposited in lakes or the oceans. Plants and animals as they live and die also form deposits; peat, for example, comes from decayed plant life, and coral reefs from tiny animal remains. The material deposited in these various ways is called sediment, and the rocks that result from consolidation of this material are collectively known as sedimentary rocks. According to their mode of deposition, these deposits are called mechanical, chemical, or organic. Most of these deposits are laid down slowly, over a long period of time, in definite layers that are spoken of as strata or beds.

Sedimentary rocks occur through much of Minnesota, but the largest and most important area occupies the southeastern part of the state, extending along the St. Croix River east of Pine City southward along the St. Croix and Mississippi rivers to the Iowa line.

Mechanically formed sediments are classified according to particle size, beginning with the smallest, as follows: clay, silt, sand, gravel, cobbles, and boulders. Sedimentary rocks are, as a rule, classified as to mode of formation, composition, and physical character. There are only a few common varieties and these require no elaborate classification.

A conglomerate is essentially consolidated or cemented gravel. Rounded pebbles of rocks and minerals of various sizes are bound together by finer material, such as sand and clay (Figure 37). Some conglomerates consist mainly of pebbles which are all of one material, such as quartz. The quartz has remained as pebbles while softer material was broken up and carried away. Such pebbles vary greatly

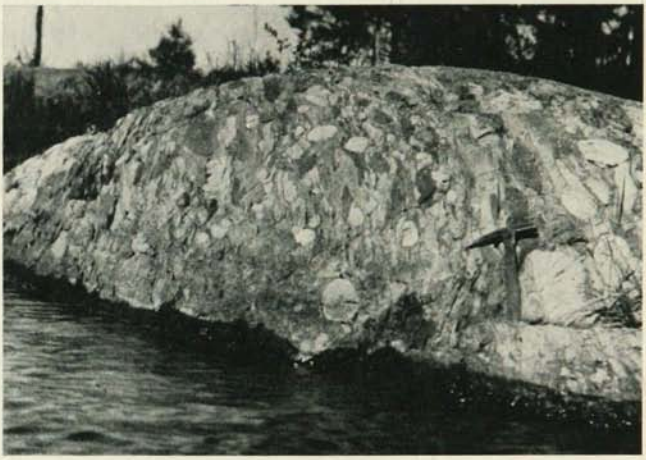


Figure 37. Outcrop of conglomerate on shore of Ensign Lake, Lake County.

in size, some being so large that they might more properly be called boulders. In the so-called Ogishke conglomerate of the Vermilion district, boulders up to two feet and more in diameter have been observed incorporated in the matrix.

There are numerous conglomerates in Minnesota. Several different beds have been recognized in the ancient Knife Lake group of rocks, among them the Ogishke conglomerate referred to above. Several conglomerates exist between lava flows in the area from Duluth to Grand Portage, and a conglomerate of Cambrian age rests directly on the lava flows at Taylors Falls. Conglomerate also occurs with quartzite in the Minnesota River Valley east of New Ulm.

Sand grains compacted and held together by various cementing materials, such as quartz, calcite, and iron oxides, form the sedimentary rocks we call sandstones. Most sandstone is composed largely of grains of quartz, but many other mineral grains, such as feldspar, may be present. Small, rounded rock fragments may also occur in sandstones. Their color varies from white to gray, buff, brown, red, and green. Sandstones usually show a well-defined bedding, or layered formation, varying from very thin layers to those several feet in thickness, and are often highly porous. Those with grains of uniform size, rather perfectly rounded, and with a small amount of cementing material may absorb water up to 30 per cent of their volume. Such porous sandstones may serve as valuable reservoir rocks for water, petroleum, and natural gas.

Sandstones are abundant in Minnesota, particularly in the area from Duluth to the southeast corner of the state. They have been quarried at the town of Sandstone and to a lesser extent near the Minneapolis–St. Paul area. They constitute the major part of the Cambrian rocks exposed along the St. Croix Valley and extend over a large area from Cambridge to Fond du Lac at the outskirts of Duluth.

Another kind of sedimentary rock is formed from clay. When compacted, clay becomes hard and usually develops a thinly laminated, or layered, structure, and the resulting rock is called shale. If subjected to still further pressure and diastrophic folding, shales may become slates — dense, compressed metamorphic rocks with a characteristic cleavage. Shales are normally very fine-grained, so that the mineral constituents cannot be recognized with the naked eye or a hand lens. With a microscope, however, it is possible to recognize many minerals in shale—various clay minerals, quartz, mica, carbonates, iron oxides, organic matter, and other materials. Both the composition and the color of shale vary widely. Many are dark gray to black; others are red, buff, brown, or green. In Minnesota shale is found principally in the southeastern portion of the state. Shales also occur at many places in southwestern Minnesota, but they are not well exposed and our knowledge of them is derived largely from samples brought to the surface during the drilling of wells.

As we mentioned earlier, limestone is a chemical or organic sediment composed mainly of calcite. With an increase in magnesium content, limestone is called dolomite. Pure limestones or dolomites are the exception rather than the rule, as they may contain some sand, clay, and other minerals. When the amount of impurities becomes great, they grade into shales or sandstones. Limestones and dolomites are normally fine-grained and vary in color from light gray to dark gray or black, or to yellow, buff, brown, and red. Many limestones contain the remains of animal or plant organisms, called fossils, which give us important clues to the time when the rocks were formed and the kind of climate, terrain, and forms of life that existed then (Figures 57 and 59).

In Minnesota, dolomite and limestone are important rocks in the southeastern counties of the state (Figure 38). Dolomite is quarried extensively along the Minnesota River near Kasota and Mankato (Figure 83) and also at Winona in the Mississippi Valley. Smaller quarries of both limestone and dolomite have existed at

Figure 38. Massive bedded dolomite along Stockton Hill road cut in wall of the Gilmore Valley, near Winona, Winona County.

times in most of the counties along the Mississippi River downstream from Minneapolis.

The quarried rock is used for building stone, crushed rock, natural cement, and rock wool. The same material that makes up limestone, calcite or calcium carbonate, is called marl when it is unconsolidated — that is, not compacted by pressure. Such marl is constantly being deposited in many Minnesota lakes, and in some it has accumulated on the bottom to a thickness of more than 20 feet.

Iron formation is a general term applied to complex, iron-bearing sedimentary rock formations. Although these iron formations are not common, they are very important as the parent rocks of all the Minnesota iron ores (Figure 39). The rocks vary considerably from place to place and even within a single formation. Some beds are essentially jasper, a fine-grained quartz stained red with hematite. Chert, another iron-bearing quartz, is also abundant, but others of the parent rocks may be composed mainly of iron carbonate (siderite). Some hematite and magnetite are normal constituents in most iron formations, and greenalite, a complex hydrous iron silicate, is abundant in some, notably on the Mesabi Range.

Certain silicates peculiar to the iron formations develop in these rocks when they are subjected to metamorphism — the environmental changes, usually caused by diastrophism, that produce metamorphic rocks. These silicates include such otherwise rare minerals as grunerite, minnesotaite, and stilpnomelane. The names applied to specific rock varieties in the iron formations include jaspilite, ferruginous chert, slaty iron carbonate, cherty iron carbonate, and taconite, the last being the most familiar to most of us, since new mining processes are being developed in Minnesota to extract the iron from our abundant taconite rock. The development of high-grade iron ores from the iron formations is discussed in a later chapter.

METAMORPHIC ROCKS

During its long existence, the earth has been undergoing continual change. There is much evidence that the earth has shrunk during the geological past, thus setting up stresses that required an

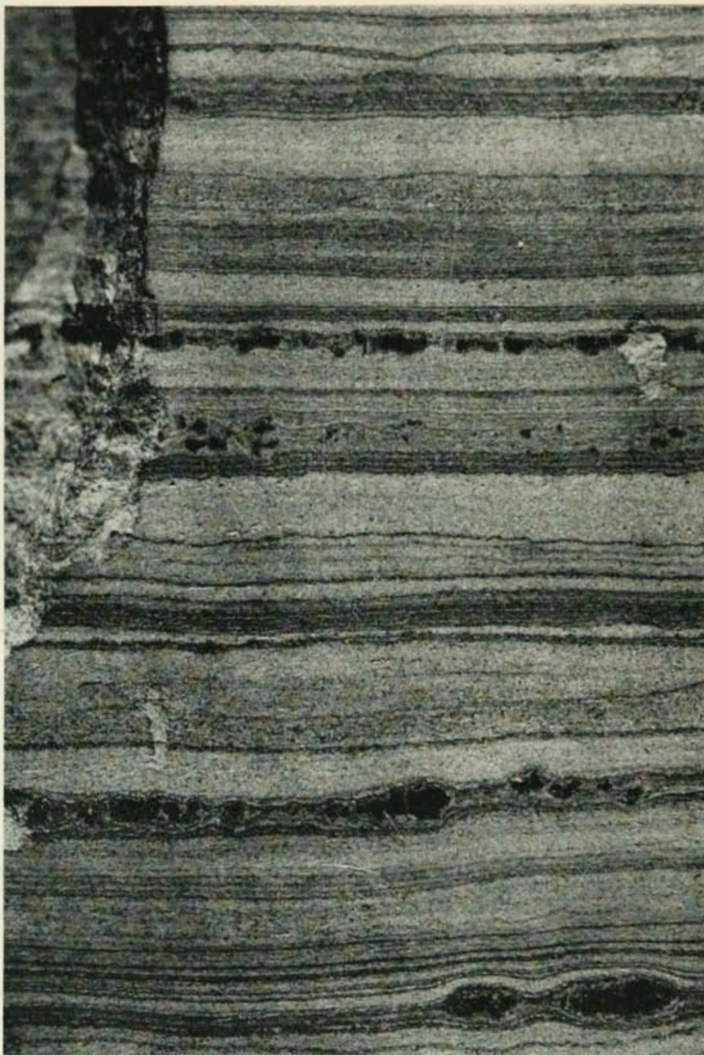


Figure 39. A finely laminated rock from the Biwabik formation consisting of iron carbonate and iron oxides. Sawed surface approximately natural scale.

adjustment of the earth's crust to its shrinking interior. We might think of the earth's crust as resembling the skin of an apple, which wrinkles and develops ridges as the apple dries and shrinks. We have seen how diastrophic processes raise these great wrinkles in the form of mountain ranges, and how the mountains are then eroded away, furnishing sediments that bury other rocks under a thick cover. This is how the sedimentary rocks were formed. We have seen, too, how masses of rock become molten and migrate upward into the crust to form various intrusive bodies of igneous rock (Figure 34) and to erupt at the surface as volcanic phenomena. Such migrations of molten material carry much heat into the earth's crust. All of the accompanying complex processes subject the pre-existing rocks of the crust to pressure, differential stress, and heat and to the attack of hot solutions and gases.

Generally when such a process, by the action of pressure, heat, and water, effects a pronounced change in rocks resulting in a more compact and crystalline structure, the process is called metamorphism and the resulting rocks are called metamorphic rocks. These rocks result only from the transformation of pre-existing sedimentary, igneous, or metamorphic rocks. For example, under metamorphic conditions limestone changes to marble, shale to slate, and the slate may be further metamorphosed to a rock called schist. From all these facts it is evident that the metamorphic rocks of Minnesota, or of any other locality, are intimately related in distribution to the occurrence of igneous rocks, since magmas bring much heat into the upper crust.

Metamorphic rocks may be classified into a few general groups based on variations in mineral composition, texture, and structure. The most common groups are gneiss, hornfels, marble, quartzite, schist, and slate.

Gneiss is a general term applied to banded, coarse-grained metamorphic rocks in which feldspar is an important constituent (Figure 40). The light and dark minerals occur in more or less definite zones, thus producing the alternate bands that characterize a typical gneiss. Gneisses may be derived from any kind of igneous or sedimentary rock, but granite gneisses are most abundant. They may be

Figure 40. Granite gneiss, Morton, Renville County. The bands of light and dark minerals are characteristic of a gneiss.

formed by movements in the granite mass before it becomes entirely solid, or by deformation of granite after it has hardened. Gneisses are also formed by intense metamorphism of sedimentary rocks whose composition is such that they will yield light and dark bands of quartz, feldspar, and black mica or some other dark mineral. There are gneisses in many areas in northeastern Minnesota, but the best known gneiss occurs at Morton in the Minnesota Valley, where it is extensively quarried and shipped throughout the United States for monumental stone and other purposes. Gneisses also occur at other places along the valley from Franklin to Ortonville.

When fine-grained rocks, such as shales, slate, and lava flows, are metamorphosed at places of contact with igneous rocks that are still molten, they often recrystallize to a finely granular rock called hornfels. The hornfels contain a variety of minerals and are gray to black in color. These rocks are common along the edges of the Duluth Gabbro and of many of the larger diabase dikes and sills of northeastern Minnesota.

Marble is produced by the metamorphism of limestone or dolomite. It is a relatively coarse-grained aggregate of calcite or dolomite or both. Marbles vary greatly in color, although a pure calcite or dolomite marble is white. Gray, yellow, red, and black are common colors. Marble is of little importance as a rock in Minnesota. There is a small outcrop of marble about a mile southeast of Denham in Pine County, however, and underground drilling in the Cuyuna Range area has revealed some marble under the glacial drift.

Quartzite is a metamorphic rock formed from sandstone, with silicon dioxide as a cement, and recrystallized as a result of heat, pressure, and the effect of various chemical solutions. It is the hardest of the common rocks and usually has a low porosity, since the pores of the original sandstone have been filled by silicon dioxide or eliminated by recrystallization under pressure.

Quartzite occurs at several places in Minnesota. The Pokegama quartzite lies beneath the iron formation along the Mesabi Range; a somewhat similar quartzite occurs at places in the Cuyuna district. Far to the southwest a small area of quartzite occurs in the Minnesota Valley downstream from New Ulm. Other occurrences are in Cottonwood and Watonwan counties, and another is in the region where the corners of Cottonwood, Jackson, Nobles, and Murray counties meet. Much better known is the large area along the southwest border of the state from west of Lake Benton southward. There extensive exposures occur in the vicinities of Pipestone, Jasper, and Luverne.

Slate is a dense rock characterized by a highly developed cleavage that permits it to split into thin, broad sheets (Figures 41 and 42). It is formed by the metamorphism of very finely divided sedimentary rocks, such as shales, siltstones, volcanic tuffs, and others. The color varies from medium to dark gray if the slate is contaminated with carbonaceous material, to green if chlorite is abundant and red if earthy hematite is present. Slate is the most abundant metamorphic rock in Minnesota. Some so-called slates are not typical, however, in that they lack cleavage developed by pressure and movement; but otherwise they resemble true slates, and for our pur-

Figure 41. Slate near Cloquet, Carlton County. The slaty cleavage is responsible for the planes facing the camera. Other flat surfaces are a result of joints.

pose the distinction may be ignored. The Virginia slate of the Mesabi Range and its counterpart, the Rove slate in Cook County, are such formations.

In the Vermilion district the Knife Lake slates extend westward from Saganaga Lake on the east, beneath a cover of glacial drift,

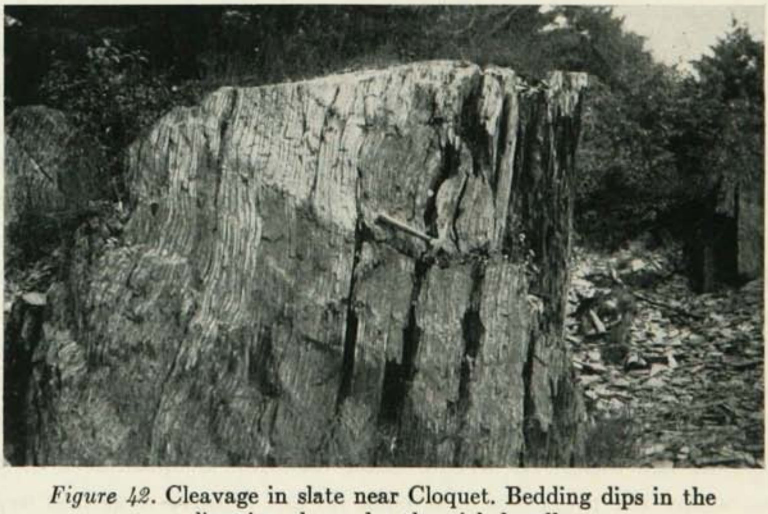


Figure 42. Cleavage in slate near Cloquet. Bedding dips in the direction shown by the pick handle.

to beyond Vermilion Lake. It is probable, however, that the slates continue across the state to disappear beneath younger rocks near the Dakota border. Along the south border of the Mesabi Range, the Virginia slate dips gently southward beneath a heavy cover of glacial drift. In Carlton County, slate crops out again, but this rock has highly developed cleavage; its relations to other rocks indicate that it is much older than the Virginia slate and should perhaps be correlated with the Knife Lake slates. The exact relations between these formations have not been determined. Associated with the slates are many beds of impure sandstone, usually called graywacke.

The crystalline schists form a group of rocks characterized by a well-developed cleavage or foliation which is a result of the parallel orientation of platelike and needle-like mineral grains. Many schists are formed by the recrystallization of slates, but other varieties are derived from basalts, felsites, and several other kinds of rocks. The principal minerals of schists are mica, chlorite, amphiboles, talc, and graphite, all of which form either long or flat crystals and thus develop the foliation that characterizes the rock. Schists are abundant in the pre-Cambrian rocks of northern Minnesota, especially where earlier rocks are intruded by granite. Greenstone, the oldest rock in Minnesota, is essentially a chlorite schist.

MANTLE ROCK AND SOIL

The surface of the earth is largely covered by a varying thickness of loose rock material called mantle rock. It lies on top of the deeper masses of igneous, metamorphic, and sedimentary rocks and consists of fragments of all the other kinds of rock. This mantle rock results from the weathering processes to which all surface rocks are subject. In general, weathering takes place more rapidly in warm, moist climates and therefore is not very active in a temperate to cool climate such as Minnesota has today. At times in the geological past, however, climatic conditions were more favorable, and deposits of decomposed rock accumulated to a considerable depth at various places in the state. As a rule such material accumulates only in areas where the processes of erosion do not remove it as fast as it is formed. Such conditions existed over many counties in south central

Minnesota, and as a result clays were formed from the decomposed rock. These residual clays are well exposed at Morton and in Ramsey State Park in the Minnesota Valley.

By far the greater part of Minnesota, however, is covered by mantle rock deposits brought down from farther north by the continental glaciers. Part of this material was dropped at the place where the ice melted, as ground or recessional moraines, while other parts were transported some distance from the melting ice by both water and wind. The deposits formed by glacial meltwater, like those dropped by the ice, are varied in form. As we noted in a previous chapter, a widespread sheet of stratified silt, sand, and gravel is called an outwash plain. Such a plain is formed by the merging of the numerous small alluvial fans of the many meltwater streams flowing away from the ice mass. There may also be long, winding ridges, known as eskers, formed by under-ice streams (Figure 78); and a rounded, cone-shaped hill of stratified sand and gravel is called a kame.

Where temporary glacial lakes formed in front of the ice, fine-grained sediments, mainly clay and silt, were deposited in the lake basins. Where these basins are now drained, the sediments form rich soils like those of the Red River Valley. The soil of the area that was formerly covered by Glacial Lake Duluth is characteristically a red clay, with occasional limy concretions occurring within it (Figure 43).

Strong winds, as well as ice and water, have the power to move large amounts of fine rock material. This material is then dropped wherever the wind loses velocity. During certain phases of the glacial periods, large areas of bare drift and fine debris were left behind by the retreating glacier. Strong winds blowing off the cold ice mass picked up large amounts of fine "rock flour" from these bare areas and deposited it beyond the margins of the ice. Such fine, wind-deposited material, called loess, covers much of southeastern Minnesota, particularly the counties of Houston, Fillmore, Winona, Olmstead, and Wabasha, and considerable areas of adjacent counties.

The upper part of the unconsolidated rock mantle is the soil. It is composed chiefly of more or less finely divided, physically and chemically altered rock fragments, together with organic material that has accumulated through the growth and death of many generations of plants. Many people think of the soil as a lifeless residual layer that has somehow accumulated over a long period of time and that contains a supply of material for plant growth. Far from being a lifeless layer, however, it is constantly changing. It is now known that soils become adjusted to conditions of climate, topography, and vegetation and that they change internally when these controlling conditions change.

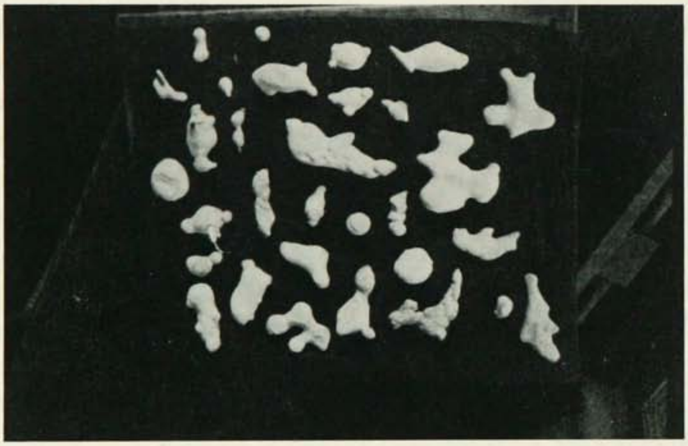


Figure 43. Concretions from Glacial Lake Duluth clay bank along Baptism River Valley, Lake County. About one fifth natural size.

The character of soil in the early stage of its development depends mainly upon the composition of the parent rock and mineral material, but older and more mature soils are influenced more by their environment than by the composition of the original mineral matter. The same kind of rock may produce totally different soils under different environmental conditions, and conversely, similar environments eventually tend to produce similar soils, even from rocks that are quite unlike in character.

The parent material for nearly all of the soil of Minnesota is glacial drift, but not all of the drift is of the same age, nor is it all from the same source area. Furthermore, some of it has been sorted by wind, some by running water, and some by wave action in the glacial lake basins. Thus the texture and composition of the parent material for the soils have varied greatly. In northwestern Minnesota the parent material is fine, sandy silt deposited on the floor of Glacial Lake Agassiz. In the southeastern counties, it is wind-transported silt and clay deposited as loess. In east central Minnesota, north and northwest of the Twin Cities, it is wind-drifted sand. Over most of the remainder of the state the glacial drift deposits are mainly unsorted clayey and sandy till, except in the zones of outwash sands and gravel.

Rainfall and evaporation are important factors in the formation of two major classes of soils, the pedalfer soils and the pedocal soils. Pedalfer soils show pronounced leaching — that is, a dissolving away of their soluble minerals — and occur in the eastern and central part of the United States, where the rainfall is more than 25 inches annually. The pedocal soils contain an excess of calcium carbonate and occur in the western United States where the annual rainfall is less than 25 inches. The soil names are coined from their chemical contents. The syllables *al* and *fer* in "pedalfer" refer to aluminum and iron as residual substances in the soil. The syllable *cal* in "pedocal" refers to calcium, which is abundantly present in this soil in the carbonate form.

All but the most westerly counties of Minnesota have pedalfer soils. These of the southern part of the state belong to the Northern Prairie soil group, whereas the northern counties have the so-called podsolic soils, which are intensely leached. The prairie soils are extremely fertile and productive, but the podsolic soils are low in fertility because most of the calcium, magnesium, potassium, and phosphorous which many plants require have been leached from them. Such areas support evergreen forests, however, because the cone-bearing trees do not require large amounts of these soluble elements for their growth. Each of Minnesota's characteristic vegetational regions is determined largely by the nature of its soils

—the pine forests of the northeastern third of the state, the strip of deciduous woods from the northwest to southeast corners, and the remaining western and southwestern prairies. Thus the rocks and minerals that make up the bedrock and surface topography of Minnesota determine the nature of our forests and farm lands as well.

CHAPTER

4

Clues to the Span of Geological Time

ONE of the exciting rewards of the study of geology is the glimpse it gives us into secrets of the past. Through geology we may gain at least a partial understanding of the vast time it has taken the earth to form the record we see in its rocks.

Man measures his movements and things close to him in feet and inches, in hours and minutes, in pounds and ounces. He may extend his measurements to larger units, but in so doing his ideas about what he is measuring become progressively more vague. As we think of the six or seven thousand years of recorded human history, its beginnings seem farther back than our familiar, accurate units will permit us to measure with real understanding. When we try to imagine a unit of time as vast as a billion years, our known units are so small that we cannot use them to make comparisons.

To assist us in attempting to comprehend the meaning of a billion years, a geologist once made the following calculation: Imagine a man so small that he has to take sixteen steps to go one inch, and so slow that he can take but one step a year. If he decided to walk from New York to Chicago, it would take him approximately a billion years. During that time the earth could pass through many cycles of change of great magnitude. Furthermore, there would be ample time for the slow development of the almost infinitely varied forms of plant and animal life.

Difficult though the process is, geological time must be measured if we are to unravel the tangled clues to the earth's long history. Only in the last hundred years or so has man learned some indirect ways to do this. Some constant geological processes, we have learned, serve as crude hourglasses of the ages. Erosion is one of these processes. Ever since the earth has had water on its surface — that is, since the earth cooled enough so that surface water did not boil away —rivers have flowed across the land. As rivers flow, they wear away the rocks and soil they flow through; and steadily, year after year, they carry this debris down to accumulate in low-lying depressions. The amount of sediment transported and deposited in a year by a single large river is very great.

The Mississippi River annually carries to the Gulf of Mexico about 22,000,000,000,000 (or 22 trillion) cubic feet of water, containing in suspension 340,500,000 tons of sand, silt, and clay, rolling on the bottom 40,000,000 tons and carrying in solution 136,400,000 tons of dissolved mineral matter. This is a total of 516,900,000 tons of rock waste per year. If all of these products of erosion were loaded on ordinary freight cars, it would make a train that would reach around the earth six times in the region of the equator.

Estimates like this of the rate at which certain rivers today are eroding the areas they drain give us a measuring stick for past erosion. The Mississippi River and its tributaries, draining an area of approximately 1,265,000 square miles, are lowering the basin of that river system at the average rate of about one foot in 9000 years. At that rate, it would take a tremendously long time to reduce a large land area to essential flatness. Yet the rocks of the earth's crust give good evidence that this long process has occurred over and over and that the earth has undergone repeated peneplanation, the reduction of great land areas to near flatness by erosion. Putting all this evidence together, we must conclude that the age of the earth, based on present estimates of river erosion, is several thousand million years.

Here is another clue to the span of geological time. During the earth's history the products of erosion have accumulated in beds of sedimentary rock to a total thickness of approximately 75 miles.

If we knew the average rate of deposition of this sediment, the length of time required for the accumulation of such a great thickness of sediment could be computed. This rate we do not know with certainty, but an approximate estimate of the time required to deposit a thickness of one foot of sandstone over the floor of a large inland sea is 450 years. For one foot of shale the time is 900 years, and for limestone 2250 years. Even though such figures are no more than rough estimates, they nevertheless indicate the magnitude of time involved in the transportation and deposition of the great thickness of the earth's sedimentary rocks.

Another indirect time measurement geologists use depends on the amount of salt in the sea. When the seas we know today first collected in their basins they were no more salty than any other waters of the earth. But as the rivers flowed down across the land to the oceans, they carried with them, among other products of erosion, many dissolved mineral salts. Since the oceans occupy the lowest hollows on our globe, there was no way for the salty water to flow out again, and so salts have been collecting through the many years. Water evaporates from the great ocean surface, but again the salts remain. The total amount of salt in the sea today can be estimated quite accurately, and the approximate rate at which it is now supplied to the sea by rivers has been determined. If we assume that the rate of supply was as constant in the past as it appears to be at present, an estimate of the age of the ocean can be made. It has been figured that approximately 158,000,000 tons of salt per year are added to the sea at the present time. At that rate it would require many hundreds of millions of years to carry to the seas the millions of millions of tons of salt now in the ocean.

Unfortunately our figuring cannot be as simple as this, however, for it is known that actually the land areas being eroded in the past were not the same in size as those of today, nor did they stand at the same elevation above the level of the sea. Thus this method of calculation, too, gives us no more than a very rough estimate, even though it helps us to realize in part the magnitude of the time involved in changing the oceans from fresh water to the degree of saltiness they have today.

If one clue does not give a perfect answer, the geologist turns to still another—this time the fossils, the animal and plant remains that are imbedded in the rocks. These preserved records of life on earth show that the oldest known forms of life were vastly different from those of the middle geological eras, and those of the middle eras in turn differ widely from the animals and plants of today. The record of life as revealed by fossils indicates that the simpler, lower orders of living things appeared first, and that progressively higher and higher forms developed in succession. We know also, from drawings made by prehistoric man and from written biological studies made by later men, that forms of animal and plant life change very slowly. From all these different facts we can begin to piece together a coherent story.

During the first two thirds of earth history, small invertebrate creatures were the sole representatives of the animal kingdom. Then fossils of fishes appear in the rocks, and for several geological ages they were the highest forms of vertebrate life in existence. Later the amphibians make their appearance and these are followed by reptiles and birds. In rocks of a still more recent date, the fossil remains of mammals are found imbedded in nonmarine shales and sandstones. Each of the groups of animals referred to represented a distinct advance over the one that preceded it, yet we know that such marked changes in groups of living creatures take place only with extreme slowness. Thus all our evidence fits together to show again that the earth is very, very old.

Still another time clue that scientists use is a very technical one based on rates of atomic disintegration of radioactive elements. Some of the heavy atoms found in rocks, such as atoms of thorium and uranium, are unstable and are constantly breaking down into atoms of lighter elements. The rate of disintegration has been determined, and it is known to go on at a constant rate regardless of extreme conditions of temperature and pressure. Thus if a certain amount of a radioactive element is present in a rock at the time of its formation, after many years a fraction of that element will have decayed and disappeared.

For instance, uranium disintegrates by a series of steps into other radioactive elements, such as radium and polonium, which then in turn break down further into end products—helium and an isotope of lead. From the amount of either lead or helium in a rock, the amount of uranium that has decayed can be calculated. This figure added to the amount of uranium still undecayed gives the original quantity present. Since the rate of decay is accurately known, from measuring the same process as it occurs today, a comparison of the initial amount of uranium with the amount which has decayed yields data from which the age of the rock in years can be calculated.

Time measurements by this method tell us that rocks with the first fossil remains of mammals are about 200 million years old, and that invertebrate animals with hard shells first became abundant about 500 million years ago. The oldest rock whose age has been determined by this method is a granite exposed along the Winnipeg River in Manitoba, Canada. Its age is over *2 billion years.*

We can see now that our story of Minnesota's rocks and the land they compose must be told in the context of giant time spans. Geology has to deal primarily with physical processes that have been at work shaping and reshaping the surface of the earth since the oldest known rocks were formed. As our knowledge of these physical and dynamic processes has increased, it has become apparent that they tend to operate in great cycles or rhythms, and that such cycles can be used to construct a chronological background for geological history. The sequence of events has been determined by (1) the actual sequence of the sedimentary rocks, from the early, bottom layers to the latest ones on top; (2) the degree of development attained by animals and plants, as shown by the fossils in the rocks; and (3) the breaks or gaps in the sequence of the rocks at a given place.

Geological history, like human history, falls into major and minor divisions, and these in turn into smaller ones. Thus, as we see in the classification of the main divisions of geological time, the longest divisions are the eras. These may be regarded as volumes in our long treatise of earth history. The eras are divided into periods, corresponding to chapters in the geological volumes. The chapters in a book are rarely of equal length, and similarly, the periods of geological history have no regularity in their length of time. Some are two or three times as long as others. Each period is characterized by one or more advances of the sea over parts of the continental areas. The names of the periods are generally taken from the regions in which the rocks of that period were first studied and classified, or from some striking characteristic of the rocks of that period.

The eras are bounded by pronounced changes, both in the physical aspect of the earth and in its living organisms. The physical changes are a result of mountain-making diastrophism, commonly called orogenic diastrophism, which causes the continents to stand higher above the level of the seas. As a consequence of these uplifts of the land, climates may become colder and drier. Such environmental changes bring about accompanying organic changes, and it is after these diastrophic events that bound the eras that the greatest changes among fossils of organisms are found.

Not all the subdivisions of geological time are necessarily represented by the rock strata in any one geographical region. The succession of rocks in any region from the oldest on the bottom to the youngest on top, constitutes the geological column of that region. Thus we speak of the contents of the accompanying list of rock formations as the geological column for Minnesota.

If we look at the legend of a geological map of Minnesota (Figure 44), and at the list of rock formations, we see that in Minnesota no rocks of the Upper Paleozoic and Lower Mesozoic ages have been mapped. In other words, rocks of Cretaceous age rest directly on pre-Cambrian and early Paleozoic formations. This is interpreted to mean that Minnesota and adjoining areas in Wisconsin and North Dakota were above sea level during Upper Paleozoic and Lower Mesozoic time. If sediments of those ages were deposited in this region, they were eroded away completely before the time of the advance of the Cretaceous sea.

Most of the northern two thirds of Minnesota is underlain by very ancient rocks of Archeozoic or Proterozoic age (Figure 44). They include the rocks of the iron ranges and the lava flows and

MAIN DIVISIONS OF GEOLOGICAL TIME
(Read up from the bottom)

Period	Some Outstanding Physical Events	Life Development
	Cenozoic Era (beginning 70,000,000 B.C.)	
Pleistocene	Postglacial changes The Great Ice Age	Advent of man
Pliocene	Formation of Coast Range	
Miocene		Primitive horse and other ungulates
Oligocene		Numerous placental mammals
Eocene	Extensive volcanic activity in western United States	
Paleocene		First placental mammals
	Mesozoic Era (beginning 200,000,000 B.C.)	
Cretaceous	Folding to form Rocky Mountains	Extinction of dinosaurs Climax of reptiles on land, air, and sea First flowering plants
Jurassic	Beginning of Sierra Nevada uplift	First birds
Triassic	Extensive volcanic activity in New England	First dinosaurs and primitive mammals
	Paleozoic Era (beginning 500,000,000 B.C.)	
Permian	Folding to form Appalachian Mountains	First reptiles
Pennsylvanian	Extensive coal-forming swamps	Large nonflowering plants
Mississippian		First land vertebrates
Devonian	Acadian Mountains	Age of fishes
Silurian		Rise of land plants
Ordovician	Taconic Mountains	First known fishes
Cambrian	Green Mountains disturbance	Age of invertebrate dominance
	Proterozoic Era (beginning 1 billion B.C.)	
Keweenawan	Folding to form Killarney Mountains Extensive lava flows	Scanty record of primitive plants and animals
Animikian	Iron-bearing rocks deposited	Scanty record of primitive plants and animals
Knife Lake	Folding connected with igneous intrusions — Algoman Mountains formed at end	Scanty record of primitive plants and animals
	Archeozoic Era (beginning 2 billion B.C.)	
Laurentian	Folding to form Laurentian Mountains	
Keewatin	Rocks much altered and history obscured Extensive lava flows	Primitive life

related intrusions of the North Shore of Lake Superior. Rocks of similar age are exposed at the surface as far southward as Stearns County, and erosion has exposed a narrow zone in the valley of the Minnesota River. The very oldest rocks of Minnesota are greenstones that form a continuous belt from the region of Basswood Lake southwestward across St. Louis County and into northeastern Itasca County. These rocks are predominantly volcanic in origin, usually basaltic lava flows that have been intensely altered by metamorphism.

ROCK FORMATIONS IN MINNESOTA
(Oldest at the bottom)

System and Rock Formation	Average Thickness in Feet (Approximate)	Character of Strata
	Cenozoic Era	
Quaternary — Recent	0–200	Alluvial and lacustrine gravels, sands, silts, and clays
Quaternary — Pleistocene:		
Glacial drift	150±	Unsorted sands, silts, and clays
	Mesozoic Era	
Cretaceous:		
Coleraine (Benton)	50±	Gray or iron-bearing shales
Dakota	125	White to brown sandstone
	Paleozoic Era	
Devonian:		
Cedar Valley	100	Limestone and dolomite
Ordovician:		
Maquoketa	85	Buff shaly dolomite Shales and limestones
Galena	150	Buff, mottled dolomite White to gray limestone
Decorah	60	Greenish-gray shale
Platteville	30	Gray to buff limestone
St. Peter	125	White uniform sandstone
Shakopee	100	Buff to gray dolomite
Root Valley	15	White to brown sandstone
Oneota	100	Buff to pink dolomite
Cambrian:		
Jordan	100	White to buff sandstone
St. Lawrence	30	Buff sandy dolomite
Franconia	290	Green silts and sandstones
Dresbach	450	Sandstones and shales

ROCK FORMATIONS IN MINNESOTA — *continued*
(Oldest at the bottom)

System and Rock Formation	Average Thickness in Feet (Approximate)	Character of Strata
	Proterozoic Era	
Keweenawan:		
Hinckley	200	Buff to pink sandstone
Fond du Lac beds	2,000±	Red sandstone and shales
Duluth Gabbro and Beaver Bay complex	?	Basalt and felsite lava flows, local tuffs and sediments
Puckwunge beds	100	Conglomerates and sandstones (granite)
Animikian:		
Virginia (and Rove)	3,000±	Slates and carbonate cherts
Biwabik (and Gunflint)	750	Taconite, iron-bearing chert, iron ore
Pokegama (and Sioux quartzite)	200	Quartzites, slates, and conglomerates
Algoman Intrusives	?	Pink and gray granites and porphyries
Knife Lake	11,000	Slates, graywackes, and conglomerates
	Archeozoic Era	
Laurentian:		
Saganaga granites, etc.	?	Granites, gneisses, and porphyries
Keewatin:		
Soudan iron formation and Ely greenstone	?	Chert, jasper, and iron ore; green schists, greenstones, and basalts

The slightly less ancient Paleozoic rocks occur in the southeastern counties from Mankato eastward to Winona and northward as far as the southern part of Pine County. The Mesozoic era is represented by both marine and nonmarine rocks of Cretaceous age. They cover most of the counties in the southwestern part of the state from southern Stearns County southward into Iowa, and from Blue Earth County westward into South Dakota. Locally within this region there are areas where glacial erosion removed most if not all of the Cretaceous strata. In the extreme southwestern part of the state, in Rock and Pipestone counties, the Sioux quartzite

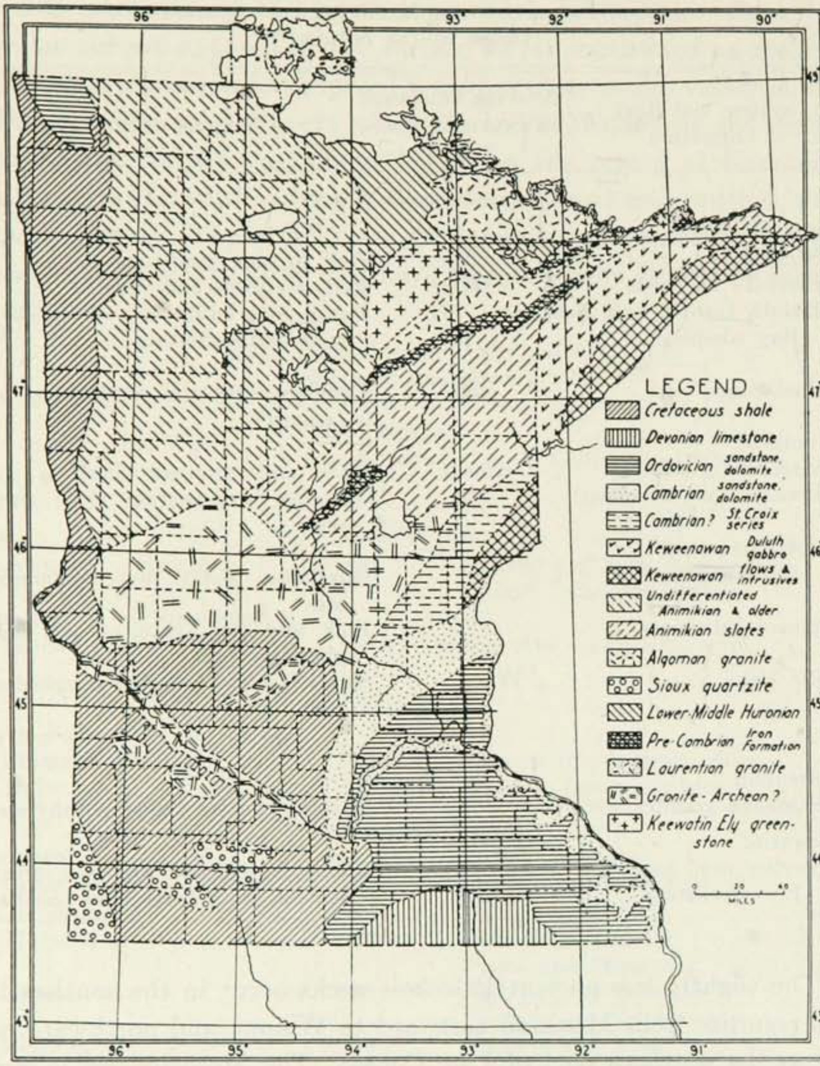


Figure 44. Geological map of Minnesota. What is here called Lower Middle Huronian is better known as the Knife Lake Series.

occurs at such a high elevation that it is doubtful if Cretaceous sediments were ever deposited over the quartzite rocks.

During the Cenozoic era the central part of the North American continent was above sea level, and consequently no marine sedimentary rocks were formed in Minnesota. Some of the nonmarine sediments under the glacial drift in the southwestern part of the state may be of early Cenozoic (Tertiary) age. The absence of marine fossils and the scarcity of nonmarine forms makes an accurate age determination almost impossible.

The late Cenozoic or Pleistocene epoch is by comparison almost modern times. It is represented by the various drift sheets that were deposited during successive ages of glaciation. The entire epoch was not subject to a glacial climate, however. After each age of glaciation there was a warm interval probably twice as long as the period of glaciation. It is in the latest warm period after the latest glacier retreated that we in Minnesota are living today.

CHAPTER

5

The Most Ancient Rocks in Minnesota

ACCORDING to most of the clues that geology can decipher, the oldest rock in Minnesota — and among the oldest known in the world — is the Ely greenstone. This rock formation is probably somewhat more than two billion years old, a legacy to us from the earth's beginnings. It crops out on the surface in hills and ridges near the mining town of Ely, in the Vermilion iron-bearing district, and along the north side of the Mesabi Range in the region between Virginia, Eveleth, and Gilbert, and also north of Biwabik (Figure 44). Farther west in Minnesota there are other areas where this ancient greenstone lies deeply concealed below the surface glacial drift.

The Ely greenstone is a metamorphic rock, altered from lava flows of basalt. A high concentration of the mineral chlorite gives it a gray-green color, from which it gets its name; and in places it still encloses small cavities, or vesicles, where gas bubbles were once trapped in the molten lava. One of the greenstone's strangest characteristics is the presence of large ellipsoidal shapes in the body of the rock, like eggs embedded in aspic (Figure 45). Geologists know that this ellipsoidal structure is typical of lava flows that solidify under water, so we have strong reason to believe that the greenstone began its existence on the floor of some long-departed Minnesota sea.

Figure 45. Ellipsoidal greenstone, the oldest rock in Minnesota, near Saganaga Lake, Cook County. (Photograph by J. F. Hayden, Jr.)

The Archeozoic Era

What was happening in Minnesota in that long-ago time when the first rocks were formed? This was the Archeozoic era, the opening chapter of the earth's long history. The earth itself, if it is as old as recent estimates indicate — about 3.35 billion years — had been condensing from a gaseous mass and cooling for over a billion years before the Archeozoic era began; but natural records of earth history could begin only as the earth's crust began to solidify. Most of those early events have been obscured by subsequent alterations of the rocks. All the periods of geological time before the Cambrian, which started the Paleozoic era (see p. 99), have been difficult to decipher, but slowly the record has been made clear. We know that one of the first major episodes in Minnesota was the pouring out of many basalt lava flows. This was one of the greatest periods of volcanic activity the earth has ever known, and Minnesota was one of the centers of this volcanism. At least the northern part of the state must have been covered by inland seas at this time, and the lava flowed out beneath the water as well as on land.

During later periods the lava flows were altered by complex processes, and the Ely greenstone was formed. Chlorite, a hydrous iron-magnesium silicate, was produced from the original iron- and magnesium-bearing minerals of the basalt. At many places the chlorite and other minerals of the newly formed greenstone were compressed and folded into layers paralleling the flat or curved surfaces of other hardened lava flows. This compression resulted in a foliated structure, or rock cleavage, in some of the greenstone; and where this occurs the greenstone may be called a chlorite schist. The perfection of cleavage in the altered rock varies so greatly, however, that the general term "greenstone" is preferred.

The structure of the whole greenstone formation is complex, and much of it is hidden today beneath younger rocks. It is therefore impossible to make a reasonable estimate of either the number of lava flows that were altered into greenstone or their combined thickness. It is certain, however, that the number of flows is large, and the thickness of the greenstone masses is doubtless several thousand feet.

During the latter part of the volcanic activity, waters accumulated on the surface of the recent flows, and silica and iron oxide were precipitated to form the Soudan iron formation. Strictly speaking, this is a part of the Ely greenstone formation, since greenstone and iron formation are interbedded. The Soudan formation of the Vermilion iron range district consists of jasper and associated slaty beds. There are several varieties of jasper: cherty, black-banded, red-banded, and one banded with white quartz (Figure 46).

The main mass of the Soudan formation probably lies near the top of the Ely greenstone, but beds of jasper lie between and parallel to the original lava flows. The total thickness of the jasper beds is several hundred feet, but exact measurements are impossible because of the complex structure. The original sediments of the Soudan formation were probably precipitated chemically from the water of Minnesota's Archeozoic seas, and the presence of graphite, usually derived from organic matter, suggests that plant life existed even in these ancient waters.

The Soudan formation in its original state contained a considerable amount of iron distributed through the rocks but did not con-

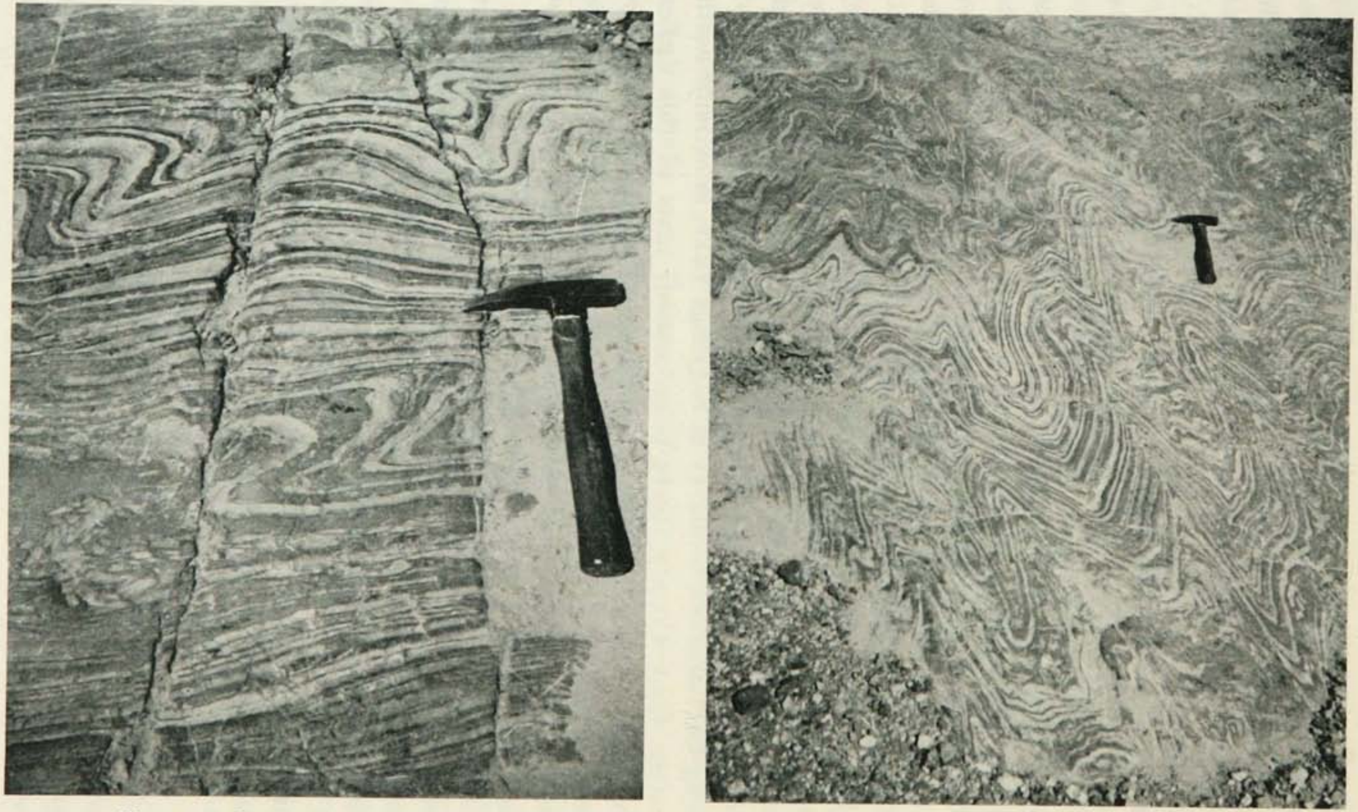


Figure 46. Contorted, banded jasper of the Soudan formation near the Soudan mine, St. Louis County.

tain any concentrated iron ore. At a later time, however, probably during the Proterozoic era, leaching of silicon dioxide and its replacement by hematite enriched certain zones of the formation to form the high-grade Vermilion iron ore that has been mined almost continuously since 1884.

Some time after the deposition of the Soudan formation, Minnesota was subjected to overwhelming mountain-making movements. A high range of mountains rose up, extending from the southwest corner of the state to the region of Saganaga Lake and on across Canada following the present course of the St. Lawrence River into the province of Quebec. This great period of diastrophism is known as the Laurentian orogeny, or folding of the crust, and with it the first era of the earth's history, the Archeozoic, came to an end.

Erosion then set in, wearing down the mountains wherever they stood above the level of the inland seas, and after a long period of time only the coarse-grained, deep-seated granite and other igneous and metamorphic rocks of the mountain roots were left exposed. Along the Canadian boundary at Saganaga Lake, in extreme northwestern Cook County, there is an ancient mass of this earliest Archeozoic granite that extends into Canada for many miles. On the basis of its relations to other rocks, this mass has been correlated with the granites of the Laurentian peneplain, and we know that both date from the same early period.

At the time of this great Laurentian uplift, the Saganaga granite also intruded parts of the Ely greenstone deep underground, and along the borders of the intrusion the greenstone was altered to a schist. In other places, where the Saganaga granite became exposed at the surface by erosion, this most ancient granite contributed its weathered boulders and pebbles to the sediments that were to form the rocks of the next great era of geological history.

The Proterozoic Era

The sediments that weathered from Minnesota's earliest rocks are known as the Knife Lake sediments, and are consolidated into Minnesota's next oldest rocks. These are metamorphosed sedimentary rocks that lie on top of the older Archeozoic rocks, forming a series of alternating slates, impure quartzites, conglomerates, iron formations, and interbedded volcanic tuffs and agglomerates at least 11,000 feet thick. These rocks are generally referred to as the Knife Lake group, named for Knife Lake on the Canadian border in Lake County.

The Knife Lake rocks are best exposed from Vermilion Lake to Gunflint Lake. A larger area exists west of Vermilion Lake and northward to the Canadian boundary, but in that region most of the rocks are covered by glacial drift. The Knife Lake sediments may well have been of continental origin — that is, deposited by erosion in valleys and local inland bodies of water rather than in an extensive sea. The conglomerates of the Knife Lake group consist of many kinds of pebbles, including weathered pieces of the ancient greenstones, granites, jasper, and chert (Figure 37). These products of erosion undoubtedly took many centuries to wear away and then consolidate. A long period of continuous gradation must have followed, during which many fluctuations of climate, sea level, pressure, and volcanic activity caused the different kinds of sedimentary rocks to form in turn. Thousands of feet of these sedimentary strata were laid down, altered by heat and pressure into their metamorphic equivalents, and finally folded and faulted into complex new patterns by a new diastrophic uplift.

This new uplift of the land in Minnesota heralded the start of a new period called the Algoman interval. It was probably at this time that many of the Knife Lake sedimentary rocks became crumpled and altered into their metamorphic forms. At the same time huge new intrusions of magma rose beneath the surface in Minnesota and Canada, forming giant granite batholiths. Many of the granites of Minnesota were intruded at this time, including the Vermilion and Giant's Range batholiths, the Snowbank and Kekebabic granite masses, and probably many of the granites now quarried in central Minnesota.

The rocks that had formed up to this period in the earth's history, in Minnesota and in other parts of the world, are sometimes called "the basement rocks" of the earth's crust. These ancient pre-Cambrian lavas, altered sediments, and granites underlie all other rocks everywhere. If we drilled down deep enough through the surface rocks in any part of the state, or on the continent, we would eventually strike some of these earliest pre-Cambrian rocks. The Laurentian peneplain, or Canadian Shield, with its western tip in Minnesota, is the largest area in the world where these old-timers now lie at the surface, although they are also exposed deep in the Grand Canyon, in North American mountain areas, and over parts of Scandinavia, Australia, northeastern South America, and Africa south of the Sahara.

After the Algoman interval of diastrophism and volcanic intrusions, a very long period followed during which erosion was the dominant geological process. Eventually the complex mountain folds were again eroded to a plain, and a new sea, the Animikie, encroached upon the area that now is Minnesota.

This Animikian period was one of long, slow erosion and the continuous deposition of sediments in the wide, shallow sea. Sand that was deposited along the shore of the Animikie sea in the Mesabi region now forms the metamorphosed sandstone that is called Pokegama quartzite. Probably at about this time, too, other sands were deposited in the Cuyuna area and in the region from New Ulm southwestward. Today a number of counties are underlain by the Sioux quartzite formed from these sands.

In the Mesabi area the deposition of sand did not continue for very long, as geological time is reckoned, for the Pokegama formation does not exceed 200 feet in thickness (see p. 101). Instead, the sea became clearer, and chemical sediments, consisting essentially of silica, iron, and carbonates, were deposited to form the iron-bearing formation of the Mesabi Range, called the "Biwabik" from the Ojibway word for a "fragment of iron." Chemical sediments of this kind accumulate very slowly, and a million or more years may have passed in the deposition of the 700 feet of iron-bearing material that now forms the Biwabik formation.

Originally this formation was more extensive, joining the Gunflint iron formation of Cook County in an eastern extension of the Biwabik, but the continuity of the rocks was later interrupted for a distance of forty miles by the intrusion of the Duluth Gabbro. Figures 49 to 51 show how some rocks were engulfed by this magma. The Gunflint iron formation is known to extend for twenty miles in Cook County and far beyond in Canada. The Biwabik formation at present is known from Pokegama Lake in Itasca County to Birch Lake in St. Louis County, a distance of more than 100 miles.

The word taconite, now well-known in Minnesota, was first used to refer to the peculiar, complex, iron-bearing rock of the Biwabik formation. About twenty minerals are known to occur in the formation, and these vary greatly in relative abundance. There are accordingly several varieties of taconite, which we will examine more closely, along with the iron ores, in a later chapter.

After the chemically precipitated sediments of the Biwabik formation were deposited, changes in the Animikian environment produced a shallower water and a new kind of deposit in the sea — several thousand feet of clayey mud. This mud has been converted by pressure and time into a rock that is slatelike but that lacks the typical slaty cleavage. This rock formation is called the Virginia slate. In Cook County the Rove slate formation is the equivalent of the Virginia slate, just as the Gunflint iron formation is the equivalent of the Biwabik, but impure sandy beds are much more numerous in the Rove formation than in the Virginia slate.

The top of the Virginia slate is not exposed at the surface — only the tilted edges of the beds appear (Figure 51) — and its relations to younger rocks are therefore obscure. In Cook County the relations of the Rove formation are better known. Its thickness is estimated at from 2000 to 3000 feet, and in the valley of Otter Creek and in the Grand Portage region the Rove is overlain by the lowest layers of conglomerate and sandstone of the Lower Keweenawan (Figure 47).

We have come now to the last period of the Proterozoic era, the Keweenawan, and the "Lower" rocks of that period are naturally the earliest. These earliest Keweenawan rocks are conglomerates and sandstones, products of erosion and sedimentation like the iron formations and slates that just preceded them.

The relations of these first Keweenawan rocks are generally obscure, except near Duluth and at Grand Portage. The period began with the deposition near shore of a thin conglomerate, followed by deposits of sand that are not known to exceed 200 feet in thickness. This conglomerate, known as Puckwunge conglomerate, was so named because of its exposures on Puckwunge Creek in eastern Cook County. The deposition of sand was apparently brought to a close by the sudden pouring out of basalt and felsite lava flows, which may be seen lying directly on the sandstone in several places — near Duluth, south of the Pigeon River in Cook County, near the village of Grand Portage (Figure 47), on Grand Portage Island, and on Lucille Island in Lake Superior.

This outburst of great lava flows was only the beginning, for new volcanic eruptions poured out extensively on both sides of Lake Superior. Rocks of this Keweenawan period occupy a large area of Minnesota, extending from Taylors Falls on the south to Pigeon Point at the extreme northeast tip of the state on the North Shore of Lake Superior (Figure 44). Some of Minnesota's most scenic spots are within the area occupied by Keweenawan formations (Figures 11, 48, 98, 99, 100, 103, and 106).

This was the last great period of igneous activity in Minnesota, and the flows, once started, poured out intermittently until hundreds had accumulated. The total number will always remain un-

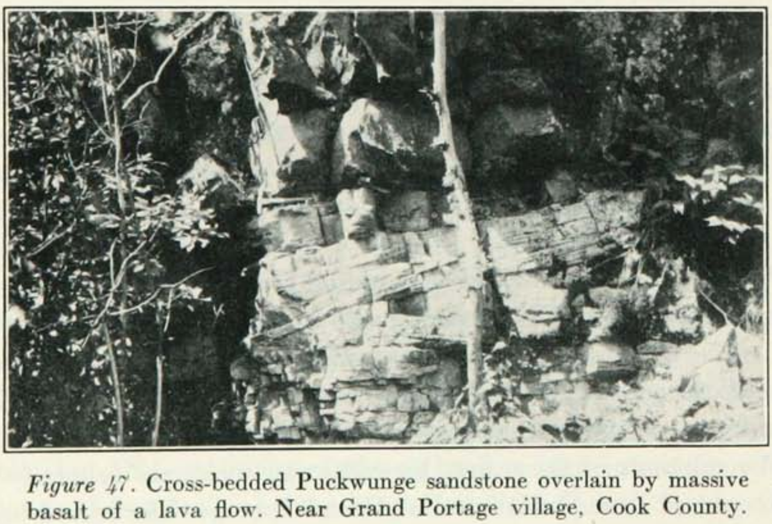


Figure 47. Cross-bedded Puckwunge sandstone overlain by massive basalt of a lava flow. Near Grand Portage village, Cook County.

Figure 48. Columnar jointing in the Beaver Bay diabase sill, U.S. Highway 61 near Split Rock, Lake Superior, Lake County.

known, because in Minnesota the later flows lie under Lake Superior, and on Keweenaw Point on the Michigan shore — the point that gave this volcanic period its name — the earlier flows have been dropped out of sight by a slippage of the earth along the great Keweenaw fault. In Minnesota, however, it is possible to count and measure a great thickness of flows from their base at the southwest edge of Duluth to the uppermost visible flow near the line between Cook and Lake counties. The top of a flow can usually be recognized by the vesicles formed by an accumulation of gas bubbles. Measurements have not yet been completed, but the number of these exposed flows approximates 300, and their total thickness is about 30,000 feet.

Flows of such extent and thickness could scarcely have come from volcanoes, but evidence elsewhere in the world shows that they may pour out of great cracks in the earth's crust, as has happened in Iceland in modern times. It is probable that the flows often followed each other in rapid succession; but at times an interval of erosion and deposition occurred, and sands and pebbles accumulated on top of one flow before another followed. An example of this sandwiching occurs about four miles west of Grand Marais, where a red sandstone lies between the lava flows and forms low cliffs along the highway. After the vesicular tops of lava flows were hardened, hot waters from other volcanic events often deposited silicon dioxide and other substances in the vesicles, thus forming agates, thompsonite, and other interesting minerals.

On Keweenaw Point in Michigan we can learn something of the late stages of these great lava outbursts. As the outpourings of lava continued, the frequency of the volcanic activity evidently subsided, allowing conglomerates and sands to be deposited between more and more of the flows. Eventually the thickness of the individual sand beds increased until the sedimentary deposits exceeded the lava flows in thickness, and finally the flows ceased and only sandstone accumulated. This deposition of the sands of late Keweenawan time is represented in Minnesota by the Fond du Lac and Hinckley sandstones and farther south by the so-called "red clastic" sediments found in deep well borings. These sediments are called clastic because they are fragmental rather than chemical in origin. At some places these deep-lying sedimentary rocks are over a thousand feet thick.

This account of the events of Keweenawan time has so far omitted one of the most important episodes of the entire period, one that took place, however, beneath the surface of the earth. As the great thickness of lava flows accumulated, it evidently became difficult for subsequent molten material to force its way to the surface. Instead, large amounts of magma were forced between the flows to form sills, or cut upward across the flows to form dikes (Figure 52).

Eventually a huge mass of magma forced its way between the older rocks and the base of the Keweenawan flows. Thus was formed the Duluth Gabbro, one of the largest intrusions of gabbro in the world (Figures 50 and 51). This huge mass of molten material, called a lopolith, was shaped like a giant underground basin (Figure 49). The first part of the word "lopolith," derived from the Greek, means "basin" and the last part means "rock." It continued to cool for thousands of years, and during this time a certain amount of

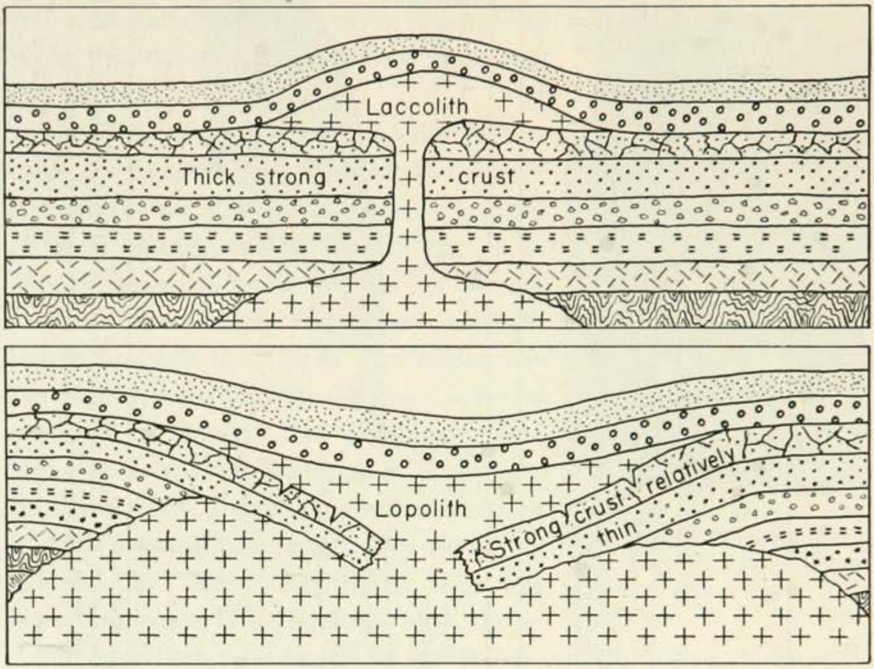
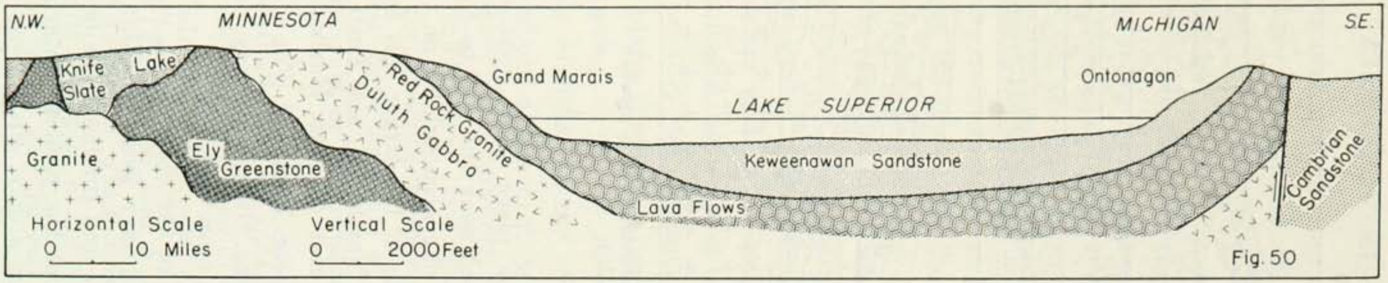


Figure 49. Diagram showing the possible origin of a lopolith by collapse of a laccolith.

segregation of the lighter material took place. This light-weight fraction floated upward and accumulated near the top to form a "red rock," a type of granite, much as slag accumulates on top of the molten iron in a blast furnace. Some of the larger sills formed during this episode include the Endion, Northland, and Lester sills at Duluth, the Silver Creek Cliff sill east of Two Harbors, the Beaver Bay sill (Figure 48), and the Pigeon Point sill. For a closer look at the Duluth Gabbro and its origins, the reader may turn to pages 201–207, where its story is told in more detail.

The magma forced its way into some of the older rocks, notably the Rove slate along the Canadian boundary from Gunflint Lake to Pigeon Point. Literally dozens of large and small sills lie between the slaty beds in that area, and at places the molten material cut across the beds along a fracture to form a dike. Prominent ridges



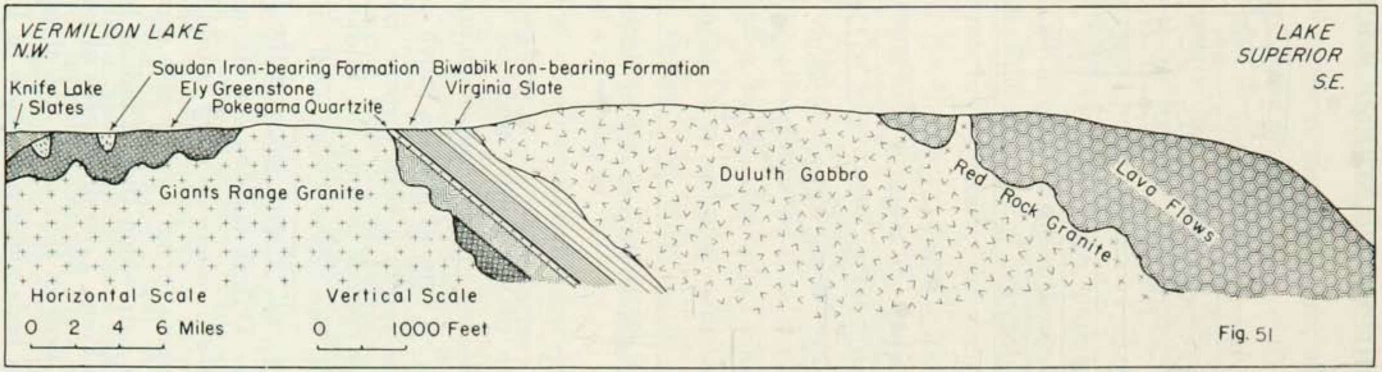


Figure 50. Cross section of Lake Superior basin showing the Duluth Gabbro lopolith. *Figure 51.* Cross section from Lake Vermilion to Lake Superior showing the detail of the Duluth Gabbro lopolith and associated formations.

and waterfalls result wherever these dikes project above the slate, which is more easily eroded.

Figure 52. Basalt dike in lava flow, lake shore at Seventh Avenue East, Duluth.

The Keweenawan period and the Proterozoic era came to an end as all the eras of geological time have ended — with a great physical change on the face of the earth and subsequent readjustments by all the forces of nature. This time it was the Killarney orogeny that lifted and folded the continental crust, but the diastrophic forces centered in Ontario and Wisconsin. The high mountain ranges missed Minnesota this time, but instead a great downward fold of Minnesota's recent lava flows developed, and the rocky trough that was later to become Lake Superior took shape.

The new high land began its inevitable loss to erosion during the long interval that followed. Then gradually another chapter in Minnesota's history began to be recorded; but this time the new era brought a crucial difference. With the Cambrian seas of the new Paleozoic era, plant and animal life appeared for the first time in great abundance. Earlier rocks had borne some scanty indications that primitive algae-like forms of life already existed, but there were few direct proofs. Now one of the earth's critical turning points was reached, for with the Paleozoic era, life on earth developed in fantastic variety and profusion.

CHAPTER

6

Minnesota under Paleozoic Seas

THE geological history of the earth had already covered one and a half billion years before the Paleozoic era began about 500,000,000 years ago. The Archeozoic and Proterozoic eras were vastly longer than any that have followed, and the physical changes and time spans of those eras may seem too immense for our minds to grasp. In contrast, the Paleozoic era lasted only about three hundred million years, a more comfortable span for our imaginations, and its physical history in Minnesota was mostly calm and placid.

All through Paleozoic times North America was washed by repeated invasions of shallow, shifting, epicontinental seas. Even when Minnesota and other parts of the continental interior stood raised above the waters, their elevation was not great. In northeastern Minnesota and up through Canada most of the broad, stable back of the Laurentian peneplain probably remained above the seas, and during all the eras that followed this ancient plateau was never again entirely submerged. The level face of most of the land and the wide, shallow waters had a tempering effect on the climate, and as the mild, uneventful centuries passed, life in the warm seas multiplied at a spectacular rate.

The term Paleozoic means "ancient life," and the era is well named. During those few hundred million years innumerable kinds of water and land plants developed, and animals belonging to every phylum and class except the mammals (see accompanying classification) appeared on earth and left their fossil remains. The great abundance of marine invertebrate fossils in the earliest Paleozoic rocks is evidence that the ancestors of these forms of life must have lived even before the Cambrian period. Life could not possibly have sprung up so fully developed from the start, and in such diverse forms. Why there are so few traces of these more primitive ancestors in the older pre-Cambrian rocks is still not well understood.

A SIMPLE CLASSIFICATION OF ANIMAL LIFE — PHYLA AND CLASSES

(Beginning with most primitive)

PROTOZOA
- amoeba
- foraminifera
- radiolaria

PORIFERA
- sponges

COELENTERATA
- corals
- jellyfish
- graptolites

VERMES
- worms

ECHINODERMA
- crinoids
- starfish
- sea urchins
- blastoids
- cystoids

BRACHIOPODA
- lamp shells

BRYOZOA
- moss animals

MOLLUSCA
- pelecypods (clams, oysters)
- gastropods (snails)
- cephalopods (nautilus, squids)

ARTHROPODA
- crustaceans (lobsters, trilobites)
- insects
- myriapods
- centipedes
- arachnids (spiders, scorpions)

VERTEBRATA
- ostracoderms (extinct fish)
- fish
- amphibians
- reptiles
- birds
- mammals

The Cambrian Period

Each new Paleozoic invasion of the sea left a record of sedimentary beds with enclosed fossils of the life of the time the sediments were deposited. By reconstructing the environment in which the rocks were formed, the probable history of a given period of the era can be determined. The Cambrian was the first period of the Paleozoic era, and it in turn is usually divided into three parts — Lower, or early Cambrian; Middle; and Upper, or late. The advance of the Cambrian seas over the continent was undoubtedly very slow, for there are no Lower or Middle Cambrian marine sediments in Minnesota. The age of the Hinckley sandstone and the Fond du Lac sandstone and shale beds has not been established definitely, but they probably are deposits of the late Keweenawan period (see p. 101).

It is very probable that Minnesota remained above water, and subject to continuing erosion, during the first part of the Cambrian period. Only later, toward the end of Cambrian times, did the sea encroach, covering all but the most northern and northeastern part of the state. Possibly much of that area was also covered and the sediments later eroded away. We do not know whether the advance of the sea occurred because the central area of North America was gradually and uniformly depressed, or because the level of the sea was significantly raised. At any rate, during the late part of the Cambrian period marine water flooded more than 35 per cent of the continent (Figure 53), and an extensive series of sedimentary beds were deposited in Minnesota (Figures 54, 55, and 56).

The positions of the shorelines of such epicontinental seas are not stable; rather, they advance and retreat with many fluctuations and eventually reach their maximum extent. The time required for such a great inundation to reach its climax may be several million years. If the land over which the water advances has very little relief, a downward movement of only a few feet would submerge a large area of the continent. Similarly a comparatively small upward movement of the land would cause a widespread retreat of the marine waters. If the continent of North America should sink at the rate of one inch per century, for example, at the end of about 700,000 years the total sinking would amount to 600 feet. The difference of those few feet would bring the sea up the Mississippi Valley almost to southern Minnesota. The river valleys tributary to the Mississippi would make a system of gulfs, bays, and estuaries much like Chesapeake Bay, and many of the states bordering the Atlantic Ocean and the Gulf of Mexico would be entirely submerged.

Such movements and changes are going on constantly. The coast-

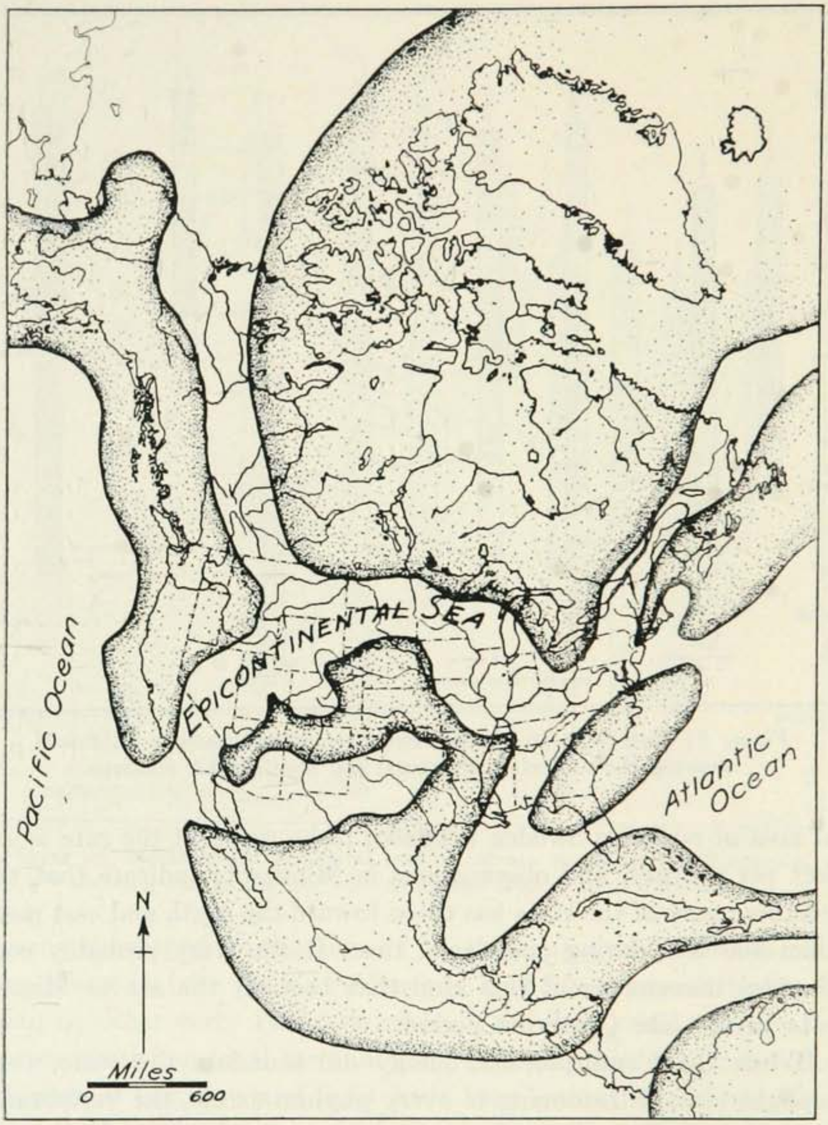


Figure 53. Map showing distribution of land and sea in North America during Upper Cambrian (St. Croixian) time. Land areas are dotted.

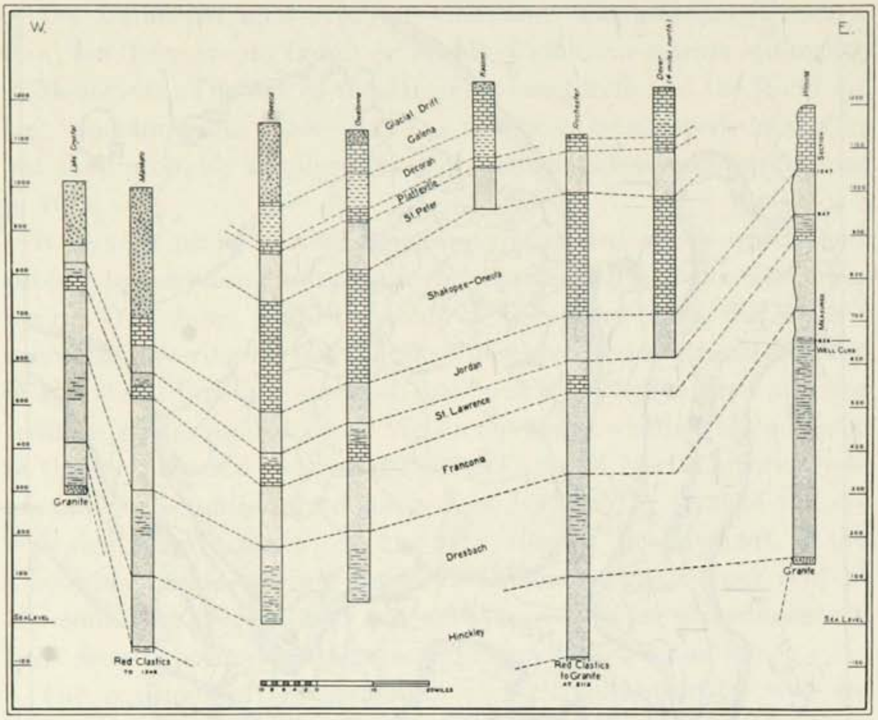


Figure 54. East–west geological section across southeastern Minnesota, showing the subsurface structural and stratigraphic relations.

al area of northern Sweden is known to be rising at the rate of six feet per century, and observations in Minnesota indicate that the northern part of the state has tilted toward the south and east more than 100 feet during postglacial time. It was very probably continental movements of this kind that brought the sea to Minnesota in the late Cambrian period.

When the Cambrian seas finally did inundate the state, they brought animals belonging to every phylum except the vertebrates (see p. 119). Their fossils appear in many Cambrian rocks in such vast numbers and varied forms that paleontologists are convinced that animals were living beyond the present continental areas not only during the long erosion interval between the Cambrian and older rocks, but also during the earlier eras. Fossil evidence indicates that nearly nine tenths of all significant structures in animals had

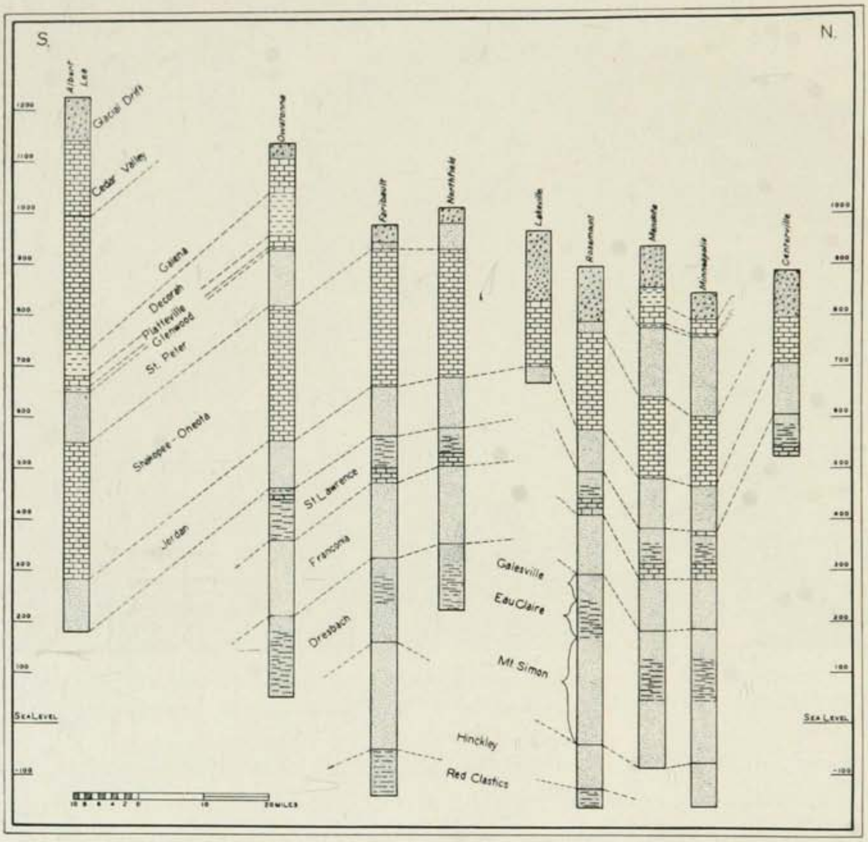


Figure 55. North–south geological section across southeastern Minnesota, showing the subsurface structural and stratigraphic relations.

already developed at the time of the beginning of Cambrian history. There is, however, no evidence of land life in any of the Cambrian or other early Paleozoic rocks. The warm, saline sea water was evidently an ideal medium for developing organisms, but the expanses of low, flat land must have been rather forbidding, without a blade of grass or tree or single moving animal among the barren rocks.

Two groups of animals that were of great importance throughout most of the Paleozoic era are the brachiopods and the trilobites. Brachiopod fossils are very abundant at several levels in the beds of Cambrian rocks of Minnesota, and a relatively small number of

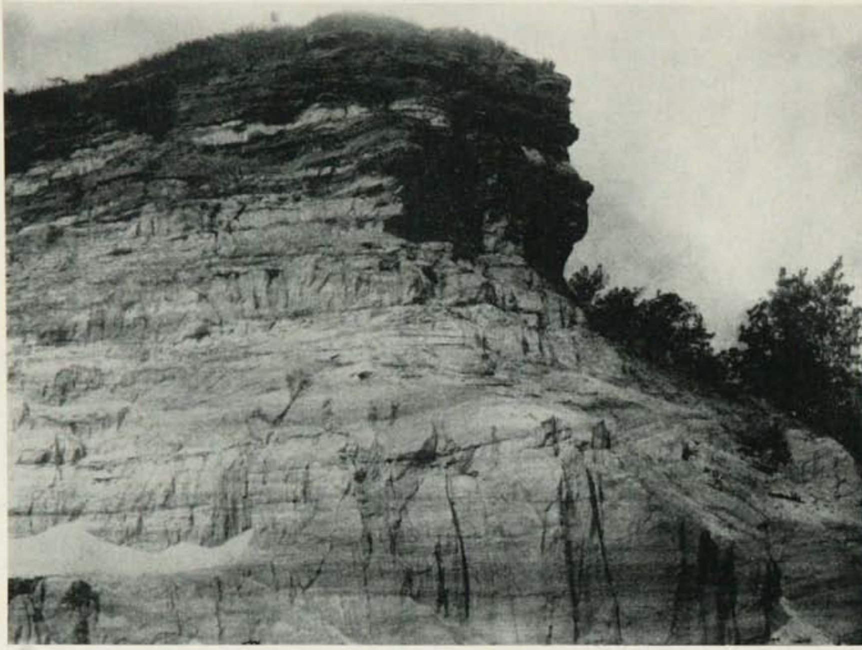


Figure 56. The Jordan sandstone capped by basal Oneota dolomite at sand mine of the Red Wing Filter Sand Co., Red Wing, Goodhue County.

these animals still exist in the sea today. The brachiopod is an animal that is enclosed in a bivalved shell, but the two units of the shell are quite different from those of the clam or oyster. The upper shell is somewhat smaller than the lower, and the two are hinged together at one end rather than on the side as is the case with the clamshell (Figure 57). At the posterior of the lower shell there is an opening through which a fleshy stem or stalk projects. The animal attaches itself to rocks or other objects in the sea by means of this stalk. The organism in the shell consists of a skin which lines the shell, digestive and circulatory systems, and two spirally coiled ridges or "arms." The ridges are really a pair of gills, which have rows of hairlike tentacles that wave in the water to set up currents and sweep minute organisms toward the mouth.

Brachiopods made their first appearance in the Cambrian seas, and before the period was ended they constituted about one third of the Cambrian fauna. They reached their climax of development

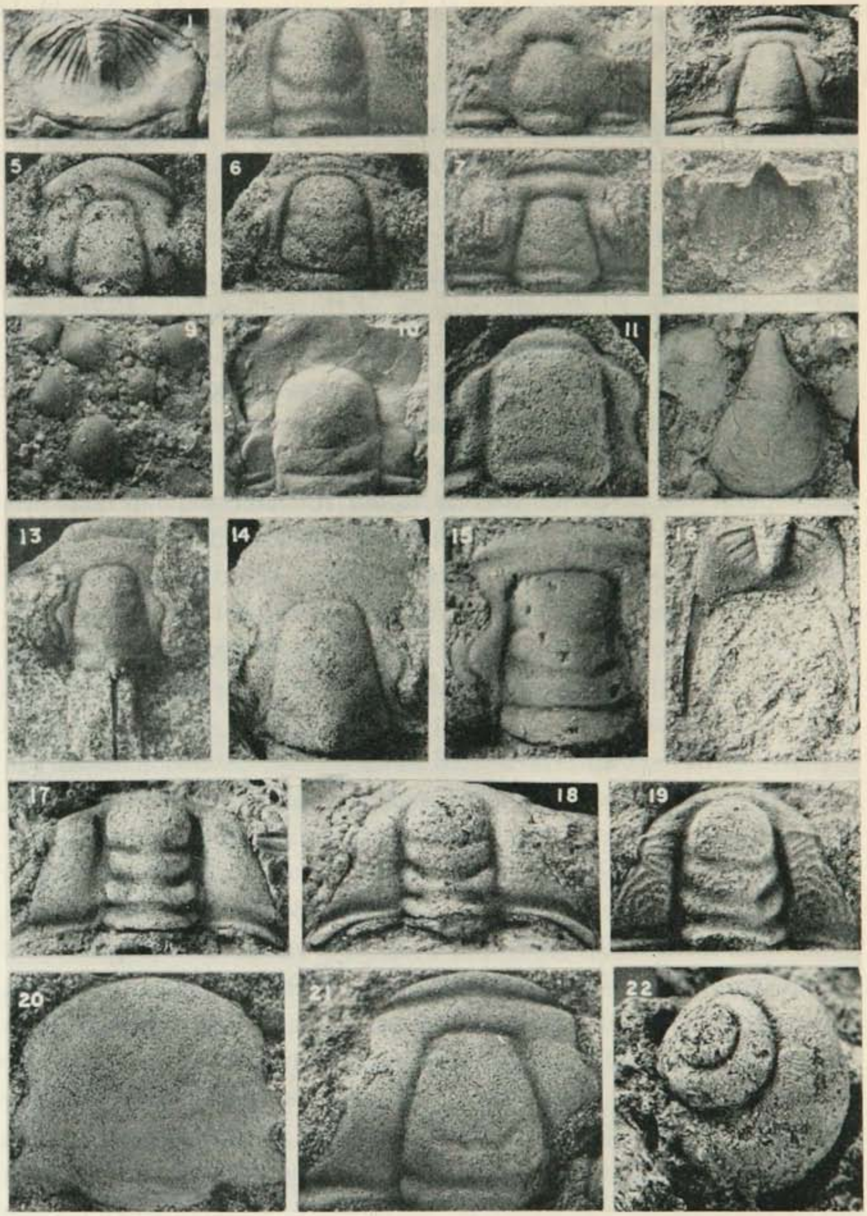


Figure 57. Typical fossils found in Cambrian rocks of Minnesota. Numbers 1 and 16 are tails of trilobites; 2–7, 10, 11, 13–15, and 17–21 are heads of trilobites; 8, 9, and 12 are brachiopods; and 22 is a gastropod.

during the Devonian period of the Paleozoic era, and for hundreds of millions of years they were an abundant form of life in the sea. Their fossils are so widespread and their various forms so characteristic of different geological epochs that some of them have long been favorite fossils for correlating and determining the age of marine sedimentary rock formations.

The trilobites, the other major group of Cambrian fossils, were the undisputed rulers of the Cambrian seas. They were the largest and most highly developed animals of their time, some attaining a length of nearly two feet. These curious-looking, segmented animals had bodies that were divided into three flattened, longitudinal lobes (Figure 57). Their heads were covered by shieldlike plates and they had a pair of compound eyes, each with thousands of lenses. The thorax and abdomen had an upper chitinous shell, which was segmented; the last few segments were cemented together to form a tail shield. They belonged to the phylum Arthropoda, which includes such other segmented animals as the lobster and crawfish. The trilobites reached the climax of their development in the early Paleozoic and then gradually declined toward the end of the era, when they became extinct.

Other forms of life represented as fossils in Cambrian rocks are snails, sponges, and worms. The Cambrian plants consisted of single-celled algae and several types of algal seaweeds.

In Minnesota the rocks in which these various fossils are found are all of the Upper Cambrian epoch, since no earlier Cambrian rocks were formed. These Upper Cambrian rocks lie mostly in level sedimentary strata in the central and southern parts of the state, just as their original sands and silts were deposited in the shallow Cambrian seas (Figures 54 and 55). The term "St. Croixian series" has been applied to them because of their easily studied exposures along the St. Croix River Valley. The formations that make up this series have much in common. They are mainly sandstones with interbedded shales and siltstones. Glauconite, a green, hydrous silicate mineral, occurs throughout the series, but it is rare in some localities and very much concentrated in others, where it forms a green sandstone called greensand. Some of the sandstone beds grade into sandy dolomite, and in some places the beds are very rich in fossils.

The four rock formations that make up the St. Croixian series — Minnesota's only Cambrian rocks — are known as the Dresbach formation, the Franconia formation, the St. Lawrence formation, and the Jordan sandstone (see p. 100). The Dresbach formation is the oldest and lies below the others, and the Jordan sandstone is the youngest and lies on top of the group. All are named from the places in Minnesota where they were first studied and best exposed.

The Dresbach formation consists of light-colored, fine- to coarse-grained sandstones, occurring in thin to massive beds. The beds contain varying amounts of glauconite and sometimes approach the texture of shale. The middle, fine-grained portion of the formation contains an abundance of marine fossils. Outcrops of these sandstones occur in the valley of the St. Croix River, along the lower portion of the Mississippi River bluffs from Minnesota City southward, and up the Root River Valley as far as Hokah. The formation also lies directly beneath the glacial drift over a wide zone in southwestern Minnesota, where all the later-formed rocks have evidently been worn away by long erosion.

The Franconia formation contains the strata of the St. Croixian series that are high in glauconite and is therefore often referred to as the greensand and green shale "horizon." The color of the formation varies greatly, however, from green to pink to buff, white, and brown. The lower part of the formation is a medium to coarse, yellow to brown sandstone. At places the upper beds of the sandstone are very fossiliferous, with an abundance of brachiopod shells and trilobite fragments. The thickness of this sandstone portion ranges from 25 to 45 feet, and in many localities it is difficult to distinguish the lower part of this sandstone from the upper sandstone strata of the Dresbach formation. The upper part of the Franconia formation in general contains the most glauconite. It is a sandy siltstone that is characterized by numerous worm trails and burrows which tend to obliterate the original planes between the beds of sediment. This part of the formation is well exposed along the Mississippi River bluffs from Frontenac southeastward.

The St. Lawrence formation varies a great deal in composition, from dolomitic sandstones and siltstones in some places to dolomitic and glauconitic limestone elsewhere. The upper part of the formation contains beds of a buff to ash-colored siltstone which is famous for its fossils of trilobites and graptolites. The latter creatures, now extinct, were early coelenterates, somewhat related to the modern corals and jellyfish, which left their remains looking like carbon hieroglyphics on the rocks. These fossil-bearing beds are widely distributed and easily recognized along the St. Croix and Mississippi rivers. Excellent outcrops may be seen in Fairy Glen at Stillwater and at La Grange Mountain (Barn Bluff), Red Wing (Figure 139).

The Jordan sandstone is the uppermost formation of the St. Croixian series. It is a light-colored sandstone ranging from 90 to nearly 110 feet in thickness and is exposed in the Mississippi and Minnesota river valleys and along tributary streams. It is a conspicuous rock high up in the bluffs, where it usually forms a vertical face beneath the capping of Oneota dolomite, the earliest rock of the next geological period — the Ordovician (Figure 56). To the west of the Mississippi Valley the Jordan is deeply buried beneath younger rock. The sands of the Jordan formation are well sorted and poorly cemented. Because of the absence of cementing materials between the sand grains, the rock is highly porous and permeable and serves as an ideal reservoir for underground water. It is the chief source of water for the hundreds of artesian wells in the Twin Cities basin and in counties between the valleys of the Minnesota and Mississippi rivers.

The Ordovician Period

In North America the Cambrian period ended as it had begun, quietly and with no great disturbances of the earth. But in Europe and elsewhere in the world, volcanic action and mountain-building changed the face of the globe enough to cause a gradual withdrawal of the Cambrian seas in North America. The epicontinental seas returned very soon, however, to start the Ordovician period of the

Paleozoic era, causing hardly a break in the long record of quiet sea deposits over most of North America. During the millions of years of Ordovician time, the seas advanced intermittently farther and farther (Figure 58). Clear arctic oceans spread southward to join an extension of the Gulf of Mexico and another arm from the Pacific Ocean, until at the time of maximum submergence fully 60 per cent of the continent lay below marine waters.

The sediments deposited in these epicontinental seas were varied, but in Minnesota muds and fine calcareous sediments must have been more abundant than the coarser sands, since most of Minnesota's rocks of this period are mud-compacted shales and limestones rather than sandstones. From the nature of these rocks geologists have concluded that the land areas were unusually low, and that the rivers were too sluggish to carry heavy loads of sands and gravels. Great hordes of marine creatures inhabited the seas, and fossils entombed in the Ordovician rocks represent all major animal groups up to and including the fishes (see p. 119 and Figure 59).

These Ordovician seas literally swarmed with life. Paleontologists have reported more than 1600 species of animals from the middle Ordovician rocks alone. There are few systems of rocks that contain a fuller record of marine forms in as good a state of preservation — probably a result of the mild climate and quiet waters, which did not disturb the animal corpses once they had fallen to the sea floor and been buried by sediment.

The rock collector, in comparing a piece of Cambrian rock with one from the Ordovician period, each containing typical animals, will find that the fossils of the first will almost all be brachiopods and trilobites, whereas the Ordovician rock will have, in addition, cephalopods, crinoids, and several other animal types. Trilobites and brachiopods are considerably more abundant in Ordovician than in Cambrian rocks, but they no longer dominated the life of the seas. It was an increase in other types of life, rather than a decrease of these forms, that ended their dominance.

The largest and most powerful of the earth's inhabitants during the Ordovician period were the cephalopods, of which the pearly nautilus and the octopus are modern representatives. During the

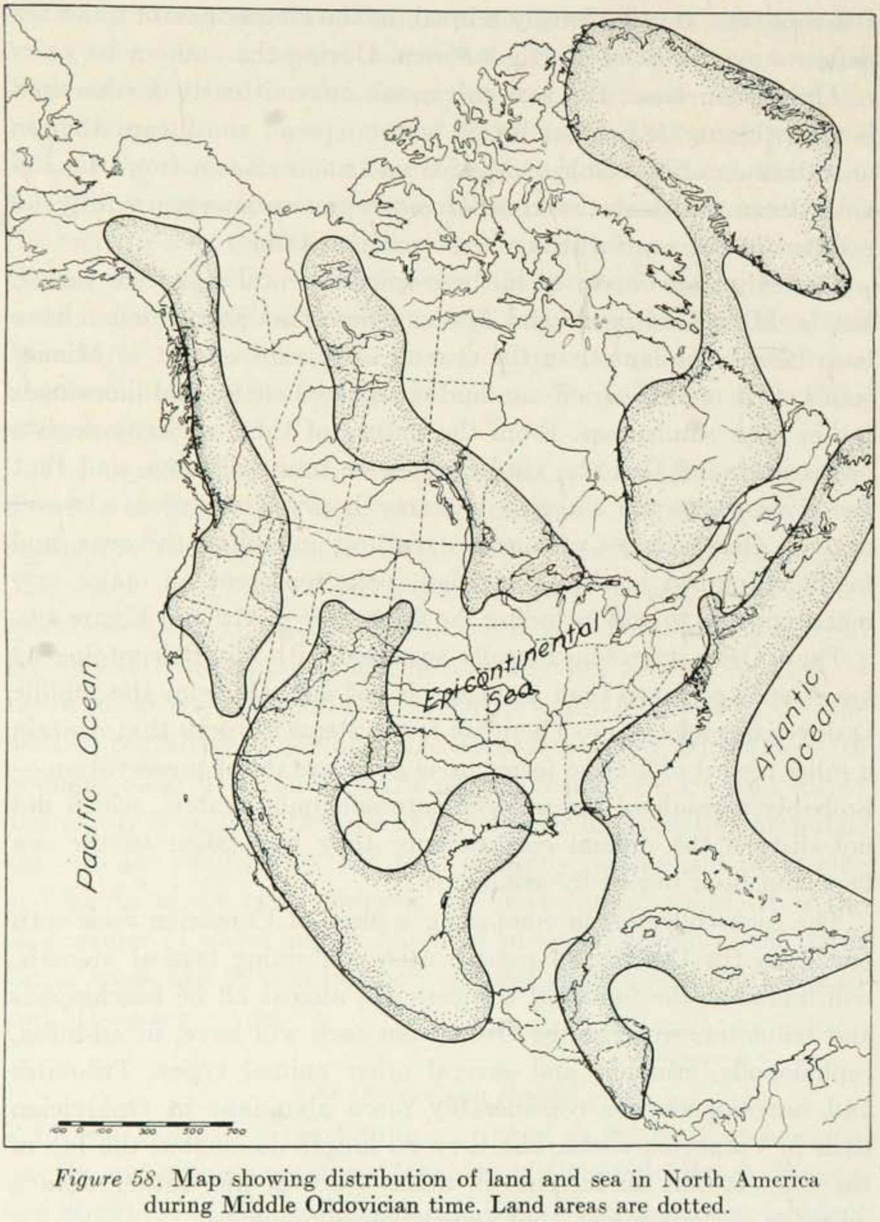


Figure 58. Map showing distribution of land and sea in North America during Middle Ordovician time. Land areas are dotted.

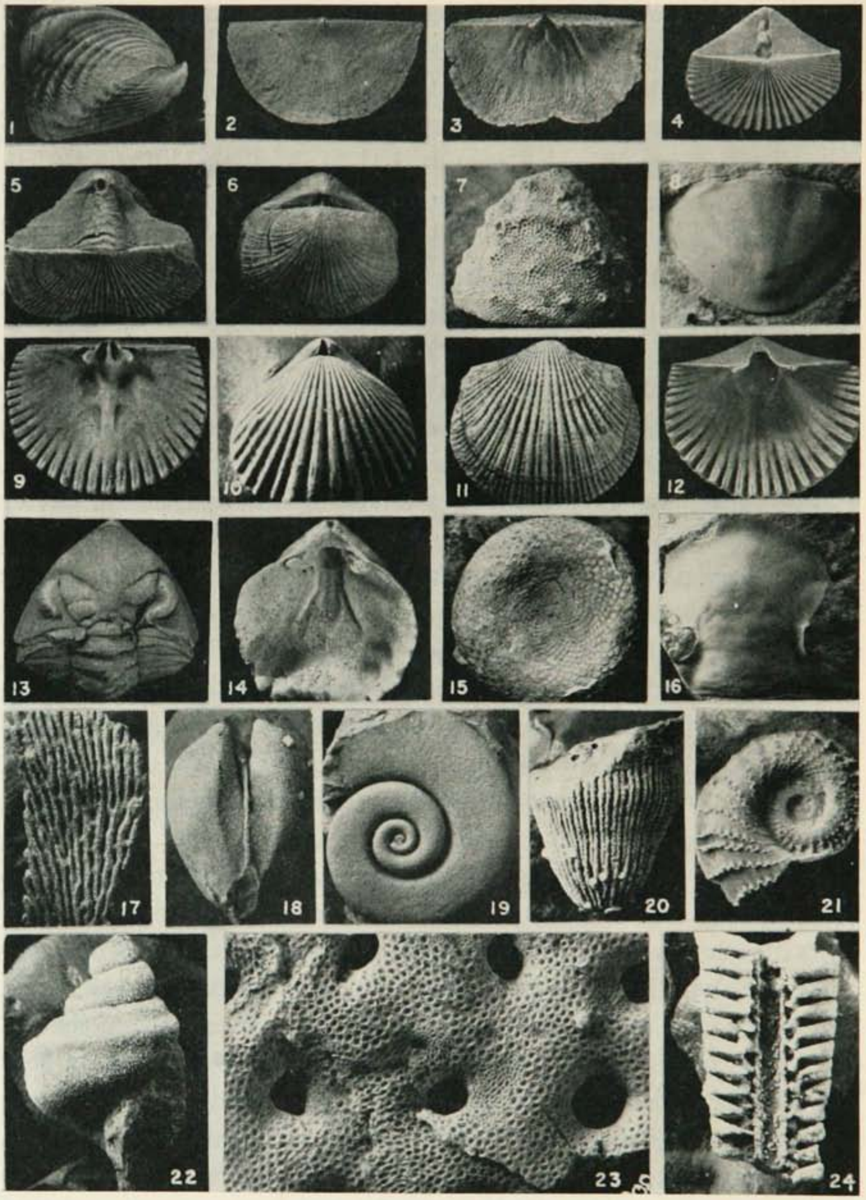


Figure 59. Typical fossils found in Ordovician rocks of Minnesota. Numbers 1–6, 9–12, and 14 are brachiopods; 7, 17, and 23 are bryozoa; 8, 13, and 16 are parts of trilobites; 15 is a sponge; 20 is a coral; 19, 21, and 22 are gastropods; 24 is a cephalopod; and 18 is a pelecypod.

first part of the period, the cephalopods were represented only by small and inconspicuous individuals, but by middle and late Ordovician times some of the straight-shelled types were more than a foot in diameter and twelve to fourteen feet long. The early, small varieties had conelike shells, and as they developed, the cone increased in length and became a long, slender, straight shell. As the individual cephalopod grew, it added to the length of its shell and left the older, slender part unoccupied, thus eventually forming a "chambered" shell like that of the chambered nautilus.

Sponges were also very common in Ordovician time, and a few of them are valuable for correlation with rocks in other areas. One of the most important is the "sunflower" sponge (*Receptaculites*), so called because its markings resemble the pattern of the seeds in a large sunflower. These animals are now classed as sponges, but in those early times they may have represented an entirely distinct class of organisms. Cross sections of large specimens of these disclike animals appear in the rocks as serpentine objects as much as a foot long, and are sometimes called fossil "snakes." They are fairly common in the middle Ordovician Galena limestone, where they may be seen in the walls and on the ledges of quarries.

The Ordovician echinoderms are represented by abundant fossils of crinoids, or "stone lilies," named for their resemblance to plants. Crinoids have long, slender stems on the upper end of which is an oval, bud-shaped organism that supports a crown of feathery arms or tentacles. They stir the water with these arms and create currents to waft particles of food to their mouths. Crinoids are rare at the present time, but they grew in great profusion in the warm Ordovician seas and for long ages thereafter. In many places the sea floor was carpeted with these graceful, flower-like forms, like a field of long-stemmed lilies. The bottom-attached crinoids are relatives of the higher, free-moving classes of echinoderms, such as the starfish and sea urchins; but although these forms were present in the Ordovician sea, they left few fossil remains.

Marine plants are represented in Ordovician rocks by calcareous, or lime-secreting, algae, which were widespread and fairly abundant, especially during the time of the deposition of the earliest

Ordovician dolomites. The algal remains consist of calcareous masses that are varied in size and irregularly rounded in shape. They show a finely laminated, concentric structure that stands out conspicuously on weathered rock surfaces. Some clusters are so large that they form domelike masses called "cryptozoon domes" or reefs.

There is very little difference between the marine faunas in Ordovician rocks on the islands of arctic Canada and those from rocks of similar age in the southern part of the United States. Thus definite climatic zones, such as characterize the modern world, do not seem to have existed during the Ordovician period. We know that the sea is an equalizing climatic factor, whereas large land areas, especially those having mountains, are characterized by climatic variations, both in temperature and humidity. We can therefore be quite sure that times of extremely widespread shallow seas and low-lying lands were marked by a relatively warm and even climate. These conditions applied generally to the Ordovician period and were undoubtedly a factor in the prolific life of the shallow seas.

In Minnesota the sedimentary rocks of Cambrian age in general grade almost indistinguishably into the Ordovician strata. This gradual change can be seen at the contact between Cambrian and Ordovician rocks exposed along the bluffs of the Mississippi River. We may interpret this fact to mean that there was no complete retreat of the sea in this area, and that continuous deposition took place, without interruption, from the sandy sediments of the Cambrian to the fine-grained dolomites of the Ordovician. In the valley of the Minnesota River, however, the change is more abrupt, and there was probably a period of erosion between the withdrawal of the Cambrian and the advance of the Ordovician seas.

The Ordovician rocks in Minnesota are listed on page 100. They consist of dolomites, limestones, sandstones, and shales, compacted from very fine marine sediments, with a few of the coarser sandstones lying between. Like the Cambrian rocks, their locations are limited mainly to the southern parts of the state.

The Oneota dolomite, the oldest Ordovician formation in Minnesota, is thick-bedded, buff or pink in color, and sometimes sandy or shaly. In many places it is porous or even cavernous, with huge, calcite-lined pockets and many cavities and joints lined with quartz crystals. In the southeastern counties, in the bluffs of the Mississippi and its tributaries, there are extensive underground channels through the dolomite, dissolved out by ground water (Figure 134). Some of these channels reach the dimensions of caves and are penetrable for some distance. Many of the small shapeless cavities in the Oneota dolomite doubtless represent molds of fossils that are no longer recognizable because of the extent of solution of the surrounding rock. That this is true is indicated by occasional molds which may be traced through every stage of decay from easily recognized fossil molds to irregular holes or cavities.

The thickness of the Oneota formation varies greatly, from about 45 feet at Mankato to over 150 feet in the region of Albert Lea and Austin. Outcrops may be seen along the Minnesota Valley and along the St. Croix and Mississippi rivers. This dolomite caps the bluffs (Figure 139) over much of this area, and many fine exposures may be seen where the tributaries of the Mississippi River have cut their valleys down through the formation.

The white Root Valley sandstone, the next oldest Ordovician layer, lies between the Oneota and Shakopee dolomites. It ranges in thickness from a few inches to as much as 40 feet. In general appearance this sandstone is very similar to that of the Cambrian Jordan sandstone and the later St. Peter sandstone. Its resemblance to the Jordan sandstone, both in appearance and mineral constituents, together with its geographic distribution, suggests that the Root Valley sands were eroded from the earlier Jordan sandstone and were deposited as a series of sand bars in the early Ordovician sea. In Winona, Fillmore, and Houston counties, hard, angular blocks of the sandstone, where it is exposed on the high land, may be seen strewn over the surface. These are well-cemented residual boulders that have resisted weathering.

The Shakopee dolomite overlies the Root Valley sandstone. It is much more similar to a limestone than is the Oneota dolomite, and its lower beds are sandy. Because of its high lime content it was formerly quarried and burned to produce quicklime for plaster, mortar, and other building materials.

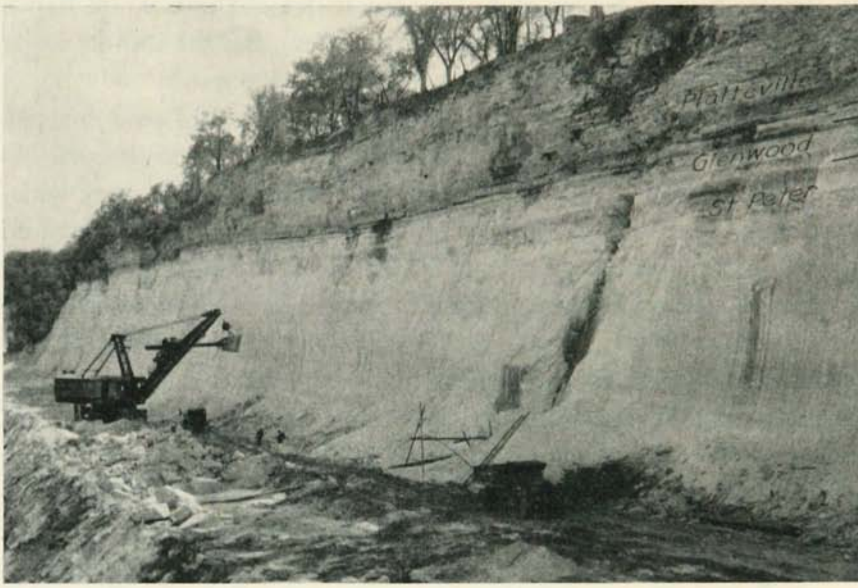


Figure 60. The Platteville limestone and Glenwood beds overlying the St. Peter sandstone at Soldiers' Home, Mississippi River, Minneapolis.

Next highest in the Ordovician layers is the St. Peter sandstone, named for the steep bluff of the St. Peter River — now the Minnesota River — where it joins the Mississippi at Fort Snelling. The St. Peter sandstone is composed of clean, white grains of quartz and is one of the purest quartz sand formations in the world (Figure 60). The sand is so poorly cemented that in many localities it may be scooped up like sugar or blown from place to place by the wind. The sand grains are well rounded, well sorted, and usually white, but sometimes stained yellow or brown by the oxidation of small pyrite concretions or by the percolation of iron-bearing waters from the rocks above it.

The St. Peter sandstone varies from 75 to 175 feet in thickness. It underlies the greater part of the area between the Minnesota and Mississippi rivers; and in the region from St. Paul southward to Northfield, it is generally found directly below the glacial drift, or with a thin layer of limestone over it. From Northfield eastward to the Mississippi Valley and along the valley of the Cannon River, the St. Peter sandstone is conspicuously exposed in the flanks of the flat-topped, mesa-like hills and in the valley walls.

On top of the St. Peter sandstone lies a thin bed of pale greenish shale, called the Glenwood shale (Figure 60). Even though no more than three or four feet thick, these shale beds are very widespread geographically. The lower layers contain much sand, and the upper beds carry typical Platteville limestone fossils. This shale, in fact, is sometimes regarded as a lower layer of the Platteville formation.

The Platteville limestone, next highest in the geological column, is the dolomitic limestone that lies above the Glenwood shale and below the Decorah shale. It ranges from several feet to more than 40 feet in thickness, and its lower beds are separated by shaly partings. On fresh surfaces the limestone is pale blue or gray in color, but where it has been exposed to weathering its color is changed to tan or buff. In many places the upper beds of the Platteville limestone are rich with fossils, and a great number of brachiopod shells are preserved as molds. The interiors of these molds are blackened by the presence of finely divided pyrite, and some contain small crystals of calcite and quartz that sparkle when the cavities are broken open. The Platteville limestone crops out above the white St. Peter sandstone more or less continuously in the walls of the Mississippi gorge below St. Anthony Falls in Minneapolis to the Robert Street Bridge in St. Paul, and can also be seen on both sides of the Minnesota River for a short distance above its mouth. It is quarried extensively near the Twin Cities.

More shales follow the Platteville limestone, and the term "Decorah" is applied to all of these shale beds, ranging from 20 to 90 feet, between the Platteville and Galena limestone strata (see p. 100). The lower few feet of the Decorah shale are composed of beds of alternating blue limestones and blue to green shales. The upper portion of the Decorah is closely related to the Galena limestone that lies on top of it. For the sake of convenience, however, all these shales are treated as a unit. Basically they are calcareous or limy shales with numerous layers of shaly, shell limestone. The lower layers contain an abundance of fragments of bryozoan, or moss animal, fossils which at certain localities form veritable reefs. On weathered slopes where much of the clay in the shale has been washed away, broken stems or branches of the bryozoa occur as a residual concentration.

Another unusual feature in the shale is the occurrence of layers of bentonitic clay — several inches of altered tuff or volcanic ash that settled on the floor of the Ordovician sea from some isolated volcanic explosions. The thin beds in the Decorah occur throughout southeastern Minnesota wherever the lower part of the shale is exposed, and they have been reported also in Iowa, Illinois, and Wisconsin.

The Decorah shale grades upward into the Galena limestone, the thickest and purest limestone in Minnesota. This lime rock, which is evenly bedded and has a bluish or gray to buff color, varies from a fine-grained and compact rock in the lower part to one that is more porous and dolomitic in the upper third. In some localities it is more than 200 feet thick. The rock forms a great many precipitous and castellated bluffs along the creeks and canyons in Fillmore and Olmsted counties, and occasional rock chimneys of the Galena limestone, like Eagle Rocks near Forestville, stand isolated in the valleys.

The upland areas that are capped by this limestone are pitted with sinkholes, and many of the stream canyons disappear upstream in a succession of sinks which become smaller and smaller and more and more distantly spaced as one approaches the general prairie level. In the region of Fountain, Preston, and Harmony, a number of these sinks serve as openings to underground caverns — for example, the Underground Niagara southwest of Harmony.

Latest of all the Ordovician rocks in Minnesota is the Maquoketa formation, part gray to bluish-gray limestone and part blue to brown shale interbedded with each other to a total thickness of 50 to 75 feet. The formation covers a relatively small area in several of the southeastern counties, in some places being covered by the glacial drift and in others by later Devonian limestones and small remnants of Cretaceous strata. It is well exposed in the walls of a quarry a short distance southeast of Clinton Falls, and occurs almost continuously along the highway that parallels the railroad east of Spring Valley. An excellent section of the formation is exposed in the walls of Mystery Cave near Spring Valley (Figure 148).

Maquoketa limestones and shales were the last Ordovician rocks to form from the water-borne lime and mud sediments, for now a new diastrophic uplift toward the east coast of North America — the Taconic disturbance — caused the great Ordovician seas to withdraw from Minnesota. The next period, the Silurian, was still one of generally low land masses and epicontinental seas, but part of the North American continent evidently stood high enough to keep all of Minnesota above the seas. There are no Silurian rocks or deposits in Minnesota, not even remnants, and most of the next period, the Devonian, is missing too.

This discontinuity in the column of Minnesota's sedimentary rocks indicates a long span of time after the Ordovician period, maybe as long as 50 million years, during which erosion was the only major geological process at work in Minnesota. Much was happening elsewhere in the still warm and teeming seas, and new land life probably started to appear on Minnesota's drying sediments; but winds and rainfall erased all traces of what happened. The next rocks laid down in Minnesota are middle or late Devonian in age. They lie on top of the Maquoketa formation in strata so nearly parallel to it that we know that no folding or tilting of the earth's crust took place in the region during the long intervening span and that the dry land must have been so low and level that erosion was slow and moderate.

The Devonian Period

When the next rocks were laid down in Minnesota, sometime in the latter part of the Devonian period, they were all limestones and dolomites, a sure indication that the epicontinental seas had returned. Rocks formed during this time occur only in the southeastern part of Minnesota. Devonian rocks of other states, however, give us more extensive clues to what went on during those times.

Land plants and marine fishes are abundantly represented as fossils for the first time in the rocks of Devonian age. Land areas were probably covered with at least some vegetation even during Silurian times, for remains of ferns and other lowly types of plants have been found in the strata of that period. It is in Devonian rocks, however, that there appear for the first time the remains of extensive and luxuriant forests of primitive trees. It is probable that these primeval forests developed over large parts of Minnesota during the long, unrecorded interval that followed the retreat of the Ordovician seas. We can never be certain of this, however, for the Devonian rocks of Minnesota are all limestones and dolomites formed from sediments deposited in clear, offshore marine environments, and consequently no fossils of land plants have been found in them.

The earliest known fish remains, representing a very primitive group of bony, armored fishes called ostracoderms, occur in the Ordovician rocks. These fossils consist of bony fragments that reveal little of the nature of the fishes themselves. The Silurian rocks also contain scattered bony spines that were borne by some of the early sharklike fishes. But not until the fossils of the Devonian period do true fishes occur in profusion, so abundantly in fact that the period is often referred to as the Age of Fishes. This does not mean that at this time fishes reached the peak of their career in earth history or that they exceeded in number and variety all other kinds of life. Rather, for the first time fishes became well represented in the fossil record, and because of their great advancement in development over any of the invertebrate creatures, they are termed the dominant animals of the period.

A few fish fragments have been identified in the Devonian limestone of Minnesota, but no complete fossil specimens have been collected. In Minnesota the most abundant fossils in the Devonian rocks are still the brachiopods and corals, old inhabitants of the seas since early Paleozoic days.

The limestone mentioned above is known as the Cedar Valley limestone and is the only formation of Devonian age in Minnesota. It covers the southwestern corner of Fillmore County, about three fourths of Mower County, and a small corner of southeastern Freeborn County. The formation is exceedingly variable both in composition and in fossil content. The lower portion is a gray to buff or yellow limestone, heavy-bedded, tough, porous, and dolomitic, and has several brecciated or fragmented layers in the upper part. Near the middle of the formation, a fine-textured, compact, gray to white limestone of high calcium content is interbedded with brown dolomitic limestone; the whole forms a unit referred to as "lithographic" limestone.

In the vicinity of Le Roy, these "lithographic" beds have been quarried extensively and the rock crushed and sized for chicken grit, stock feed, agricultural lime, and concrete. Still higher in the formation is a massive, soft, sandy dolomitic rock above which occur the earthy and sandy beds that crop out in the vicinity of Austin. In many localities the upper surface of the formation is covered by a mantle of white residual clay or residual iron ore. All these various types of rocks have a total thickness of about 130 feet.

This formation of Devonian limestone is the last legacy of the Paleozoic era in Minnesota. The era was still many millions of years from its close when the Devonian sea withdrew from the state, leaving the land masses above sea level once more. Elsewhere in North America the warm, quiet seas continued to advance and retreat while new sediments collected in their waters, amphibians flourished, the earliest reptiles appeared, lush forests grew on the land, and the world's greatest coal deposits formed in swamps with giant ferns and mosses. The Mississippian, Pennsylvanian, and Permian periods — over a hundred million years altogether — came and went, but in Minnesota hardly a trace of their passage was left.

If any marine rocks of these late Paleozoic periods were laid down in Minnesota, they were worn away completely before the next surviving rock layers were formed during the Cretaceous period of the Mesozoic era (see p. 99). The condition of the surface on which the later, Cretaceous rocks were deposited — in some places Cambrian or Ordovician layers formed this surface, in others the Devonian limestone — indicates that Minnesota had been through another long interval of erosion. Through the late Paleozoic and early Mesozoic eras Minnesota was mostly low land except for her mountain remnants, and was covered with primitive ferns and trees.

The products of erosion accumulated as fresh-water sediments — clays, silts, sandstones, and conglomerates — in low spots over a wide area of the southern part of the state. Here and there swampy conditions prevailed, and thin beds of impure lignite were formed. In some localities the nonmarine shales and sandstones formed at this time carry numerous fossils of leaves and a few shells of fresh-water clams. In the limestone areas of south central and southeastern Minnesota the action of ground water formed numerous sinkholes and caves; and later, when the Cretaceous sea advanced over the region, these caverns were filled with clays and silts, some of which contain marine fossils.

All through the latter part of the Paleozoic era the broad, flat continental mass of North America had been rising very slowly, with here and there in coastal areas some minor diastrophic disturbances. This wide, slow uplift brought Minnesota above the later Paleozoic seas but preserved the strata of her early Paleozoic rocks, without tilting or folding, in almost perfect horizontal layers. The Paleozoic era ended with great mountain-building activity in eastern North America folding and pushing up eastern sedimentary rocks into the long Appalachian mountain chain, many times higher then than now. But Minnesota remained untouched.

For over half of geological time, Minnesota was near the center of all North American diastrophism, racked by earthquakes, volcanic eruptions, and mountain uplifts. The ancient igneous granites and lava flows and the greatly altered metamorphic rocks of northern Minnesota bear mute testimony to those more violent Archeozoic and Proterozoic times. But with the Paleozoic era this violence ceased. From that time on, Minnesota's ancient pre-Cambrian rock masses and sedimentary beds have lain more or less undisturbed, affected only at the surface by the millions of years of erosion and deposition.

CHAPTER

7

The Age of Reptiles

THE extensive earth movements that formed the Appalachian Mountains at the close of the Paleozoic era elevated the entire continent as well. This slow continental uplift had been going on through much of the Paleozoic era, keeping Minnesota dry, as we have seen; and during the next era, the Mesozoic, not only Minnesota but most of the North American continent remained above sea level for a very long interval of weathering and erosion. During the Triassic and Jurassic periods of the Mesozoic era (see p. 99), no marine sedimentary rocks were laid down in Minnesota or anywhere in the eastern half of the continent, although parts of the far west of the United States and much of Europe have ample records in their rocks of the seas and life of these periods.

The word "Mesozoic" in Greek means "middle life," and these times were indeed a kind of biological Middle Ages. With the retreat of the seas in many places, life was adapting itself more and more to land conditions. The seas still swarmed with many invertebrates and fishes, but the amphibians had already learned to breathe the air, and the reptiles became even more independent of marine conditions. Reptiles were so gigantic and numerous in the Mesozoic era that it is often called the Age of Reptiles. The biggest reptile of all, the now-extinct giant dinosaur, is familiar to almost everyone as a symbol of these medieval geological times.

The Cretaceous Period

The Age of Reptiles reached its height with the Cretaceous period, which comprised the last 70 million years or so of the Mesozoic era. By the end of the Jurassic period the western coast of North America was undergoing its first mountain-building episode since pre-Cambrian times. In the course of this diastrophism, which began to lift the Sierra Nevadas, the center of the continent was depressed low enough to be flooded once more by extensive seas. This submergence began the Cretaceous period. The period derives its name from the Latin *creta,* meaning "chalk," for during this time the English chalk cliffs of Dover and other chalk deposits were formed. The Cretaceous seas were the last of the extensive epicontinental seas, and since the end of the Mesozoic era, when they withdrew, North America has never again had a sizable marine invasion.

The Cretaceous seas approached Minnesota from the west and north, covering most of the state except the Superior Upland region. These seas, like those of the Cambrian and Ordovician periods, were literally alive with mollusks, but in far greater variety than ever before. Many kinds of gastropods and bivalves were present in abundance, the oysters being particularly conspicuous, but it was the cephalopods that were the most characteristic inhabitants of the early Cretaceous oceans. Among them were the highly varied and beautifully coiled shells known as ammonites, from a resemblance to ramlike horns of the Egyptian god Ammon. Some of the coiled ammonites became very large. One specimen has been found with a diameter of 8 feet and a length, if the coil were straightened out, of 30 feet. Both oyster shells and fragments of large ammonite shells are abundantly present in the Cretaceous rocks that were deposited on the Mesabi Range (Figure 61).

The most striking feature of Cretaceous life, however, was the dominance of the reptiles. They occupied the pre-eminent place in nature that is held by the mammals today, surpassing present-day mammals, in fact, since the reptiles ruled not only land and sea, but the air as well. These dragons of the air, known as pterodactyls, were the most extraordinary animals of the entire Mesozoic era. They were somewhat batlike in appearance, without feathers, with

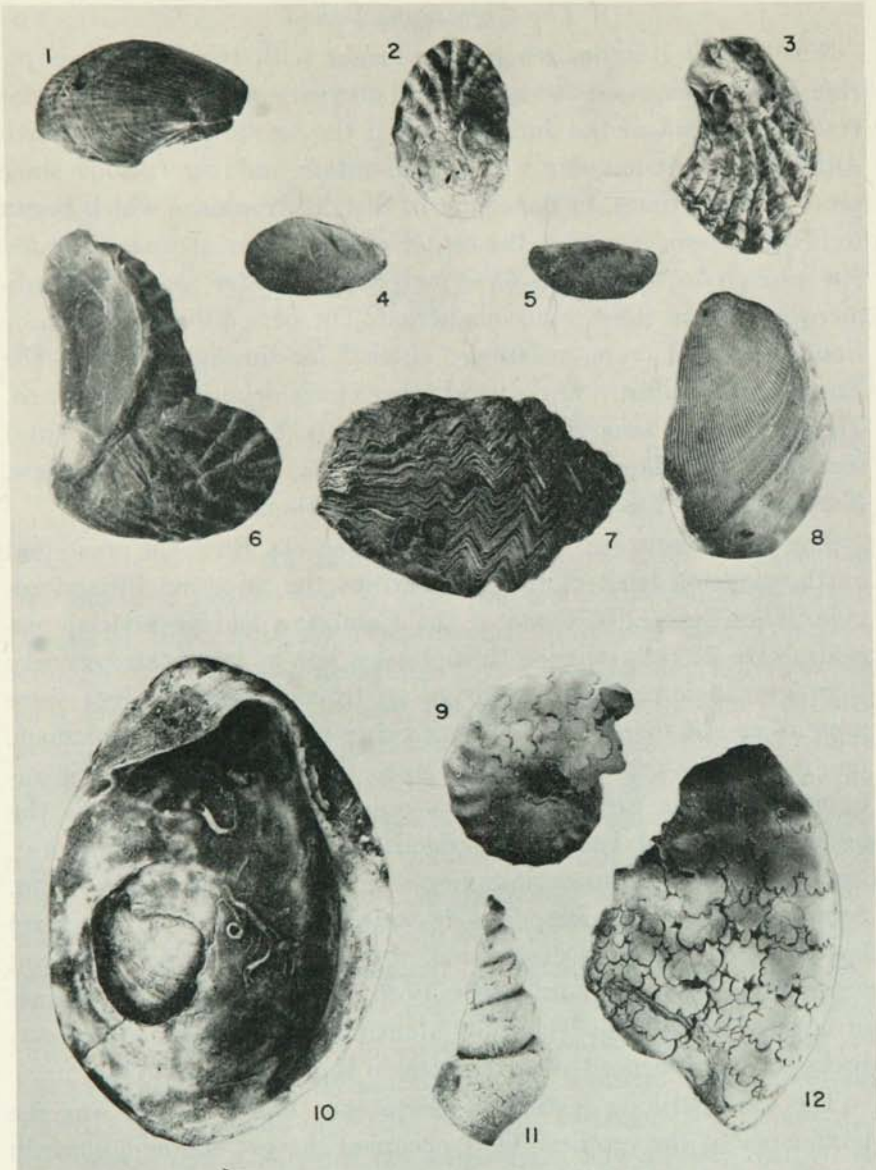


Figure 61. Marine fossil mollusks from the Cretaceous period of the western part of the Mesabi Range. Numbers 1–8 and 10 are pelecypods, of which 2, 3, 6, 7, and 10 are oysters; 9 and 12 are cephalopods; and 11 is a gastropod.

"wings" covered by a flexible, leathery skin like that of modern bats. The largest ones had a wingspread of as much as 25 feet.

On land the largest reptiles were the huge dinosaurs—the Greek word for "terrible reptiles." Some of these were giant vegetarians walking heavily on all fours, with more or less pillar-like legs, a long, snakelike neck, a far-reaching tail, and a tiny brain to govern a body up to 80 feet long, and with a weight of as much as 50 tons. Perhaps the most bizarre forms were the armored ones that were covered with plates and spikes. These reptilian tanks unfortunately had too little intelligence to maneuver themselves along the road to survival. There were many flesh-eating dinosaurs, too, roaming the Cretaceous swamps and forests semierect on two large hind legs and grasping their prey with short forelimbs. *Tyrannosaurus,* the largest of these carnivorous dinosaurs, was a monster 50 feet long and 20 feet high, with a long, balancing tail and a huge head fitted with dagger-like 6-inch teeth.

Dinosaur bones are abundant in Utah and Colorado, their fossilized footprints occur in the Connecticut Valley, and sea-going types were found in Kansas; but none have been found in Minnesota. There is good evidence that dinosaurs inhabited the state, however, for some highly rounded and polished pebbles associated with Cretaceous sandstones and conglomerates in the southeastern counties have been identified as the gastroliths or "gizzard stones" of dinosaurs, comparable to the gizzard stones of modern fowl.

Probably even more far-reaching in significance than the rise of the reptiles was the appearance in the Cretaceous period of flowering plants. They are abundantly preserved in the Rocky Mountain region in the extensively distributed Cretaceous Dakota sandstone. No other formation is better known for its plant fossils than these sandstone strata. They contain fossils of early types of maple, cottonwood, oak, walnut, sassafras, willow, and many other kinds of present-day trees, though none of the modern species had appeared. This introduction of flowering plants supplied new types of grasses, grains, fruits, and nuts that served as food for animals. These new foods were no doubt an important factor in the rapid rise of the mammals during the Cenozoic era that followed. It would not be too much to say that the great expansion of warm-blooded animals, both birds and mammals, had to wait upon the development of the flowering plants.

Fossils of plants, especially the leaves of trees and shrubs, are common in the Dakota sandstone where it crops out along the Cottonwood River near Springfield, Minnesota, and a compact bed of leaves two or three inches thick occurs in the same formation near New Ulm. Thirty different species of plants have been identified in the Cretaceous formations in Minnesota.

The rocks of Cretaceous age in Minnesota are exceedingly variable in composition. This variation is due to the long erosion interval that preceded their deposition and to the widespread submergence of areas that were not covered by the earlier, Paleozoic seas. Thus layers of Cretaceous rocks were deposited over almost the entire state, covering virtually every formation of Archeozoic, Proterozoic, and Paleozoic age. The most uniform and geographically most continuous strata occur in the west central and southwestern counties, where they lie under a thick mantle of glacial drift. Their distribution has been determined mainly by the drilling of wells. In many regions only the lower Cretaceous strata remain, for the upper beds were removed by preglacial erosion or by later glacial abrasion.

Most of the western half of southern Minnesota is covered by Cretaceous shales and sandstones that lie just under the glacial drift and on top of the ancient pre-Cambrian rocks. A study of the fossils from the shales at Springfield (Figure 62) and from the sandstone along the Cottonwood River south of New Ulm has led to the correlation of these Minnesota strata with the Dakota sandstone of the Great Plains region. At some localities in Lyon and Redwood counties, these strata attain a thickness of nearly 400 feet. An interesting feature of these beds is the occurrence of fossil fish teeth (Figure 63). The sandstone beds, which form only a small portion of the total thickness, occur chiefly near or at the bottom of the series. The beds at the base of the formation often contain layers of coarse, white quartz grit, with scattered pebbles of angular quartz resting directly over residual white clays that cap the ancient granites of that area.

Figure 62. Clay pit in Cretaceous strata, Springfield, Brown County. (Courtesy of A. C. Ochs Brick and Tile Co.)

Southeastward from the area of Springfield and New Ulm there are widely scattered deposits of Cretaceous gravels, sands, and clays that extend from Blue Earth to Goodhue and Houston counties. These sediments rest on the post-Devonian erosion surface and are in turn overlain by glacial drift. The gravels are largely composed of clear quartz pebbles, many of which are bright pink in color. Numerous chert pebbles derived from the flinty nodules of the underlying limestones are also present. In some places the sands and pebbles are cemented by iron oxides into hard, resistant sandstones and iron-bearing conglomerates. These iron oxides give both the sand and the gravel a yellowish color, so that they are often spoken of as "orange gravels."

On the Mesabi Range the Cretaceous rocks are highly fossiliferous, and the fauna they contain indicates that they are younger than the Dakota formation (Figure 61). These rocks are well exposed in the walls of the iron ore pits in the vicinity of Coleraine and have therefore been named the Coleraine formation. Their fossils are marine types, with many oyster and ammonite shells, indicating

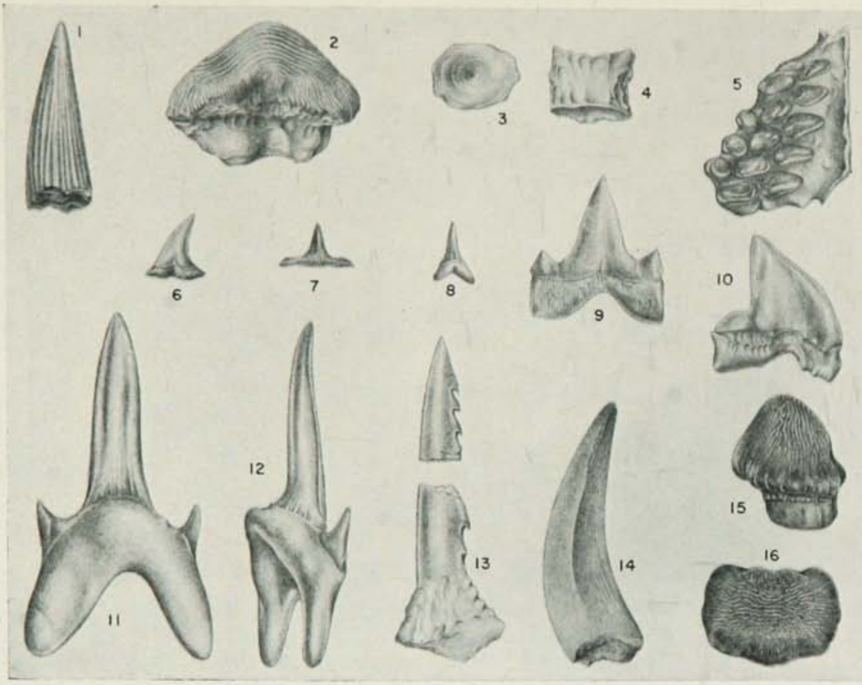


Figure 63. Fish teeth and bones from Cretaceous rocks, Big Stone County.

that the Cretaceous sea extended this far east in Minnesota. The basal part of the Coleraine formation is a series of conglomerate beds in which most of the pebbles and boulders are composed of hard iron ore. The coarse conglomerate grades vertically through a fine-pebble conglomerate or grit, which in turn grades upward into iron-bearing sandstone and shale.

These Cretaceous formations are the most recent rock layers to be formed in Minnesota. Above them lie only the glacial drift and soil, deposits so new that the slow workings of geological time have not yet transformed them into solid rock. The Cretaceous seas distributed the last broad layers of sediment over the state, and since their retreat no later seas have followed. The Cretaceous period and the Mesozoic era ended with new and widespread mountain-building, known in North America as the Laramide orogeny. The worn-down Appalachian Mountains were arched up anew, the major folding and raising of the Rockies took place, and much igneous activity occurred in the west. All the continent in between was also lifted upward.

With these great uplifts and the retreat of the tempering seas, the climate of North America, and indeed the world, soon changed. The high lands became colder and dryer, and many lush swamps disappeared. The new climate brought disaster to the clumsy giant reptiles and many other forms of life, for they were adapted to the food supply and easy movement of low lands and warm waters. More rigorous conditions encouraged the rise of the mammals. Until now the mammals had been a minor part of the earth's fauna; but the advantages of their warm blood, furry or hairy bodies, agility, and intelligence gradually brought them the dominance that they retain to this day. Finally, about a million years ago, man appeared, the supreme mammal of them all, and he shows no signs of relinquishing his reign on earth until some geological cataclysm, or his own misguided intelligence, destroys him.

CHAPTER

8

The Great Ice Age

FOLLOWING the Mesozoic era came the Cenozoic—meaning "recent life"— and this is the last great division of geological time. It is during this era, which began about 60 million years ago, that nearly all the important features of the earth's surface with which we are familiar have been gradually shaped. Extensive disastrophism continued to raise the Rocky Mountains, the Alps, the Himalayas, California's coastal ranges, and many others, while erosion again wore down the Appalachians and carved out the western Bad Lands and the Grand Canyon.

In geological history the Cenozoic era is commonly divided into two periods, called the "Tertiary" and the "Quaternary," and they in turn are subdivided into epochs. Since no Tertiary rocks have been positively identified in Minnesota, we will skip over the subdivisions of that period. Furthermore, the term "Quaternary" is no longer used by most American geologists but is being replaced by the term "Pleistocene" — "most new" in Greek — which refers to the epoch during which continental glaciers have periodically covered most of the northern part of North America (see p. 99). This epoch, often referred to as the Great Ice Age, continues to the present time. During the Cenozoic era the coolness of the climate gradually increased until at last the accumulation of snow in the highlands of Labrador and in the area west of Hudson Bay began to form extensive glaciers. The spread of these great ice sheets over vast areas of North America has been the most significant and spectacular event of the Pleistocene epoch on this continent. The tremendous masses of ice had profound effects not only upon the glaciated regions themselves but on places far beyond the reach of the ice. As the normal climatic zones of the Northern Hemisphere shifted southward, all forms of life disappeared within the ice-covered areas, and for some distance beyond the glaciated regions living conditions became very severe for many animals and plants.

Many of the smaller fur-bearing mammals were already living in Minnesota at this time, as well as species of larger mammals, such as elk, bison, musk ox, and the shaggy early elephant known as the mastodon or woolly mammoth. Most of these animals were able to move southward ahead of the ice, but the vegetation of the state suffered greatly. As the glaciers moved they scraped up most of the mantle rock and soil of the Canadian Shield and northeastern Minnesota, depositing it later as till plains and moraines in southern Minnesota and other regions. In consequence large areas of the Canadian Shield today are barren surfaces of solid rock.

Some of these Pleistocene animals did not escape the ice, however, and of course all vegetation covered by the glaciers was killed. The remains of life, both plant and animal, are abundant in the glacial drift. In some regions of Minnesota there are fossil forest beds with logs, branches, twigs, leaves, and mosses dating from the interglacial stages of even the oldest Pleistocene ice sheets—that is, the stages of mild climate between the retreat of one glacier and the advance of the next. Some of this vegetation may even antedate the earliest glacier of all. Partly mineralized wood, identified as yellow spruce, occurs at the very base of the drift and may be preglacial. Other accumulations of wood and plant material of various kinds are distinctly within the drift. Some of these beds of vegetable material may be little decayed, while others are veritable buried peat bogs that yield puffs of marsh gas when encountered by the driller's bit.

In among this vegetable matter in the old lake beds, in the gravel pits, or even within the drift itself, we may find the antlers, bones, teeth, and tusks belonging to various animals of nearly every stage of the Pleistocene epoch. Those more commonly found, however, seem to be from animals mainly associated with the later stages. These are remnants of both large and small mammals, some of which are quite different from those now forming the fauna of Minnesota and its adjacent territory.

The remains of many small mammals, such as the beaver, the badger, the skunk, the rabbit, and smaller rodents, have been found in the drift of Minnesota, but most of the bones that have been collected belong to the larger forms. Among these are the American elk, several species of bison, the horse, the moose, the reindeer, the musk ox, and especially the elephant-like mastodon (Figure 64).

American elk skulls and antlers are common and widely distributed in the drift, as well as in the peat bogs and old lake beds on top of the drift. The reindeer is also common but not quite so abundant as the elk. Where the skeletons are not accompanied by their antlers, the elk and reindeer are not easily distinguishable, especially when the remains are fragmentary. The bison is also exceedingly common in the late Pleistocene and post-Pleistocene deposits of

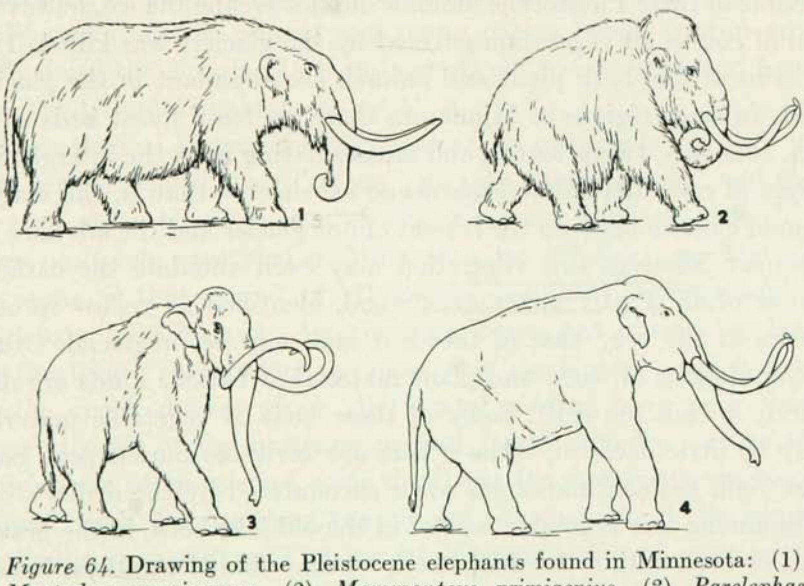


Figure 64. Drawing of the Pleistocene elephants found in Minnesota: (1) *Mastodon americanum*, (2) *Mammonteus primigenius*, (3) *Parelephas jeffersoni*, and (4) *Archidiskodon imperator*. (After Osborn.)

Minnesota. In some localities, even under thick accumulations of peat, bison bone beds have been found. Some of the larger beds are those of the peat bog at the Sagamore Iron Mine at Riverton, Minnesota, and one more recently uncovered in Itasca State Park.

Associated with these bison bone piles, pot shards and various implements pertaining to early man have been found. It is quite probable, in fact, that prehistoric man had much to do with these bone accumulations. How long man had been living in Minnesota we do not know, but in 1931 the skeleton of the famous "Minnesota Man" was found near Pelican Rapids. The skeleton was found some nine feet deep under laminated glacial lake clay, and the best guess seems to be that the person drowned in a glacial lake about 10,000 years ago.

The musk ox and the giant beaver may have been common in Minnesota, but their remains are comparatively rare. They are sufficiently distinctive, however, to attract attention, and if they had been abundant they would have been more frequently recorded. The various specimens of musk ox found in Minnesota are quite similar, and all have been classified as belonging to the same species. Musk ox remains have been reported from seven different counties, and the remains of the elephant-like mastodons have been discovered in more than one hundred localities within the state. Undoubtedly many more separate finds of teeth, tusks, and other mastodon parts have not been reported.

The glaciers that preserved and distributed these animal remains kept not only Minnesota but much of the world in an intermittent deep freeze for several hundred thousand years. All of the United States north of the Missouri and Ohio rivers, west to the foothills of the Rocky Mountains, and east to Long Island and Boston Bay bears evidence of great continental ice sheets having passed over the land (Figure 65). Similar ice sheets covered a large portion of northwestern Europe at about the same time.

In North America the glaciers moved out from east, south, and west of Hudson Bay (Figure 66). Field observations indicate that the ice spread from three main centers and that its southward movement covered most of Minnesota. The center of ice accumulation

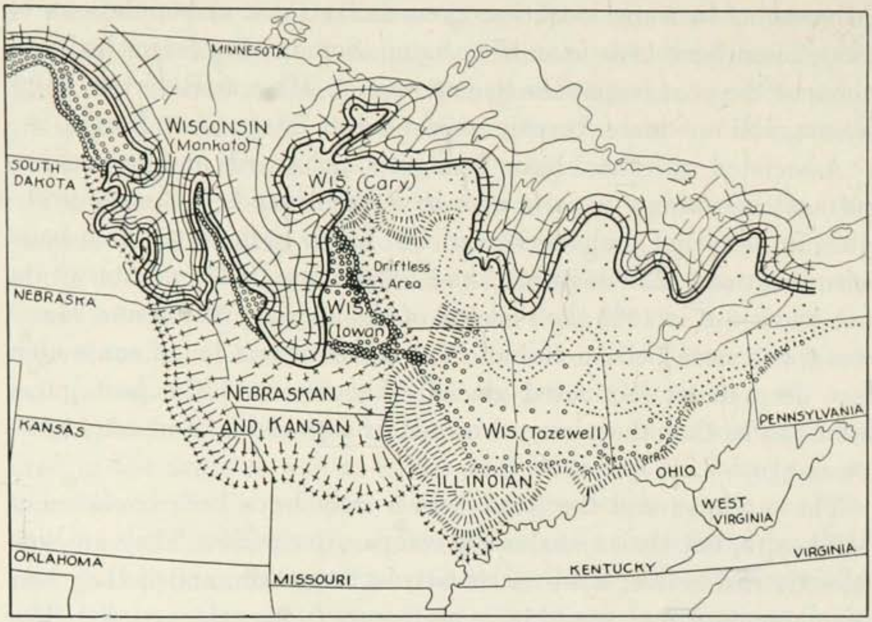


Figure 65. Map of ice sheets of the United States.

west of Hudson Bay is called the Keewatin center, from the Canadian province of Keewatin. East of Hudson Bay over Labrador was another center of accumulation, and the ice sheets that moved from that area are called Labradorian glaciers. The westernmost center was the Cordilleran. A minor center north of Lake Superior in northwestern Ontario covered most of the old province of Patricia, and the ice sheet that moved southward from this area is called the Patrician glacier.

Recent studies have led some geologists to conclude that the glaciers originated as mountain glaciers in the highlands of Baffin Land, Labrador, and Quebec. As the ice in the mountains increased in thickness, it buried the ranges and spread westward over all of Canada to the Rocky Mountains and southward to the Ohio and Missouri rivers. According to this interpretation, the centers referred to above were areas where snowfall was unusually heavy and resulted in low, broad, domelike centers from which the ice moved out in all directions.

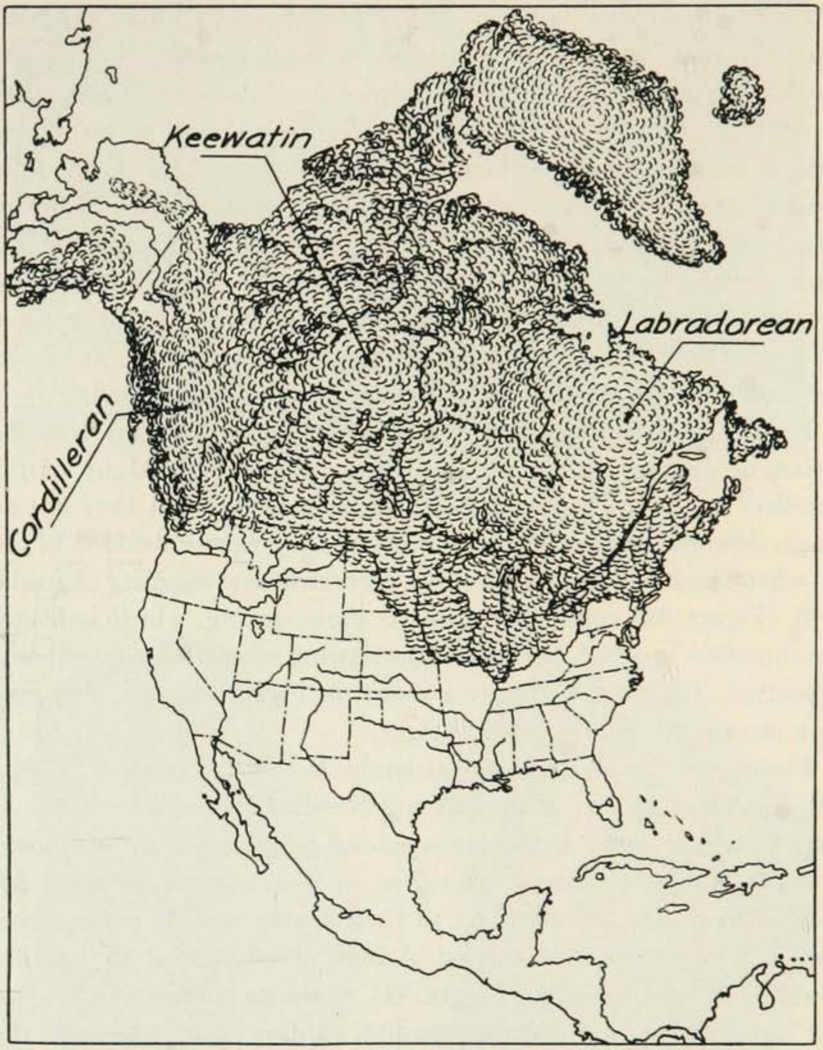


Figure 66. Map of North America showing area covered by glaciers in Pleistocene time.

The glaciers that invaded Minnesota came by three different routes. Those from the Keewatin center came by the low valley of the Red River of the North, then down the Minnesota Valley, and across a low, flat area to the valley of the Des Moines River. These valleys are the largest lowland areas of the state. The glacier from the Labrador center came along the Lake Superior basin and spread into Minnesota and northern Wisconsin. The invasion from the Patrician center came from the high land north of Lake Superior and spread southward across the iron ranges. At about the same time, ice from the Superior basin pushed a lobe, or tongue of ice, down the valley of the Mississippi southward beyond Minneapolis.

The direction of movement of the ice can be determined from the striae, or grooves on the rock surfaces (Figure 67). Many of the boulders in the drift are striated also (Figure 68), but they are no longer oriented in the direction in which they were imbedded in the ice when the striae were made. However, stratified deposits of glacial drift (Figure 69) commonly tend to show sorting, which indicates the direction in which the water was flowing when the sediment was deposited. The sand and gravel shown in Figure 69 were deposited by a stream flowing from left to right.

The exceptionally large glacial boulders called "erratics" (Figure 70) can also be used in deciphering the direction of movement of the ice. Those gigantic blocks, weighing many tons, are composed of rock foreign to that of the region in which the melting ice deposited them. By tracing them to their source, one finds the direction in which they were carried. A high percentage of the smaller boulders in till deposits (Figure 71) are commonly composed of one kind of rock, for example, granite, gabbro, or limestone. If the parent formations from which they were removed by the ice can be established, their direction of transport is readily determined.

We can gain a better idea of the enormous extent of the ice sheets by noting that in the case of the Keewatin center, for example, the ice moved southward for some 1500 miles and that during its maximum extent about 4,000,000 square miles of our continent were covered with glaciers. The ice near the center of the modern Greenland icecap is about 8000 feet thick, and there is every

Figure 67. Glacial striae on diabase in road cut, Forest Hill Cemetery, Duluth.

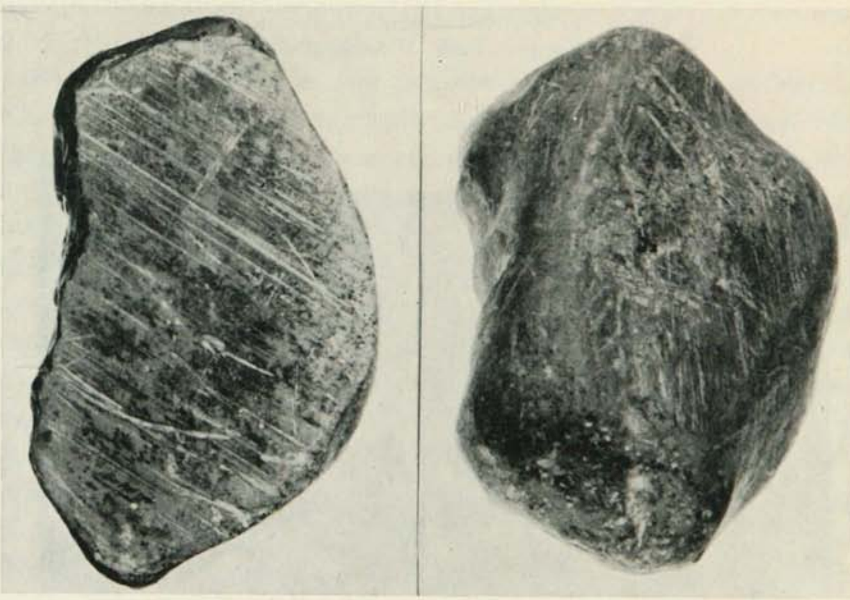


Figure 68. Striated boulders from glacial drift.

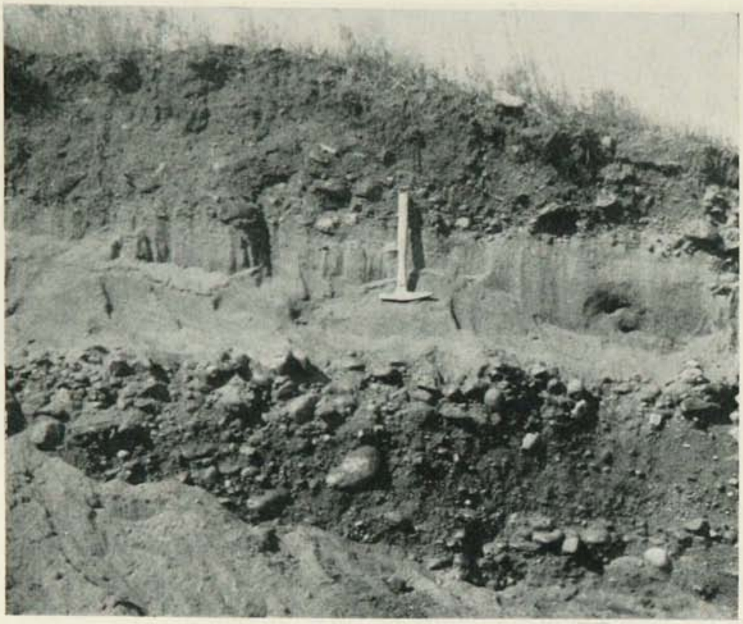


Figure 69. Stratified deposits of glacial drift, Prospect Park, Minneapolis.

Figure 70. A glacial erratic. A huge rounded boulder left by the ice and resting on glacial drift, Duluth.

Figure 71. Boulder till of the Highland moraine, St. Louis County.

reason to believe that similar or even greater thicknesses were common in the continental glaciers that covered much of North America during the Pleistocene epoch.

For a long time after the existence of continental glaciers in North America had been clearly established, geologists believed that there had been but one single glacial period, followed by a definitive retreat of the ice. Later studies, however, demonstrated that there were at least four glacial advances, and that each advance of the ice was followed by a widespread retreat. Each stage of glacial advance is named, often for the state where it reached its greatest extent; and each interglacial interval—that is, the period of milder climate that followed each glacier's retreat—is also named. These various stages are shown in the classification given on the following page.

The oldest known glacial deposits in Minnesota are referred to as Nebraskan. The ice sheet responsible for their deposition moved from the Keewatin center of glaciation and extended as far south as the lower course of the Missouri River, also invading Nebraska and thereby gaining its name. The geographical extent of Nebraskan drift in Minnesota is not known in detail because most of these early deposits have been subsequently obliterated or concealed by later glaciers. In Fillmore and Winona counties, however, isolated patches of deeply weathered drift and scattered erratic boulders occur beyond the eastern margin of the Kansan drift sheet, and similar relations are found in Rock and Pipestone counties in the southwestern part of the state.

Pleistocene History in the Upper Mississippi Valley

(Read up from the bottom)

PLEISTOCENE (OR GLACIAL) EPOCH

4. Wisconsin stage
    a. Mankato substage
    b. Cary substage
    c. Tazewell substage
    d. Iowan substage

**Sangemon* interval

3. Illinoian stage

**Yarmouth* interval

2. Kansan stage

**Aftonian* interval

1. Nebraskan stage

Interglacial deposits of the subsequent Aftonian interval in general cannot be accurately identified in Minnesota. In some places, however, Aftonian beds of peat and lake sediments with logs of trees, shells, and bones have been found at the base of the Kansan drift. On the basis of the depth of weathering and leaching of the Nebraskan drift, geologists judge that the Aftonian interglacial interval lasted as long as 100,000 years.

The climate following the retreat of the Nebraskan glacier was at least as mild as that of the present. Pollens from interglacial peat beds in Iowa, which have been studied recently, indicate that during the initial part of the first interglacial stage the forests of Iowa were coniferous. This phase of vegetation was followed by a great spread of grasslands. Then, toward the end of the Aftonian interglacial stage, oaks appeared; and as the climate grew colder, conifers returned to the forests. The skeletal remains of a great many mammals found in Illinois and Iowa indicate that large numbers of her-

*Interglacial intervals are shown in italic type.

bivorous animals lived at this time and that there was plenty of plant food available.

The second ice sheet to cover most of Minnesota also moved from the Keewatin center west of Hudson Bay. This was the Kansan glacier, and it left the Kansan drift sheet. At present the Kansan drift is exposed not only in valley walls and deep road cuts but also over the surface of extensive uplands in the region from Red Wing south to Rochester, Chatfield, and the Iowa-Minnesota state line. Its characteristic gray color is a result of a high percentage of gray Cretaceous shale and limestone, which became incorporated in the glacial debris as the ice moved over the unconsolidated Cretaceous sediments of Manitoba and northwestern Minnesota.

The Kansan drift is so intensely weathered that many of its pebbles and boulders are decomposed or partially disintegrated. In many areas the soluble carbonates have been leached out of the drift to a depth of as much as twelve feet. Such evidence of leaching is also found where the Kansan drift is covered by younger drift sheets. This relationship indicates that the second, or Yarmouth, interglacial interval was very long, perhaps several hundred thousand years. Similar conditions occur in neighboring states, where the remains of plants and animals have been found embedded in the base of the drift that rests on top of the Kansan deposits.

The third, or Illinoian, drift sheet was deposited by a glacier that radiated from the Labrador center and extended southwestward to the Ohio River and across the Mississippi and St. Croix valleys into Minnesota and Iowa. One lobe moved southwestward to the west of the Wisconsin Driftless Section—that small, central island that somehow escaped all glaciation (Figure 66)—and covered parts of east central Minnesota.

The Illinoian drift is exposed without a younger drift cover in Dakota and Washington counties. In the area between the St. Croix and Mississippi rivers it is a thin mantle no more than six to ten feet thick. Here and elsewhere this drift is red in color, and in earlier geological reports it is referred to as the "old red drift." Its sands, gravels, boulders, and other rock debris were derived mainly from the pre-Cambrian formations to the northeast and to the south of

Lake Superior. Much of the red color comes from the red sandstones of the Fond du Lac beds and from red residual deposits over which the glacier moved.

During the Wisconsin glacial stage, ice sheets radiated outward from the Keewatin, Labradorian, and Patrician centers of glaciation. Several lobes, or tongues of ice, advanced southward into the United States, and three of them covered parts of Minnesota. Detailed studies show that in many localities the ice advanced, retreated, advanced again, halted, and receded over and over again. At some places, too, it is evident that after the advance and retreat of one lobe, a neighboring lobe overrode or pushed aside deposits left by the earlier one.

The first extensive lobe of ice to invade Minnesota during the Wisconsin stage of glaciation is called the Iowan. It advanced southward from the Keewatin center and left a thin mantle of gray drift as a veneer of fresh till resting on deeply weathered Kansan deposits. This relationship is exposed at many points in the area from Red Wing southward into Iowa. During and following the retreat of the Iowan lobe, extensive deposition of loess took place (Figure 72).

These widespread deposits of wind-blown rock flour are referred to as the Peorian loess and are found lying on the Iowan drift and beyond its borders. The loess is nonstratified yellowish silt, intermediate in texture between clay and sand, and is composed of a variety of minerals, including quartz, feldspar, hornblende, calcite, and many others. The deposits are very widespread in the north central states, where they range in thickness from a few feet to as much as a hundred feet. The loess forms the parent material for most of the soils in many counties of southeastern Minnesota. Such soil is worked easily because it is free of glacial boulders, and it is very fertile because of the freshness of its mineral grains.

The ice that moved from the Labradorian center during the second, or Tazewell, substage of Wisconsin glaciation probably did not extend west as far as Minnesota. Its drift covers large areas in Illinois, Indiana, Ohio, and parts of southeastern Wisconsin. If it ever extended into Minnesota, its drift has been completely obliterated by later advances of the ice.

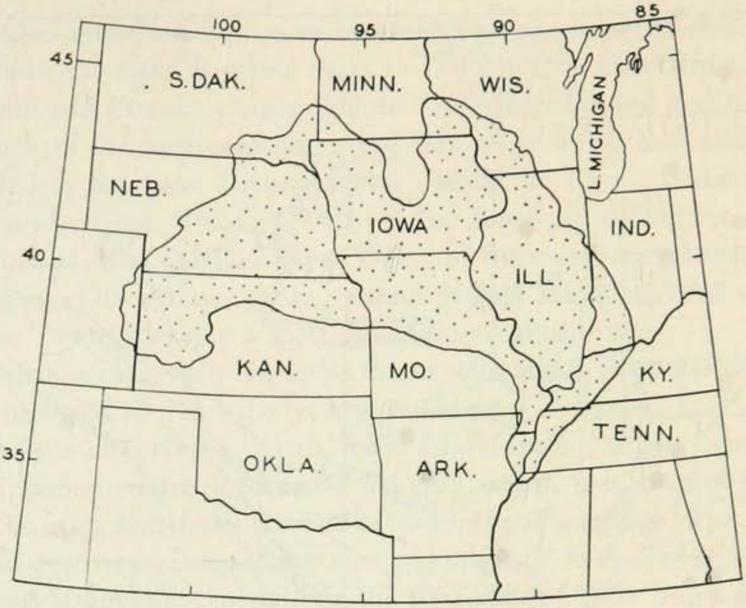


Figure 72. Map showing distribution of loess in the north central area of the United States. (Adapted from map by Geological Society of America, 1952.)

During the Cary substage of Wisconsin glaciation, lobes of ice from all three centers entered Minnesota. The lobe from the Keewatin center entered first and extended eastward from the Red River Valley to central Minnesota and southward into central Iowa. The lobe from the Labradorian center advanced down the Lake Superior basin and reached as far south as the Twin Cities (Figure 73). Here it deposited the St. Croix moraine (Figure 76), which may be traced northeastward along the St. Croix River to Taylors Falls and northwestward across Wright, Stearns, and Morrison counties. The moraine is a broad belt of complex topography, characterized by abrupt hills and hollows over a maximum width of ten miles. Beyond the moraine are many large, gravelly outwash plains, such as the Rosemount Prairie in Dakota County. The drift of this moraine is red and sandy. It contains only a little clay and very few, if any, limestone pebbles. This is in contrast to the Cary drift from the Keewatin center, which is gray or buff in color, silty or clayey rather than

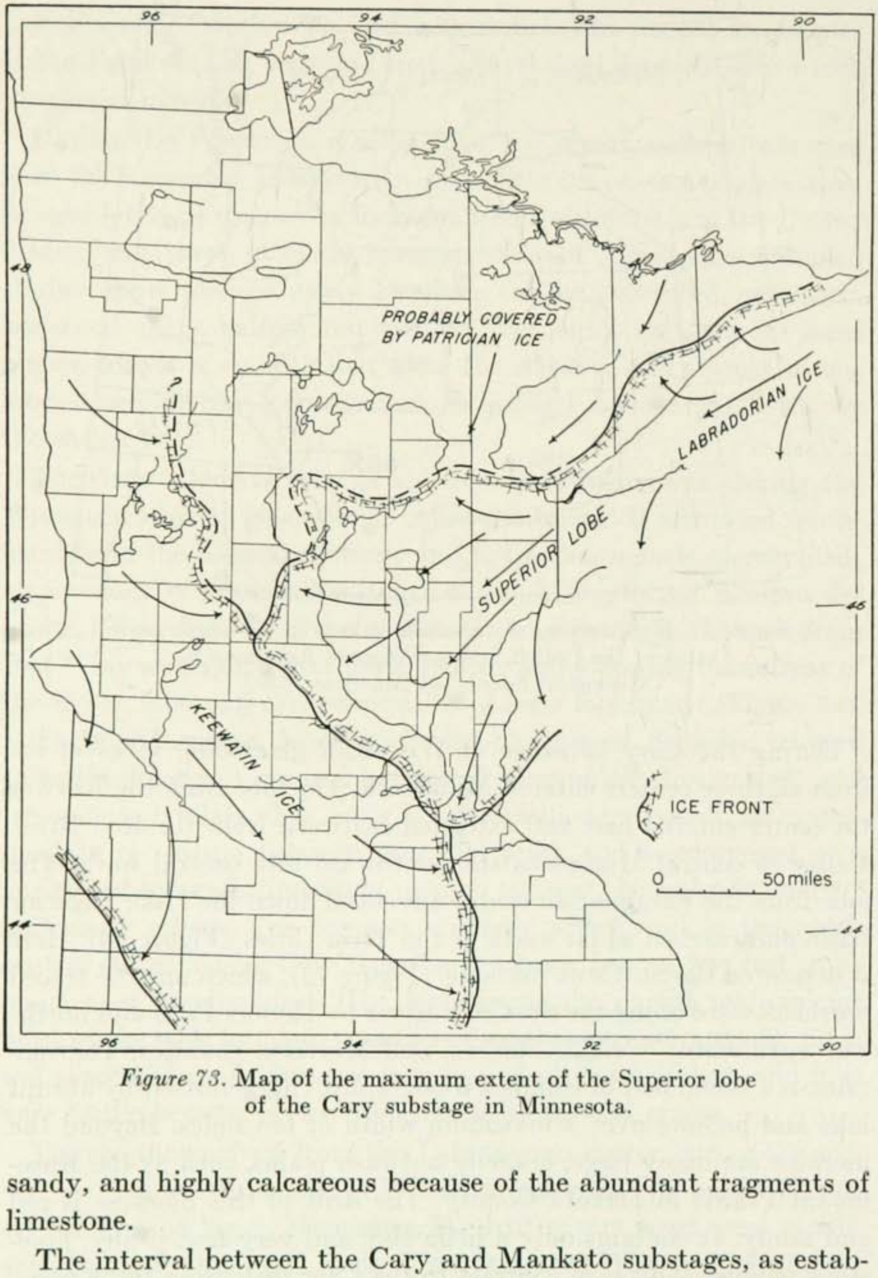


Figure 73. Map of the maximum extent of the Superior lobe of the Cary substage in Minnesota.

sandy, and highly calcareous because of the abundant fragments of limestone.

The interval between the Cary and Mankato substages, as established by the radiocarbon dating method, was approximately 11,000 years. During the Mankato substage, after the Cary ice lobes had retreated into Canada, the ice from the Labradorian center advanced down the Lake Superior basin to Duluth, then westward to the Mesabi and Cuyuna ranges (Figure 74). Its drift is red and clayey because of the incorporation of red lake clays which had been deposited in the Lake Superior basin during the Cary–Mankato interval of retreat. The ice lobe from the Keewatin center extended southward from the Red River Valley to Iowa and sent two broad sublobes eastward, one to the western Mesabi Range and one north of the Twin Cities and a short distance into Wisconsin.

This Keewatin drift is gray to tan in color and is characterized by the presence of a relatively large number of limestone and shale fragments in a clayey matrix. Near Minneapolis the ice from the Labradorian center deposited a red drift, which is in turn overlain by the gray drift from the Keewatin center (Figure 75). The Keewatin drift forms conspicuous terminal moraines in eastern and west central Minnesota, especially in the Leaf Hills of Otter Tail County (Figure 77). The position of the successive recessional moraines indicates that the outer margin of the ice was stationary many times during this final retreat northward.

The Mankato substage of Wisconsin glaciation terminated some 11,000 years ago, and since then Minnesota has been enjoying the interglacial interval of modern times. This present interval of moderate climate may last many thousands of years, or it may even mark a definite end to the Great Ice Age. In any case, man in Minnesota today can regard the glaciers with equanimity. To the men and animals of Pleistocene time the slow, frigid approach of a new ice age could have meant only suffering and hunger; but man today is reaping many benefits from the work of the glaciers.

This legacy, in fact, is of almost incalculable value. The early studies of glaciation made by geologists were largely for the purpose of establishing scientific facts, with no particular idea of discovering practical applications. However, the study of the distribution of the sand and gravel deposits formed by the streams from the melting ice (Figure 78) has been put to good use in Minnesota in connection with the building of highways. Geologists have located deposits of sand and gravel near the places where road construction work is

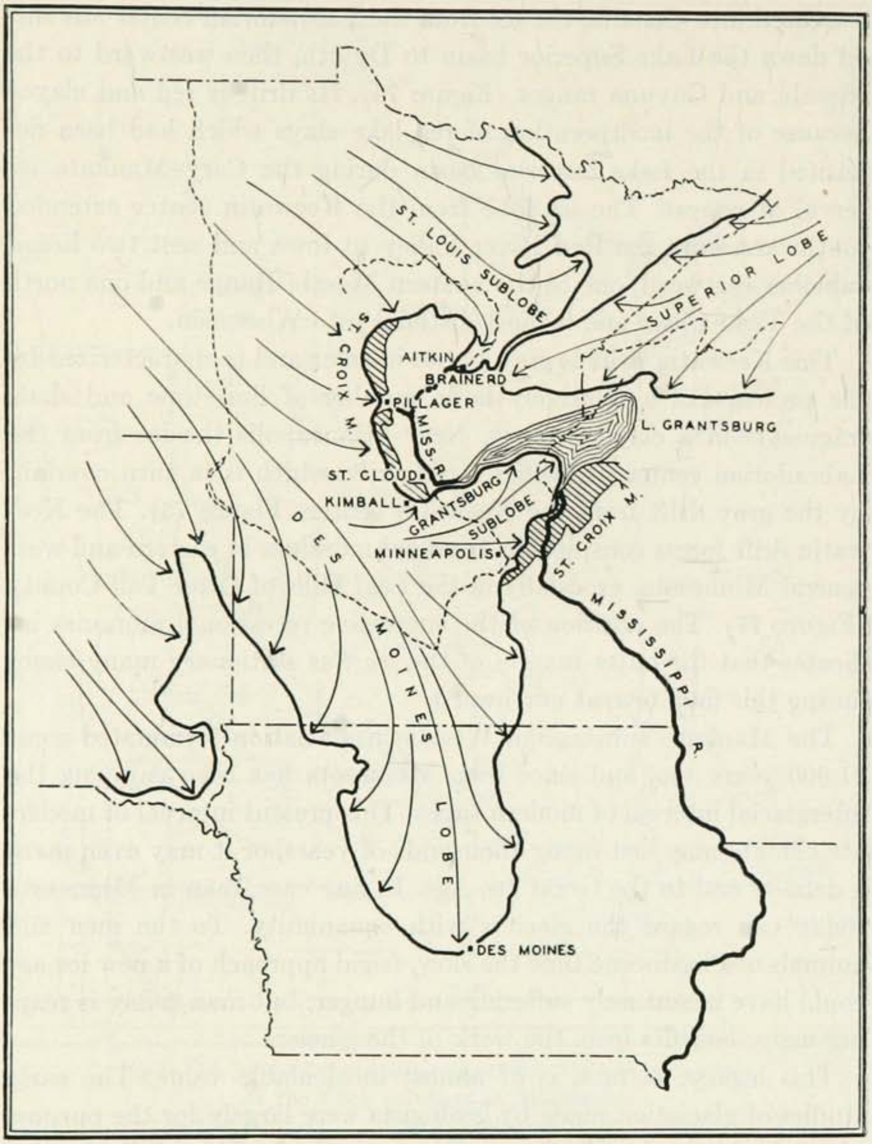


Figure 74. Map of late Wisconsin (Mankato) glaciation at its maximum extent. (Adapted from Leverett and Sardeson by W. S. Cooper.)

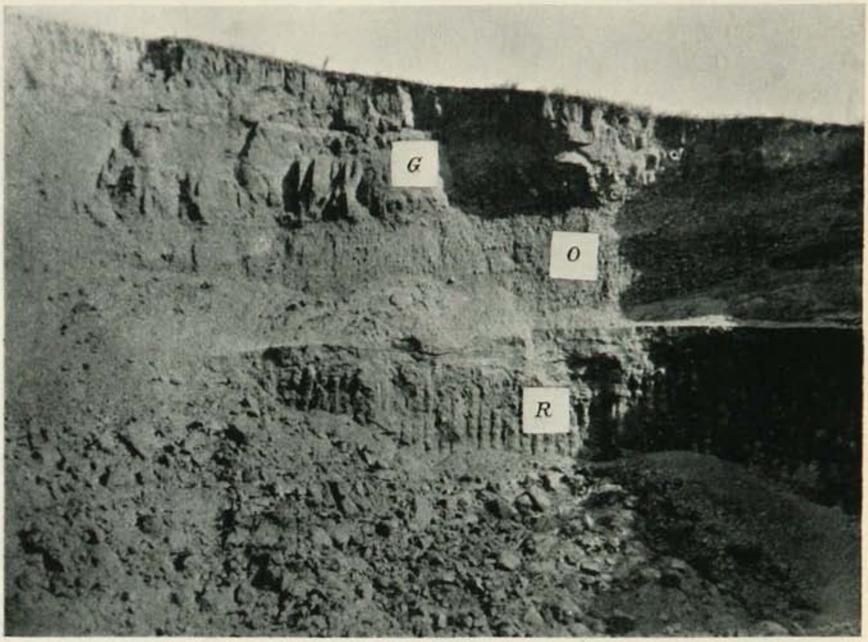


Figure 75. Red glacial drift of the Labradorian ice sheet (*R*) overlain by gray Keewatin outwash (*O*), which is in turn overlain by gray Keewatin till (*G*), Dakota County.

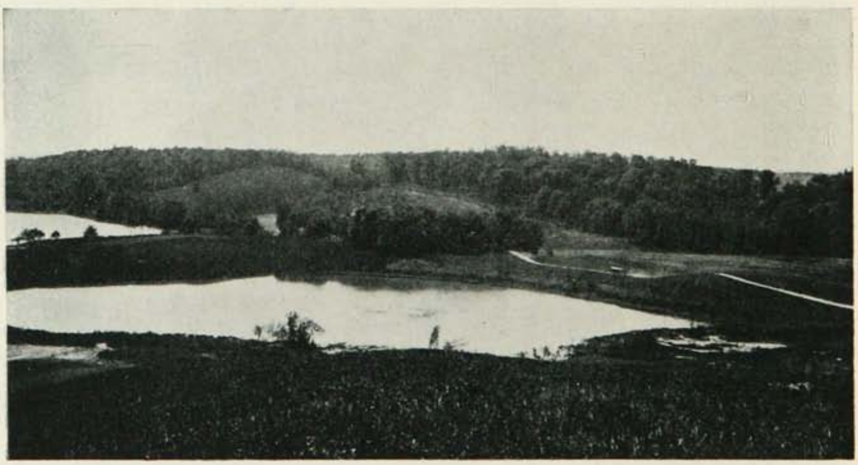


Figure 76. Terminal moraine topography, Dakota County.

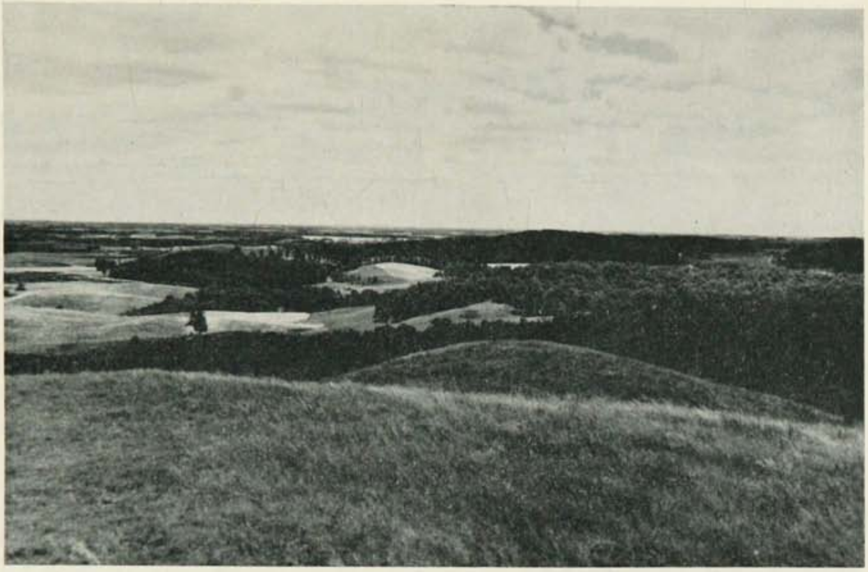


Figure 77. Terminal moraine topography east of Inspiration Peak, the Leaf Hills region of Otter Tail County. (Courtesy of Minnesota Department of Business Research and Development.)

Figure 78. A typical esker near Fort Ripley, Morrison County.

Figure 79. Typical gently rolling areas of southwestern Minnesota. Farm scene near Luverne, Rock County. (Photograph by Kenneth M. Wright.)

Figure 80. Ice-block pit lakes in outwash plain northwest of Brainerd, Crow Wing County. Gull Lake in the upper left.

contemplated and thus the expense of hauling the material long distances has been avoided.

The glaciers were also largely responsible for the fertility of the soils of Minnesota. The ice removed a thick mantle of residual rock waste that was deeply leached of the soluble mineral constituents commonly used in the making of plant food. In its place the ice left a mantle of glacial drift that contains fresh mineral matter in the form of finely crushed rock, much of which is pulverized as fine as flour. Thus the soil that has developed from this fresh material contains a much higher percentage of natural plant food. Furthermore, if the glaciers had not passed over the state many of its hills and intervening valleys would have had slopes too steep and too high for good farm land. The glacial drift has filled many of these irregularities, providing us with more farm lands, and more productive ones, than we would have had without glaciers (Figure 79). All in all, geologists have figured that the average agricultural productivity and value of the region were increased 30 per cent by glaciation.

Last, but far from least, of the blessings of the glaciers are Minnesota's lakes (Figure 80). The Great Lakes themselves owe their existence to the glaciers, formed as they were from old preglacial valleys or basins that were scoured deeper by the ice and dammed by morainic debris. As the ice sheets melted, the water was ponded in the Great Lakes basins, and their present value to the midwest states is tremendous. Because of Lake Superior and the Great Lakes' inland waterway, Minnesota has cheap commercial transport to the Atlantic Coast, and the Duluth-Superior harbor is the largest inland port in the country.

Minnesota's chain of Border Lakes is another unique waterway, much used by the fur traders more than a century ago and by vacationists today. Vacationists at all of Minnesota's lakes, in fact, are of great economic importance to the state. Probably the greatest value of the lakes, however, cannot be put in terms of trade or income. In Minnesota's lake country man can find a solitude and beauty that his spirit needs; and in the last remaining Minnesota wilderness, among the ancient rocks and clear waters, man might come close to glimpsing immortality.