UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
WILLIAM H. EMMONS, DIRECTOR

BULLETIN 30

MINERAL RESOURCES OF MINNESOTA

EDITED BY
WILLIAM H. EMMONS
AND
FRANK F. GROUT

MINNEAPOLIS · 1943
THE UNIVERSITY OF MINNESOTA PRESS

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FOREWORD

This résumé of the mineral resources of Minnesota is introduced by a brief discussion of the physiography and general geology of the state to furnish a background for a discussion of its economic geology. Since iron ores are Minnesota's most important mineral resources, they receive the most attention. Other mineral resources are discussed approximately in the order of their commercial importance, and the origin, distribution, and chief commercial uses of each are briefly noted.

Four factors determine the economic importance of Minnesota's minerals — quality, quantity, accessibility, and market. Iron ores, for example, are of high quality, they are easily mined and cheaply transported by way of the Great Lakes to the coal regions of the industrial East, and the demand for iron has been and is tremendous — that of a pioneering, progressive people.

It is very likely, however, that the high-grade iron ores will be nearing exhaustion within the next thirty or forty years, and therefore the future of the iron ore industry in Minnesota depends largely upon how well the technical, economical, and political problems connected with the industry are solved. The Mesabi range has probably reached its zenith in less than fifty years since the first discovery of ore at Mountain Iron. Yet there are many billions of tons of low-grade iron-bearing material on that range, and it is not too early to plan for its utilization. This problem, and other problems of mineral resources, are considered and discussed herein.

The Minnesota Geological Survey has been studying the mineral resources of the state for many years. The present bulletin makes use of data published in greater detail in earlier reports, brings up to date certain descriptions given in those reports, and adds descriptions of several resources not previously considered.

About 1935 the Minnesota State Planning Board, with E. V. Willard as chairman, thought it desirable to have prepared a summary report of the mineral resources of the state, and obtained WPA funds for the project. Lee C. Armstrong and Howard R. McAdams were employed to compile and write the report. In the course of this work they consulted not only with members of the Minnesota Geological Survey but also with the staffs of several other state departments and with various experts at the University of Minnesota. Contributions were made not only by the Planning Board itself, but also by the Division of Lands and Minerals of the State Department of Conservation, the Minnesota Tax Commission, the Minnesota State Highway Department, and by others. Several contributions were received from the staff of the University of Minnesota School of Mines and the staff of the Mines Experiment Station, particularly from E. W. Davis, H. H. Wade, J. J. Craig, J. C. Durfee, T. L. Joseph, E. M. Lambert, and W. H. Parker. Armstrong and McAdams presented their manuscript report in 1937, and in 1940 it was released by the Minnesota Resources Commission for revision and publication by the State Geological Survey. The valuable work of all these contributors is gratefully acknowledged.

It may be added that the useful minerals of each state of the United States were reported upon briefly by the U. S. Geological Survey in 1917,* and that one section of this report refers to Minnesota.

W.H.E. and F.F.G.

* F. C. Schrader, S. Sanford, and R. W. Stone. Useful minerals of the United States. U. S. Geol. Survey Bull. 624, 1917. Section on Minnesota, pp. 169–71.

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INTRODUCTION

MATERIALS OF THE EARTH

Minerals.—All materials in the earth are made up of atoms of chemical elements. When atoms of different kinds combine they form compounds. Minerals are natural elements or compounds with more or less definite chemical composition and physical properties. Since most minerals are solids and nearly all of them are crystalline, the earth's crust is essentially crystalline. Chemists have discovered ninety-two elements, but it is estimated that in the outer ten miles of the earth 98 percent of its material consists of only eight: oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium.

Rocks.—A rock is anything that makes up an essential part of the earth's crust, and most rocks are composed of one or more minerals. The three main classes of rocks are igneous, sedimentary, and metamorphic.

Igneous rocks are formed by the consolidation or freezing of molten matter. When this process takes place in large masses of matter far below the surface of the earth, these masses are called batholiths. Molten batholith materials crystallize slowly and are therefore relatively coarse-grained like the common granites. Some batholiths are scores or even hundreds of miles across, extending downward to great but unknown depths. Erosion (a natural process of disintegration and transportation, acting through geologic ages) has carried away the material that overlies some of the batholiths in Minnesota. Today the granites quarried from them are known throughout the country for their beauty and durability as building and monument stones.

While the molten material is still fluid underground it may escape along fissures in the overlying solid rock and later consolidate. Such intrusive bodies of igneous rock, more or less tabular in shape, are called dikes if they cut across the layers of the intruded rock, and sills if they parallel the stratification. Pegmatite dikes are a deep-seated type of dike containing large crystals. Feldspar for ceramic purposes was mined from such a body near Warroad in Roseau County, and magnetite, an ore mineral of iron, occurs in pegmatites in northern St. Louis County.

Some molten matter may reach the surface and flow out as a lava. Lavas cool rapidly and are so fine grained that minerals cannot be recognized. Traprock, a dark lava, is crushed and used in Minnesota for road material, concrete aggregate, and so forth.

Sedimentary rocks, as their name implies, are formed by the settling of material from water or air. They are derived from the waste products of older rocks. During weathering, some minerals are dissolved and others are mechanically broken from the rocks. Running water, wind, and ice remove this material. Streams eventually carry most of the fragments and solutions to lakes and seas. The coarser particles are normally deposited near the shore as gravels; sands are carried farther from shore before settling to the bottom; mud and silt are dropped still farther from shore in calmer water; calcareous matter in solution is precipitated beyond the mud zone in clear water, largely by the aid of organisms (fig. 1). In this manner beds of gravel, sand, clay, and limy muds are built up. Many deposits are mixtures of these materials. When they are deeply buried beneath successive layers of material, some of the water is squeezed out, and by cementation the sediments become consolidated. Gravels are changed to conglomerates, sands to sandstones, muds to shales, and calcareous oozes to limestones.

Metamorphic rocks are igneous or sedimentary rocks which, during their long history, have undergone great changes due to pressure, heat, cementation, and recrystallization. Textures are changed, and new min-

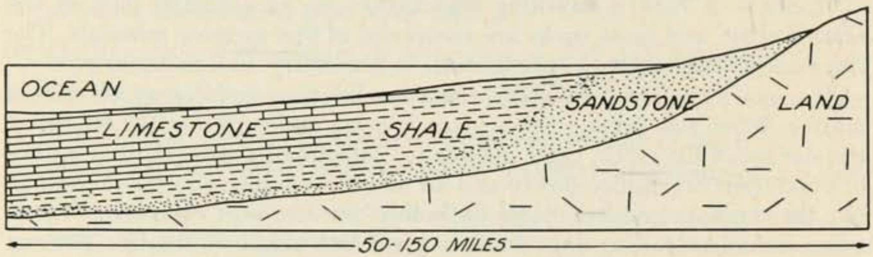

FIGURE 1. — The relation of deposition of sediments to areas of land and ocean. After Thiel and Dutton.

erals are developed. Granite may be changed to a banded rock called gneiss, and sandstone may recrystallize to quartzite. Mud that has been compacted to form a shale may be further indurated by metamorphic processes to form slate, and limestone may recrystallize into marble.

TOPOGRAPHY OF MINNESOTA

Elevations and Relief.—All Minnesota, except the eastern portions of Winona and Houston counties in the extreme southeastern corner of the state, is a broad glaciated plain. The land forms on this plain are the results of glaciation and of stream erosion since the glacial period. The major portion of the state stands between 1,000 and 1,500 feet above sea level.

In the general plain of southern Minnesota (fig. 2) a high area having an altitude of about 1,900 feet above sea level occurs in the southwestern corner. This area is known as the Coteau des Prairie. A second high area near the southeastern corner rises to 1,400 feet above sea level, approximately 400 feet above the level of the surrounding country. The extreme southeastern corner is unglaciated, and its topographic appearance is strikingly different from other areas in southern Minnesota. Here, bordering the Mississippi River, the tributary streams have cut valleys 200 to 500 feet deep; some are veritable gorges, walled in by bluffs of limestone and sandstone. The uplands between the streams are flat or gently sloping. They represent an old plain of erosion developed by streams in preglacial time.

More varied topography occurs in northern Minnesota. A feature of the land form in the northwestern part of the state is the flat floor of the Red River Valley proper, grading into the wide plain that extends east through the Red Lake area to Rainy Lake. Here is the site of the ancient Lake Agassiz. The area is bounded by a group of sand and gravel beach ridges, from 5 to 20 feet high, which were formed at different levels as the lake declined. The highest elevations in northwestern Minnesota are in Ottertail, Becker, and Hubbard counties, where belts of morainic hills and ridges trending north-south stand more than 1,660 feet and possibly as high as 1,750 feet above sea level. Locally there is a relief of 200 to 400 feet. The Red River is youthful and has hardly any flood plain.

The northeastern part of the state (fig. 2), often referred to as the Arrowhead country, is more rugged. Several low ranges of igneous and metamorphic rocks, extending in a northeasterly direction, rise to altitudes of 1,800 to 2,000 feet. This is the area of greatest relief in Minnesota. Lake Superior, with an altitude of 602 feet, is the lowest point in the state. A rock escarpment, closely bordering the lake, rises 500 to 900 feet above it, and north of it in western Cook County are high rock hills, some of which attain altitudes up to 2,230 feet.

Drainage.—The rivers and lakes of this state are familiar to almost every Minnesotan and are perhaps the most interesting physical features to visitors. They have been important factors in the history of the state and today are valuable economic and recreational assets.

Minnesota derives its name from the Minnesota River, the largest river lying entirely within the state. William Watts Folwell, in the first volume of his four-volume work on Minnesota history, states that the name may have been derived from the Dakota word *Minisota,* which means "lost water" or "invisible," referring either to the losing of its water to the Mississippi or to the fact that Pike Island partly conceals the mouth of the river from the view of travelers on the Mississippi. However, the meaning most commonly suggested is "clouded water" or "sky-tinted water."

Water from Minnesota streams flows into three widely separated basins. It is estimated that 57 percent of the drainage goes to the Gulf of Mexico, 34 percent to Hudson Bay, and perhaps less than 9 percent to the Gulf of St. Lawrence. The altitude of Lake Itasca, the source of the Mississippi River, is 1,475 feet, and at the Minnesota-Iowa line the river is 625 feet above sea level; nearly two-thirds of the entire fall in the Mississippi is within the state or along its borders. Much of the state is in a stage of extreme topographic youth. There are numerous poorly drained areas and, in the north, extensive swamps, particularly in Beltrami, St. Louis, and Koochiching counties.

Lakes.—The total area of the lakes within the state is approximately

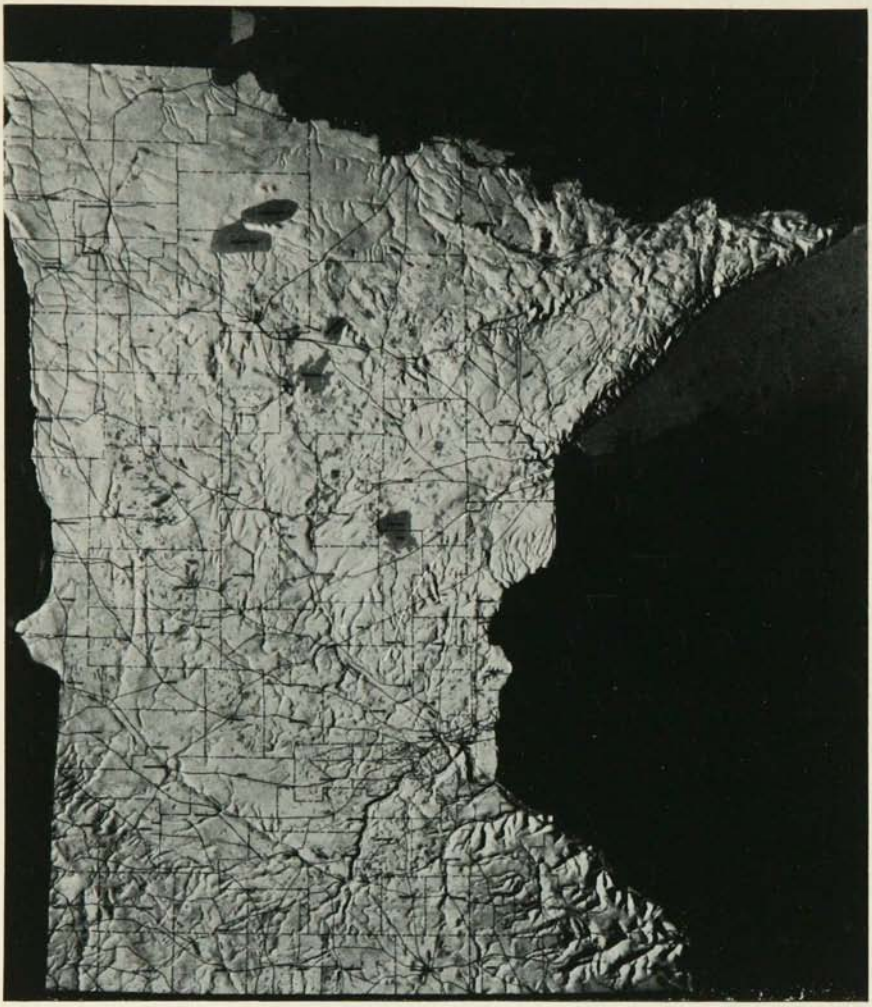

FIGURE 2. — Photograph of relief model of Minnesota, from the Geography Department, University of Minnesota.

5,650 square miles, almost 7 percent of the whole area. Lake Superior borders on Minnesota, and Duluth, situated on its western shore, is the largest harbor in the United States, in terms of tonnage loaded and unloaded. Red Lake, covering 440 square miles, is the largest lake entirely within the state, but it is very shallow. Mille Lacs, also very shallow, and Leech, Winnibigoshish, and Minnetonka are other large lakes. Minnetonka and the southern portion of Leech Lake occupy an intricate system of deep basins among ridges of glacial moraines. Other lakes lie largely in plains that are slightly lower than the adjacent areas.

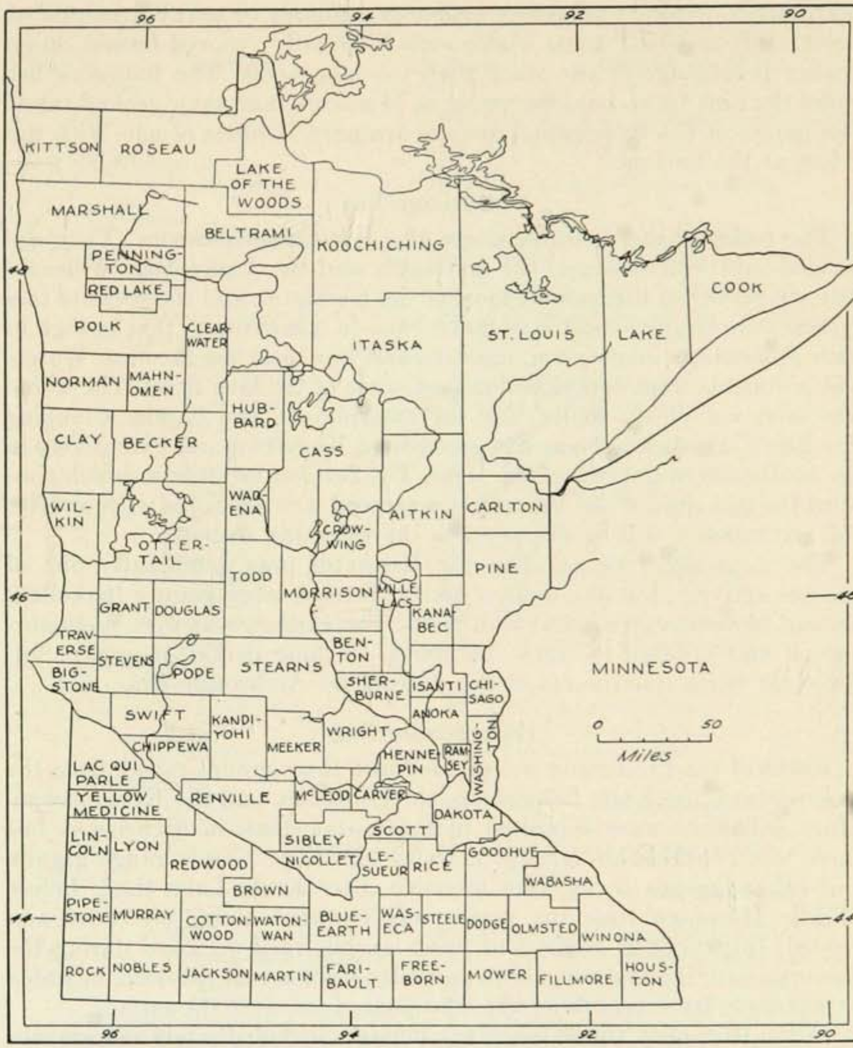

FIGURE 3. — Map showing the counties of Minnesota.

Over much of the state, except the northwestern, southwestern, and southeastern corners, small lakes are common features; their basins resulted from the uneven deposition of material by the glacier. In the northeastern part of the state some of the lake basins were formed in bedrock, at least in part by the gouging and plucking action of glaciers.

GENERAL GEOLOGY OF MINNESOTA

The geological map of Minnesota, Figure 4 on page 9, shows the areal distribution of rock formations, either as outcrops or under a mantle of glacial drift and soil. Areas where rock is actually exposed form a much smaller percentage of the state than the lake areas. The following list shows the rock formations occurring in Minnesota and their geologic ages. The names of the rock formations are arranged in order of age, with the oldest at the bottom.

Archeozoic Era

The rocks of the Archeozoic are the oldest in Minnesota. They are divided into two systems, the Keewatin and the Laurentian. Volcanic activity prevailed throughout most of the Keewatin, and the rocks of this system were largely basalt lava flows, basic in composition, that is, high in such elements as magnesium, calcium, and iron, and low in silica. Water-laid sediments were deposited between some of the lava flows. The whole was later complexly folded and metamorphosed, the basalts changing into green schists known as Ely greenstone. They crop out extensively in the northeastern quarter of the state. The Soudan formation, which contains the iron ores of the Vermilion range and was deposited with or after the greenstones, will be discussed in the following section.

The Laurentian period, like the Keewatin, was dominantly one of igneous activity, but the molten matter formed large granite batholiths instead of being extruded as lava flows. The earlier rocks were metamorphosed and uplifted by these batholiths. A long period of erosion followed the earth movements at the close of the Archeozoic Era.

Proterozoic Era

Rocks of the Proterozoic are divided into three groups called, from the base upward, the Knife Lake series, the Huronian, and the Keweenawan. More sediments were deposited in Proterozoic than in Archeozoic, but there was considerable igneous activity also. The Giants range granite and other igneous rocks were intruded after Knife Lake time. Before Middle Huronian time the region was elevated above sea level and eroded. Intrusions of acidic and basic igneous rock occurred during the Keweenawan; the Duluth gabbro and related dikes and sills were intruded at that time. Basic lava flows were also poured out on to the surface.

In the Huronian, the sedimentary deposits included sands and gravels, iron-bearing material, and mud; these have since been altered, by metamorphism acting through long periods of time, to the Pokegama quartzite, the Biwabik iron-bearing formation, and the Virginia slate. Perhaps the Sioux quartzite exposed in the southwestern quarter of the state and at New Ulm was deposited at about the same time as the Pokegama quartzite.

Sediments of the Keweenawan are thick and may be land deposits derived partly from the basic Keweenawan flows and intrusives. During this period the Lake Superior region developed into a structural basin. The thick, red, clastic series of sediments found in wells in the Minneapolis-St. Paul area are generally regarded as Keweenawan.

List of Rock Formations in Minnesota

Era	*System or Series*	*Formation*	*Approximate Thickness (in feet)*	*Character of Strata*
Cenozoic	Recent		0–200	Alluvial and lacustrine gravels, sands, silts, and clays
	Pleistocene			
		Glacial Drift	150±	Unsorted sands, silts, and clays
Mesozoic	Cretaceous			
		Coleraine (Benton)	50±	Gray to ferruginous shales
		Dakota	125	White to brown sandstone
Paleozoic	Devonian			
		Cedar Valley	100	Limestone and dolomite
	Ordovician			
		Maquoketa		
		Wykoff	50	Buff shaly dolomite
		Lime City	35	Shales and limestones
		Galena		
		Stewartville	60	Buff, mottled dolomite
		Prosser	90	White to gray limestone
		Decorah	60	Greenish gray shale
		Platteville	35	Gray to buff dolomite
		St. Peter	125	White uniform sandstone
		Shakopee	100	Buff to gray dolomite
		Root Valley	30	White to brown sandstone
		Oneota	200	Buff to pink dolomite
		Blue Earth	2	Pale green to white siltstone
		Kasota	6	White, calcareous sandstone
	Cambrian			
		Jordan	110	White to buff sandstone
		St. Lawrence	60	Buff, sandy dolomite
		Franconia	150	Green silts and sandstones
		Dresbach	300	Sandstones and shales
Proterozoic	Keweenawan			
		Hinckley	200	Buff to pink sandstone
		Fond du Lac beds	2000	Red sandstone and shales
		Extrusives and intrusives	?	Basalt flows, diabase, gabbro, and granite
		Puckwunge beds	100	Conglomerates and sandstones
	Huronian			
		Virginia (and Rove)	3000±	Slates and carbonate cherts
		Biwabik (and Gunflint)	750	Taconite, ferruginous chert, iron ore
		Pokegama (and Sioux quartzite)	200	Quartzites, slates, and conglomerates
	Algoman Intrusives		?	Pink and gray granites and porphyries
	Knife Lake-Temiskaming		5000±	Slates, graywackes, and conglomerates
Archeozoic	Laurentian			
		Saganaga granites, etc.	?	Granites, gneisses, and porphyries
	Keewatin			
		Soudan iron formation	?	Chert, jasper, and iron ore
		Ely greenstone	?	Green schists, greenstones, and basalts

Cambrian Period

From the close of the Keweenawan to the Upper Cambrian period the area stood above sea level and suffered much erosion. The Cambrian seas advanced progressively northward up the area that is now the Mississippi Valley and probably extended as far as Duluth. On the eroded older rocks there were deposited conglomerates, sandstones, shales, and dolomitic limestones (fig. 4).

The Cambrian rocks are well exposed along the St. Croix and Mississippi rivers from Chisago County to Iowa. The Jordan sandstone, the uppermost formation of the Cambrian series of sediments, ranges from 75 to 200 feet thick. It is one of the purest quartz sands in the state and is the chief water-bearing bed in the Twin City artesian basin.

The St. Lawrence formation lies directly below the Jordan sandstone. It is composed of sandy dolomitic limestone and siltstone that represents a transition from the deposition of dolomitic limestone to the deposition of the pure quartz sandstone of the Jordan. This mixture of quartz, silt, clay, and limestone has been found suitable for the manufacture of rock wool. It crops out at many places along the valleys of the Mississippi River and its major tributaries.

Below the St. Lawrence formation are the Franconia and Dresbach formations, with a variety of members, chiefly impure sandstones. Certain members are at least locally rich in glauconite.

There has been neither igneous action nor much metamorphism in the region since Cambrian sediments were deposited. These and later sediments are folded to form gently dipping basins and domes.

Ordovician Period

Apparently no elevation of the area occurred at the end of Cambrian time. Further subsidence ensued, and deposition continued without interruption into the Ordovician period. Calcareous muds now recognized as the Oneota and Shakopee dolomites were deposited early in the period. Later there was probably a slight elevation of the region, shallow water conditions extended over a large area, and a white quartz sand, known as the St. Peter sandstone, was deposited over much of southern Minnesota and farther to the south.

After the deposition of the St. Peter sandstone, subsidence recurred, and the Platteville limestone, Decorah shale, Galena limestone, and Maquoketa shale were deposited. Much of the southeastern quarter of the state (fig. 4) is underlaid by Ordovician sediments, which crop out at many places.

The St. Peter sandstone is a valuable quartz sand which has been used for glass manufacture. Building stone has been quarried from the Platteville limestone, but the Oneota dolomite is the principal source of architectural limestone in the state. At Mankato a natural cement plant and

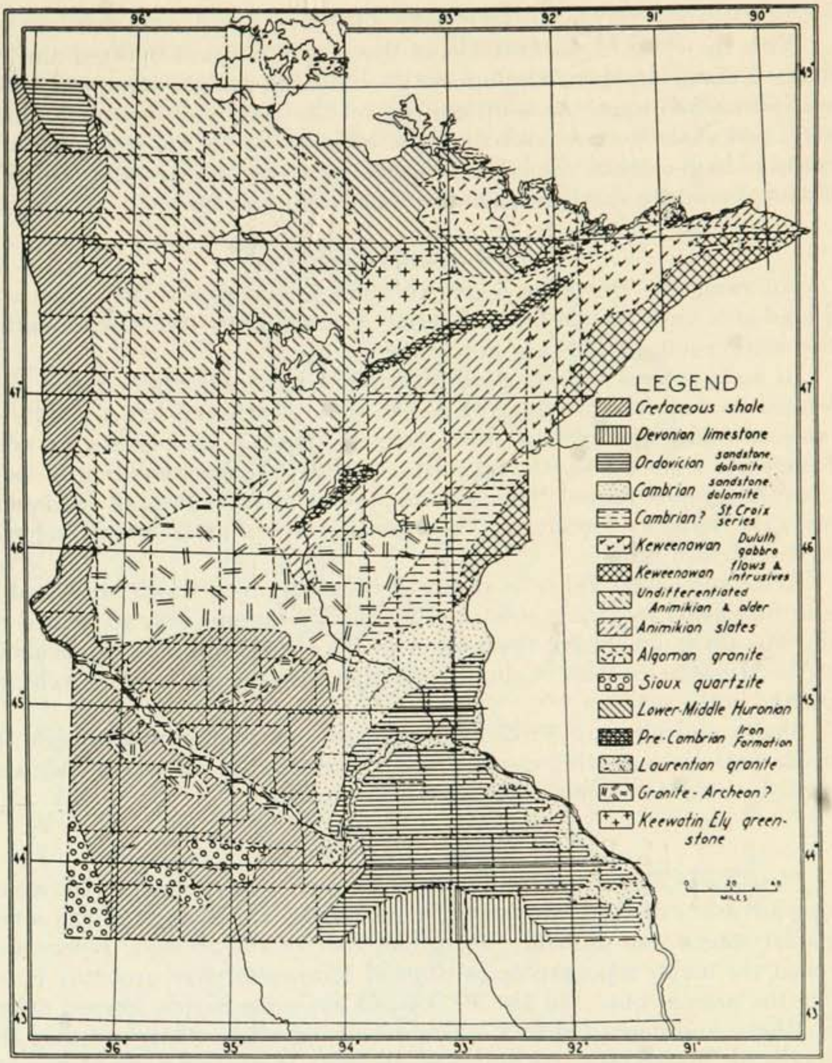

FIGURE 4. — Geologic map of Minnesota. After Schwartz. (See also the large colored map of the geology of the state available at the offices of the Minnesota Geological Survey.) What is here called Lower-Middle Huronian is better known as the Knife Lake series.

a plant producing rock wool both use the Oneota dolomite. Both the Oneota and the Shakopee formations have been used for making lime, and in St. Paul bricks are made from the Decorah shale. Weathered Decorah shale is serviceable for decolorizing oils.

Devonian Period

With the close of the Ordovician the area was again uplifted and remained above sea level throughout the Silurian period, after which the sea encroached upon the southern part of the state and limestone, dolomite, and shale were deposited. These beds are 50 to 100 feet thick and contain high-calcium limestone. Kilns operating at Le Roy, Mower County, produce excellent chemical lime from this stone.

Cretaceous Period

Following the Devonian a general uplift occurred, and the region was a land area until the Cretaceous period. Consequently strata representing the intervening periods are not known in the state.

In many places erosion during the pre-Cretaceous interval was prolonged so that weathering extended to some depth and left a mantle of loose material and residual clay deposits. The Cretaceous sea invaded Minnesota from the south and west, reworked the accumulation of loose materials, redistributed them, and deposited them as beds of sands and clays on the older formation. The deposits reached as far north and east as the Mesabi range.

Relatively small amounts of Cretaceous iron ores, which are Biwabik iron-formation materials reworked by the Cretaceous sea, are mined on the Mesabi range. Shark teeth occur in the Cretaceous ores, particularly in the Hill-Annex Mine, Calumet, showing that the ore pebbles were deposited in the sea.

Shales and clays of Cretaceous age are important raw materials for brick, pottery, and other ceramic wares fabricated in the state. They also furnish valuable supplies of semirefractory clay.

Cenozoic Periods

Pleistocene Epoch.—The Pleistocene epoch was complex, with recurring advances of thick ice sheets from Canada. The climate of the interglacial stages was probably much like that of the present. Before this epoch the major topographic features of Minnesota were probably much like the present ones, but the ice scraped out some basins, heaped debris in others, and deposited rock waste over wide areas, wholly altering the details of topography and drainage. In parts of northeastern Minnesota the ice scoured and scraped away loose material, leaving areas of bedrock exposed. Grooves and scratches made by boulders carried along at the bottom of the moving ice sheet may be observed on many rock outcrops. Most of the state, however, is covered by a thick layer of material (glacial drift) released when the ice melted. Drift deposits with a thickness of from 200 to 300 and even 500 to 600 feet occur in the area west of the Mississippi River and north of the Minnesota. At a few places in southern Minnesota the drift may exceed 100 feet, but over large areas it is very thin. The extreme southeastern corner of the state was not glaciated and is a driftless area. Figure 5 is a generalized map showing the distribution of glacial drift from the last ice sheet in Minnesota.

Drift deposits are classified into ground moraines, or till plains; terminal moraines; and outwash plains. Ground moraines are broad, comparatively flat tracts with low hills and shallow lakes where the ice, during its advance or during its final melting, deposited unassorted boulder clay. Locally the boulder clay contains lenses of sand and gravel. Terminal

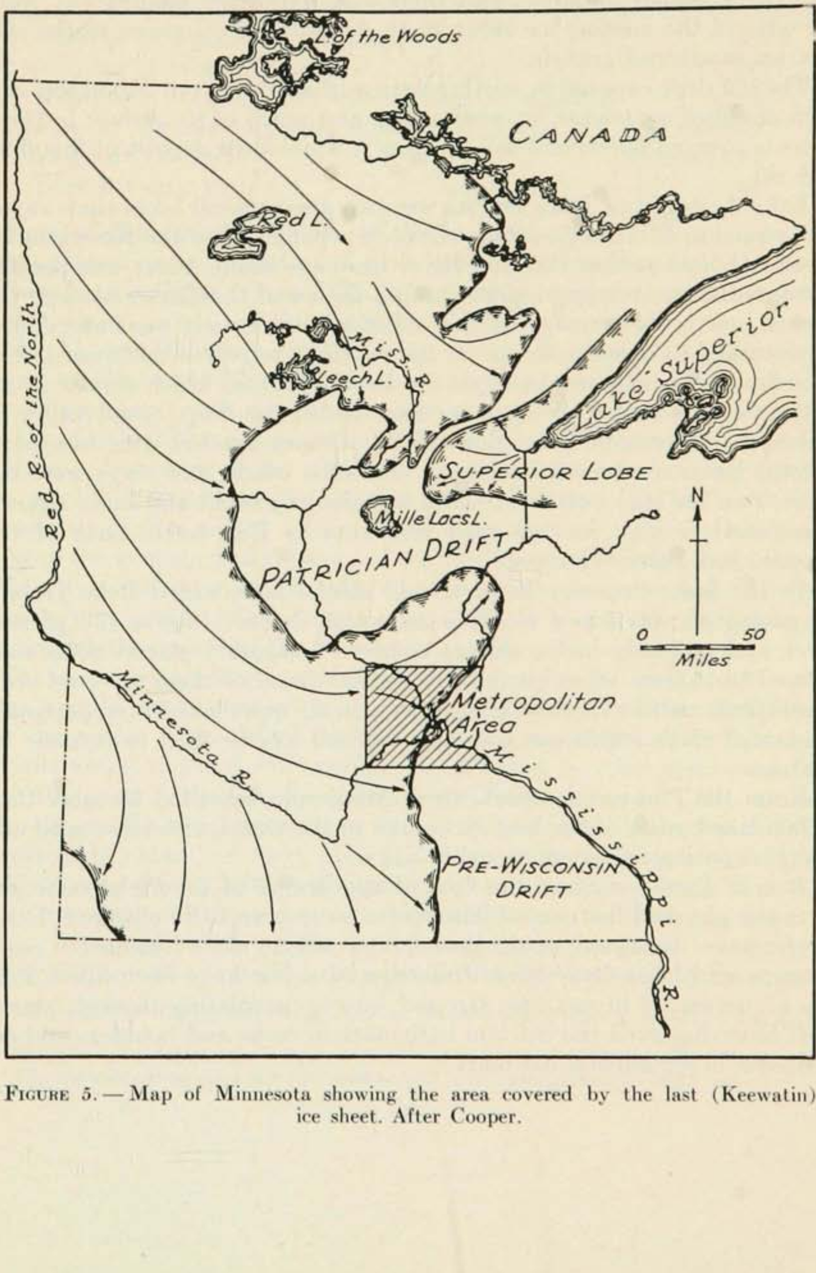

FIGURE 5. — Map of Minnesota showing the area covered by the last (Keewatin) ice sheet. After Cooper.

moraines are belts of rounded hills and short ridges, with interspersed depressions formed by the dumping of glacial debris at the edge of the glacier during a stage when the rate of melting approximately equaled the rate of advance of the ice, and thus caused the edge to remain essentially stationary. These moraines are largely boulder clay, but they contain more pockets of sand and gravel than the ground moraines. Outwash plains are broad, gently sloping plains of gravel and sand. They lie outside the terminal moraines and their materials were washed out from the edge of the melting ice sheet. Such deposits are discussed in the section on sands and gravels.

The old drift exposed in southeastern and southwestern Minnesota has been modified somewhat by weathering, and much of its surface in these areas is covered by several feet of loess, a windblown deposit of fine dust and silt.

Lake Agassiz and Lake Duluth are two great glacial lakes that waxed and waned in Minnesota during Pleistocene time. After the Keewatin ice sheet retreated within the Red River drainage basin, water was ponded between the surrounding highlands, and the ice of the glacier blocked the normal, northerly drainage. In this manner Lake Agassiz was formed, and it continued to increase in size as the ice front retreated northward. The lake drained southward through the River Warren, which served as an outlet for this vast body of water and eroded the deep, broad valley in which the Minnesota River flows today. Gravel beaches were formed at various levels as the lake declined, and silts, sands, and clays were deposited on the lake bottom. Finally the glacier melted and Lake Agassiz diminished in size, leaving such remnants as Red Lake, Lake of the Woods, and Lake Winnipeg.

In the Lake Superior basin an old glacial lake, called Lake Duluth by geologists, developed beaches and other features above the present level, and probably had a similar history. Temporary glacial lakes were formed in various other parts of the state. Some of them received sediments from melting ice and these, settling in the quiet lake water, deposited laminated clays which are now exposed and can be used in ceramic industries.

From the Pleistocene epoch, then, Minnesota inherited its more than 10,000 lakes, some of the best farm land in the world, extensive sand and gravel deposits, and some valuable clays.

Recent Epoch.—Since the final disappearance of the Pleistocene glaciers the physical features of Minnesota have been little changed. Large rivers have deposited sand, gravel, and silt in their channels. Some swamps and lakes have been drained, and a few have been filled. Peat has accumulated in swamps. Ground waters percolating through glacial drift have dissolved the calcium carbonate in rocks and boulders and deposited it in certain lakes as marl.

MINNESOTA'S IRON ORE DEPOSITS

INTRODUCTION

Minnesota iron ore[1] is not only the most important metallic mineral resource of the state, but also the most important iron ore resource of the nation. The salient statistics may be illustrated by the Census data for 1939.[2] Production has been enormously increased by the war.

Statistics of the Minnesota Iron Ore Industry, 1939

Number of operating companies	31
Number of mines	68
Number of wage earners (average for 12 months)	6,378
Tons of merchantable ore mined	32,163,859
Value at the mine	$96,241,025
Tons per man-hour	2.748

Most of this ore, 90 percent of the state's output, is from open-pit mines. Operations are conducted with heavy machinery so that the production per man-hour is large. The total tonnage shipped from Minnesota in 1941 was 67 percent of the national output.

The Mining Directory of Minnesota, published annually by the University of Minnesota Mines Experiment Station and distributed without charge, commonly includes the names of all mining properties and a partial list of names of men associated with the mining industry.

Since a discussion of the economic uses of Minnesota iron ore would also involve a discussion of the steel industry of the United States, no attempt at such a report will be made here. However, after a brief account of the geology and deposits of ore, and notes on mining and beneficiation, two major problems will be given particular attention: (1) the possible future use of low-grade material which is not merchantable at the present time, and (2) the use of manganiferous iron ores.

The use of certain portions of the iron-bearing formation of the Mesabi range usually called taconite[3] may prolong the mining industry in Minnesota for many years. Much low-grade material, intermediate between taconite and ore, is and will continue to be tested by concentration processes that may ultimately be used to beneficiate taconite. The mining industry should be encouraged to utilize this taconite in the future to a considerable extent, so that even if foreign high-grade ores should be available, we should have sufficient equipment and experience to make us independent of foreign supplies. Under certain conditions taconite, or ore as it would then be called, could probably compete with imported high-grade ore. The state has cooperated with the industry by encourag-

[1] The section on the geology of the iron ore deposits was compiled chiefly by Dr. J. W. Gruner.

[2] The iron ore industry; preliminary 16th Census of the United States, Dec., 1940.

[3] The taconite contains considerable amounts of iron, usually from 10 to 35 percent.

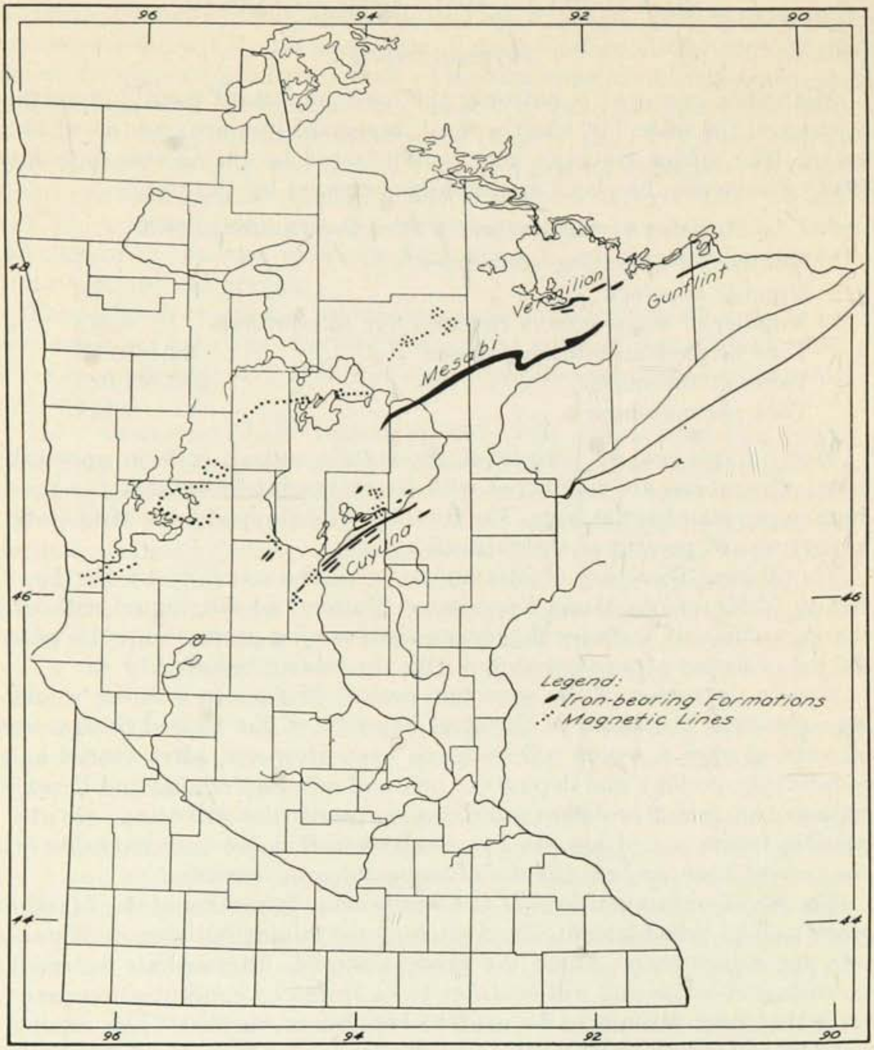

FIGURE 6. — Outline map showing locations of iron-bearing formations and of the more important magnetic lines in Minnesota.

ing research in the beneficiation of such low-grade material through its conservation department and the Mines Experiment Station at the University of Minnesota. Such cooperation should continue so that some use may be made of low-grade ores even by those who control the high-grade ores at present.

The manganese problem is of national importance, and would be even more important if supplies of foreign manganese ores should be cut off. The federal government, with the assistance of the state, should, as in the past, make detailed plans for the conservation of this metal while most of the normal requirements can still be imported. Federal, state, and private interests have made, and are making, great progress in the methods of beneficiation of manganiferous iron ores. Minnesota has no substantial amounts of high-grade manganese ore (ore containing more than 35 percent manganese), but it does possess the largest reserve of manganiferous iron ore in the United States (ore containing more than 5 percent manganese). The tonnage of manganese, calculated as metal, now proved to lie in these deposits is considerable. Estimates run from two million to five million tons. In normal years the United States has required about half a million tons of metallic manganese a year, a high percentage of it for steel.

GEOLOGY OF THE IRON DEPOSITS

A description of the geology of the Mesabi, Gunflint, Cuyuna, and Vermilion ranges will be followed by a discussion of titaniferous magnetite deposits, magnetic lines, and other deposits of iron. Figure 6 shows the locations of the iron-bearing formations and some of the magnetic lines in Minnesota.

The terminology of formations on the three principal ranges is locally somewhat modified from that given on page 7. The following outlines may serve to show the relations.

TERMINOLOGY OF FORMATIONS ON THREE PRINCIPAL RANGES

General	*Mesabi*	*Vermilion*		*Cuyuna* (Zapffe)
Proterozoic	Proterozoic	Proterozoic		
Keweenawan	Keweenawan	Keweenawan		Keweenawan
Huronian	Animikie	Huronian		Upper ? Huronian
Virginia Slate	Virginia	Rove		Crow Wing
Biwabik	Biwabik	Gunflint		Deerwood
Pokegama	Pokegama		?	Emily
Algoman	Algoman (Giants Range)			Aitkin
		Algoman		
Knife Lake	Knife Lake	Knife Lake		

THE MESABI RANGE

LOCATION AND EARLY DEVELOPMENT

The Mesabi range [4] lies northwest of Lake Superior and extends from Grand Rapids on the Mississippi River, a little north of east, about 100

[4] Leith, C. K., The Mesabi iron-bearing district of Minnesota: U. S. Geol. Survey Mon. 43, 1903. Wolff, J. F., Ore bodies of the Mesabi range: Eng. and Mining Jour., vol. 100, p. 96, 1915. Wolff, J. F., Recent geologic developments on the Mesabi iron range, Minnesota: Trans. A.I.M.M.E., vol. 56, pp. 142–169, 1917. Gruner, J. W., Paragenesis of the martite ore bodies and magnetites of the Mesabi range, Minnesota: Econ. Geol., vol. 17, pp. 1–14, 1922. Gruner, J. W., The origin of sedimentary iron formations: Econ. Geol., vol. 17, pp. 407–408, 1922. Gruner, J. W., Contributions to the geology of the Mesabi range, Minnesota: Minn. Geol. Survey Bull. 19, 1924.

miles to Birch Lake. The Giants range granite forms a ridge which is the main topographic feature of the district, and the iron-bearing rocks lie on the southern slopes. Because of differences in the dip and thickness of these gently sloping sedimentary rocks, the outcrops of the iron-bearing member range in width from half a mile to three miles.

In 1866 the first State Geologist of Minnesota referred to the ores of iron, both magnetites and hematites, in the elevated area that includes the Mesabi range. The early explorers examined outcrops chiefly at the east end of the range, where the formation is hard and not enriched. On November 16, 1890, a crew of men working for the Merritts of Duluth struck iron ore near Mountain Iron, and the discovery of other deposits followed rapidly. The railway lines reached the mines in 1892, and within a few years annual production increased to millions of tons.

Stratigraphy

All the rocks of the Mesabi district have been described in great detail by the Minnesota and United States geological surveys. Figure 7 shows a generalized cross section from north to south across the range. The succession of formations in the Mesabi range, in descending order, is as follows:

Geologic Succession of Mesabi Range

Cenozoic . . . . Glacial drift and alluvium
Unconformity
Cretaceous . . . . Conglomerate and shale
Unconformity
Proterozoic
  Keweenawan
    Duluth gabbro
  Animikie
    Virginia slate
    Biwabik formation (iron-bearing)
    Pokegama quartzite
Unconformity
  Giants range granite (includes Embarrass granite), Algoman
  Knife Lake series — slate, graywacke, and conglomerate
Unconformity
Archeozoic
  Laurentian granites and porphyries
  Keewatin greenstones and schists

Archeozoic and Proterozoic Systems. — The Keewatin greenstones and Knife Lake slates have been intruded by the great mass of Giants range granite, and together they form the basement upon which the Animikie sediments were deposited (fig. 7).

Animikie Group. — The first formation of the Animikie group is the Pokegama quartzite with a conglomerate locally at its base. The boulders and pebbles of the conglomerate can be recognized at many places as derived from the older rocks just below. Above the quartzite is the Biwabik iron-bearing formation, from 400 to 750 feet thick, which is the taconite described on page 18. The transition from the quartzite to the iron-

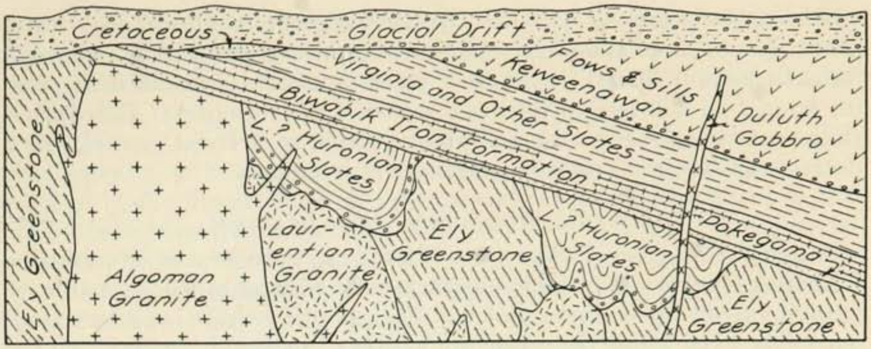

FIGURE 7. — Generalized geologic cross section of northern Minnesota in the vicinity of the Mesabi range. All of the iron ore now worked on the Mesabi range is near the eroded surface of the Biwabik iron-bearing formation, below the Cretaceous sediments and glacial drift.

bearing formation is fairly sharp and is marked by a thin conglomerate in some places and by algal structures in others. The Virginia slate lies conformably upon the Biwabik formation, but the change of material is somewhat abrupt. Immediately above the iron-bearing rocks, which may be locally as thin bedded as slates, there is a bed a few feet thick of gray-black limy slate or limestone; then come graywackes and slates of great thickness, with the upper limit of the slates not exposed.

Keweenawan System. — The Duluth gabbro and sills of basic rocks were intruded into the iron-bearing formation east of Mesaba. During recent years drilling and underground mining have disclosed a number of intrusive dioritic dikes near Aurora and dikes of highly altered igneous rocks in the Miller, Mohawk, and Belgrade mines. Other intrusions occur as far west as Nashwauk.

Cretaceous System. — Conglomerates and shales overlie a number of ore bodies west of Eveleth. Cretaceous fossils have been found in the shales west of Hibbing, but eastward the age of the conglomerates can only be inferred from their similarity to those west of Hibbing.

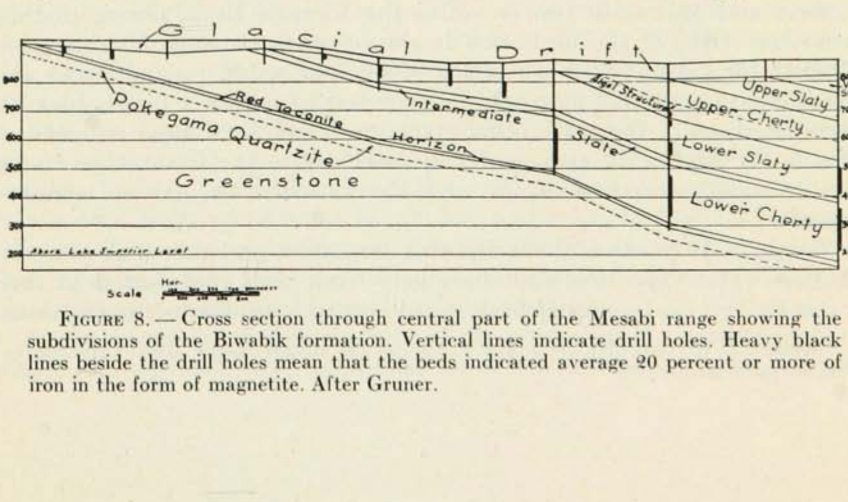

FIGURE 8. — Cross section through central part of the Mesabi range showing the subdivisions of the Biwabik formation. Vertical lines indicate drill holes. Heavy black lines beside the drill holes mean that the beds indicated average 20 percent or more of iron in the form of magnetite. After Gruner.

Pleistocene System. — On the Mesabi range, from Mesaba westward, probably not more than half a dozen natural exposures of the Biwabik formation can be found. In all other places a mantle of glacial drift ranging from 1 to 300 feet in thickness conceals the formation. The drift is thickest at the western end and relatively thin at Mesaba, east of which outcrops of the iron-bearing formation are numerous.

Biwabik Formation (Iron-Bearing)

General Character. — The least altered portions of the iron-bearing formation commonly contain a characteristic mineral called greenalite, in granules about the size of a pinhead. The granule texture is preserved remarkably, even where the greenalite has been changed by metamorphism or by weathering. The minerals of the formation include greenalite, magnetite, hematite, limonite, quartz, amphiboles, carbonates, and small amounts of graphite, kaolinite, pyrite, manganese oxides, and others. Mixtures of these minerals constitute the rock called taconite. This rock occurs in beds and lenses with a variety of recognizable facies. The different kinds of taconite are distinguished by qualifying terms such as slaty, cherty, banded, and conglomeratic. Taconite becomes iron ore where silica is removed by a natural process of leaching.

It is convenient to divide the Biwabik formation into four major divisions, the Upper Slaty, Upper Cherty, Lower Slaty, and Lower Cherty divisions. These divisions are based on certain recognizable lithological differences in the taconite. The cherty divisions consist largely of ferruginous chert in relatively thick beds. The slaty ones are thin bedded, and it is mostly in that sense that they resemble slaty rock. They are relatively high in carbonates and low in chert. The thickness of each division varies from place to place. As a general rule the Lower Cherty division is by far the most prominent (fig. 8).

Structure. — The structure is simple, with the beds dipping southeast. The dips range from 6 to 12 degrees east of Eveleth, and from 4 to 10 degrees west of Eveleth. A Z-shaped bend of the iron formation between Gilbert and Mountain Iron is called the Virginia Horn. Owing to this bend the strike of the formation is almost south between Virginia and Eveleth for a distance of four miles. Joints and bedding plane cracks are exceedingly numerous, as would be expected with such a brittle rock as taconite. Locally there are other structures, such as a large monoclinal fold in the Alpena pit area, and a normal fault in the Biwabik pit,[5] and the deformed structures on the east Mesabi where the gabbro intrudes taconite.

Origin. — Deposition of the Biwabik formation probably took place in shallow water. The iron and silica may have been contributed to this water by the weathering of basic rocks and by emanations from igneous

[5] Gruner, J. W., Contributions to the geology of the Mesabi range: Minn. Geol. Survey Bull. 19, pp. 7, 24–25, 1924.

magmas. The original precipitate on this range was probably largely greenalite, with chert, siderite, and iron oxides. These sediments have been metamorphosed and otherwise changed by hot solutions and by weathering.

Ore Deposits. — The ore deposits are concentrations of iron oxides in certain places in the iron-bearing formation. Not more than 10 percent of the area of the formation, if it were exposed to view by removal of the glacial drift, would be found to contain enriched ore. The remaining 90 percent or more would be taconite. The ore bodies occur in all four divisions of the iron formation, in the Upper Slaty, Upper Cherty, Lower Slaty, and Lower Cherty divisions.

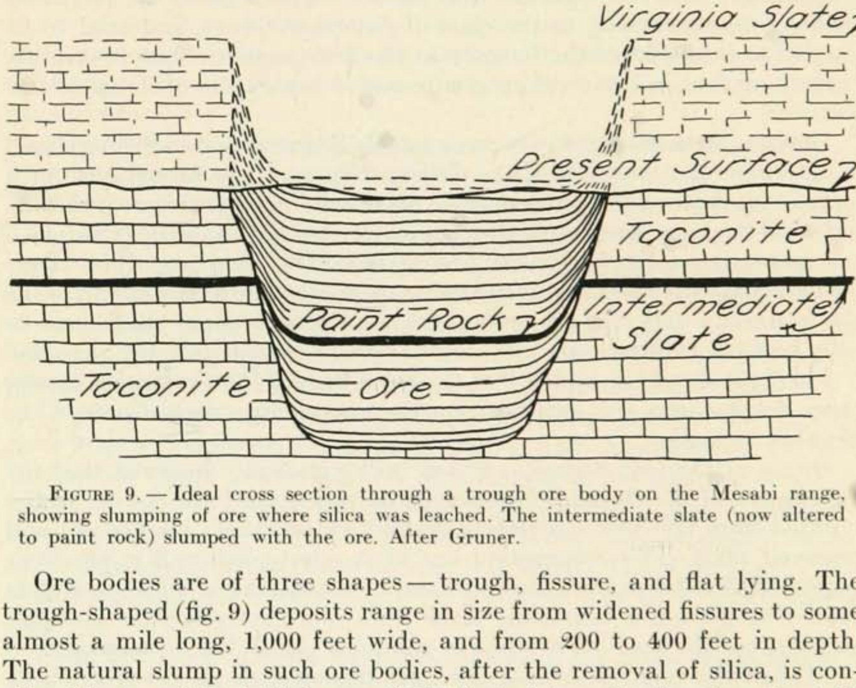

FIGURE 9. — Ideal cross section through a trough ore body on the Mesabi range, showing slumping of ore where silica was leached. The intermediate slate (now altered to paint rock) slumped with the ore. After Gruner.

Ore bodies are of three shapes — trough, fissure, and flat lying. The trough-shaped (fig. 9) deposits range in size from widened fissures to some almost a mile long, 1,000 feet wide, and from 200 to 400 feet in depth. The natural slump in such ore bodies, after the removal of silica, is considerable, an original thickness of 100 feet of taconite forming about 65 feet of ore. Paint rock layers on the edge of a trough frequently form planes along which slumping takes place. Fissure ore bodies are much smaller than troughs and may be only two or three feet wide, or even less, with a depth of as much as 100 feet and a length that may exceed 200 feet. Flat-lying ore bodies may look like troughs whose upper portions have been eroded, or they may be layers of ore which follow some particular flat-lying horizon of the iron-bearing formation.

For a discussion of local features of the ore bodies it is convenient to divide the deposits west of Mesaba into four groups: (1) the eastern group, between Mesaba and Gilbert; (2) the east central group, between Gilbert and Mountain Iron inclusive; (3) the west central group, from Mountain Iron to beyond Keewatin; and (4) the western group, around and west of Nashwauk. The first group includes several deposits of relatively small size, and two large irregular ones, the Stephens and Biwabik properties. The second group includes large trough and fissure ore bodies, with longer axes perpendicular to the changing strike of the Biwabik formation, and rather evenly distributed in all four horizons. These deposits include those of the Virginia Horn. In the third group the trend of the deposits is northwest or west and the deposits are not quite so deep as those east of Mountain Iron, but many are of great areal extent. The fourth group is in the so-called wash-ore area. The deposits are relatively shallow, usually belong to the class of flat-lying bodies, and tend to lie parallel to the strike of the formation. The Intermediate Slate is the only horizon marker in this western group, and it loses some of its usual distinctness.

Horizon markers (fig. 8) are recognizable layers or beds which are used to determine the positions of the different layers in ore formations. Such horizon markers as the Intermediate Slate,[6] the algal structure,[7] and the red basal taconite [8] are nearly always preserved even in the highly enriched ore, and they are relatively easily recognized. The slumping of the Intermediate Slate signifies the presence of ore beneath it, and the amount of the slump usually indicates the amount of ore. Figure 9 shows diagrammatically how the Intermediate Slate, now altered to paint rock, has slumped.

Finally it should be added that the basal beds of the Cretaceous locally carry detrital iron ores derived from the underlying enriched ores of the Biwabik formation.

Origin of the Ore Bodies.—It has been commonly believed that the enrichment of the Biwabik iron-bearing formation to form the ore bodies resulted from meteoric circulating ground waters which leached out and removed silica. This assumption has been questioned, and it has been suggested that hot waters from magmatic emanations or meteoric waters heated by igneous action could leach silica more actively than meteoric cold waters. The leaching of silica by solutions (fig. 9) has been recognized by all, but the temperatures of the leaching solutions have not yet been agreed upon. If any fractures crossed the original rocks they guided the solutions, hot or cold. The large ore bodies seem to occur where a considerable number of fractures are closely spaced.[9]

[6] Gruner, J. W., Contributions to the geology of the Mesabi range: Minn. Geol. Survey Bull. 19, p. 11, 1924.

[7] *Op. cit.*, p. 16.

[8] *Op. cit.*, p. 18.

[9] Students interested particularly in the origin of the ores are advised to read some of the following references: Gruner, J. W., Hydrothermal oxidation and leaching experiments; their bearing on the origin of Lake Superior hematite-limonite ores: Econ. Geol., vol. 25, pp. 697–719; 837–867, 1930. Gruner, J. W., Additional notes on secondary concentration of Lake

Distribution of Magnetite in the Biwabik Formation.— Magnetite occurs in large amounts in the taconite, but most of it is very fine grained. On the eastern Mesabi range much of the magnetite is coarser grained.

The greatest concentration of magnetite is in the Lower Cherty division, the middle portion of which consists chiefly of irregularly thick banded taconite, and to a lesser degree of mottled and greenalite taconite. This portion is thick and is fairly uniform in iron content between the towns of Mesaba and Keewatin.

Between Mountain Iron and Eveleth the Lower Slaty division holds some promise as a prospective magnetite horizon. The Upper Cherty division is much less uniform in magnetite content than the Lower Cherty except on the eastern Mesabi range, where it has been mined at Babbitt. In the Upper Slaty division magnetite is scattered and in small amounts.

The amount of iron in the form of magnetite in the richest portions of the formation varies between 20 and 35 percent, with an average of about 22 percent.

Assuming a future market for this magnetite, the size of possible open-pit mines depends on the limits placed on the quality of ore, the amount of overburden to be removed, and the depth to which open-pit mining could be carried on. By the use of present incomplete information, estimates were made of the amounts of taconite in certain areas, above a depth of 200 feet and containing 20 percent or more iron as magnetite. Of two areas, one between Mesaba and Biwabik and the other between Chisholm and Keewatin, each contained between 100 million and 200 million tons of taconite.[10] There was additional drilling in this area in 1942.

In the eastern fourteen miles of the Mesabi range the iron minerals are more largely magnetite, the grain is coarser, and the silica has not been leached out except in a few places. These magnetic but lean protores were known as early as 1866, but it was not until 1918–23 that a large experimental plant was developed at Babbitt. The company originally known as the Mesabi Syndicate later became the Mesabi Iron Company,[11] and some cargoes of rich concentrate were produced. The plant was closed in 1924.

Near Birch Lake, where this plant is located, the Biwabik formation is only about 350 feet thick. Here the Duluth gabbro has been intruded above the iron-bearing formation and has recrystallized it. This contact metamorphism has made the rocks highly magnetic. There are a few dia-

Superior iron ores: Econ. Geol., vol. 27, pp. 189–205, 1932. Gruner, J. W., Hydrothermal leaching of iron ores of the Lake Superior type—a modified theory: Econ. Geol., vol. 32, pp. 121–130, 1937. Leith, C. K., Lund, R. J., and Leith, A., U. S. Geol. Survey Prof. Paper 184, pp. 24–26, 1935.

[10] Gruner, J. W., Contributions to the geology of the Mesabi range: Minn. Geol. Survey Bull. 19, pp. 28–33, 1924.

[11] Swart, W. G., The Mesabi Iron Company enterprise: Min. Cong. Jour., vol. 12, pp. 267–272, April, 1926.

base dikes in the formation, but otherwise the best magnetite horizons are generally continuous.[12]

The main ore beds are near the center of the formation. A thickness of from 100 to 200 feet contains an average of more than 20 percent of iron suitable for magnetic concentration. Near Mesaba station the Lower Cherty beds, nearly 50 feet thick, are about equally rich. With the existing gentle dips and the considerable thickness of the beds, mining could be conducted in open pits along a belt several miles long on as large a scale as anywhere in the world. The rock is very hard to drill and break, but the problems of mining and milling do not seem insurmountable.

The milling can be regulated to furnish a high-grade product, and the operations can be modified to obtain such grades as are in demand, even those with exceptionally low phosphorus and high iron contents. One cargo of ore carrying 63 percent iron and 0.008 percent phosphorus was shipped out in 1918.

THE GUNFLINT RANGE

The Gunflint[13] area is in northwestern Cook County, T. 65 N., R. 4 W. and 5 W. (fig. 6). The iron-bearing rocks there cross the international boundary and have been traced on the Ontario side for several miles. West of Gunflint Lake the belt is about eight miles long. It is cut off by the Duluth gabbro, reappears only in small patches in Lake County, and is correlated with the Mesabi range in St. Louis County. The similarity of the iron-bearing formation to that of the Mesabi range made the area a good one for prospectors and promoters. The iron-bearing formation in the Gunflint area was altered by the heat of the gabbro so that it resembles the eastern Mesabi taconite rather than that of the main productive area of the Mesabi range.

In general the Gunflint iron-bearing rocks dip about 10 degrees to the south, but there are some minor anticlines and faults. Close to the gabbro the dip is much steeper. It happens that the gentle south dip of the formation on certain hills coincides with the slope of the hills, and a single bed, therefore, is exposed over the whole slope. Where the bed is rich in iron there is a large exposure of ore, but the thickness is not great.

Corresponding in minerals and in hardness to the eastern Mesabi ores, these Gunflint ores might be concentrated by the methods used by the Mesabi Iron Company.

The lower part of the Gunflint formation for 12 feet assays 38.23 percent iron in magnetite, which is higher than any such thickness on the Mesabi range, but would be rather lean and thin for underground mining. A bed 45 feet thick in Section 22, T. 64 N., R. 4 W., has 22.22 percent iron in the form of magnetite, but on the eastern Mesabi in more acces-

[12] Grout, F. F., and Broderick, T. M., The magnetite deposits of the eastern Mesabi range: Minn. Geol. Survey Bull. 17, pp. 1–58, 1919.

[13] Clements, J. M., U. S. Geol. Survey Mon. 45, pp. 374–390, 1903. Broderick, T. M., Economic geology and stratigraphy of the Gunflint iron range, Minnesota: Econ. Geol., vol. 15, pp. 422–450, 1920.

sible places there are more than 100 feet of equally rich ore. On the whole it seems that attempts to operate on the Gunflint range should wait until the larger and more favorably situated prospects on the eastern Mesabi have proved commercially profitable.

The Paulson mine was opened in 1892 to mine Gunflint magnetite in Section 28, T. 65 N., R. 4 W. Shafts were sunk 100 feet or more, wagon roads were built from Grand Marais, and a railroad was built from Port Arthur, Ontario. Some ore was found in the lower beds of the formation but hand-sorting was required to make it high grade and the project was abandoned in 1893, when production on the Mesabi range developed. The wagon road has been rebuilt for tourist travel, but the rails have been removed from the abandoned railroad.

THE CUYUNA RANGE

The magnetic iron-bearing rocks of the Cuyuna [14] range were discovered in 1895 by means of the dip needle, but it was not until 1903 that drilling was begun, just south of Deerwood on the South range.

This district is in the central part of Minnesota and extends in a southwesterly direction from about the center of Aitkin County through Crow Wing, Morrison, and Todd counties. The most important part of the range is in Crow Wing County (fig. 10). The district is about 65 miles long and from 1 to 12 miles wide, excluding the area north of the Mississippi River near Emily.

The Northern Pacific Railway, which ran through the Cuyuna area before ore was discovered, conveniently divides it into two parts, the so-called North range and South range. In 1914 the World War gave the Cuyuna range a great impetus, particularly in the production of manganiferous ores.

Stratigraphy

The succession and geologic age of rocks on the Cuyuna range are not completely determined. The following table gives Zapffe's idea of the stratigraphy of the rock formations.[15]

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

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

[14] Harder, E. C., and Johnston, A. W., Preliminary report on the geology of East Central Minnesota, including the Cuyuna iron ore district: Minn. Geol. Survey Bull. 15, pp. 1–178, 1917. Zapffe, C., Geologic structure of the Cuyuna iron district, Minnesota: Econ. Geol., vol. 23, pp. 612–646, 1928.

[15] Zapffe, C., The Cuyuna iron-ore district: 16th International Geol. Congress, Guidebook 27, pp. 72–88, 1933.

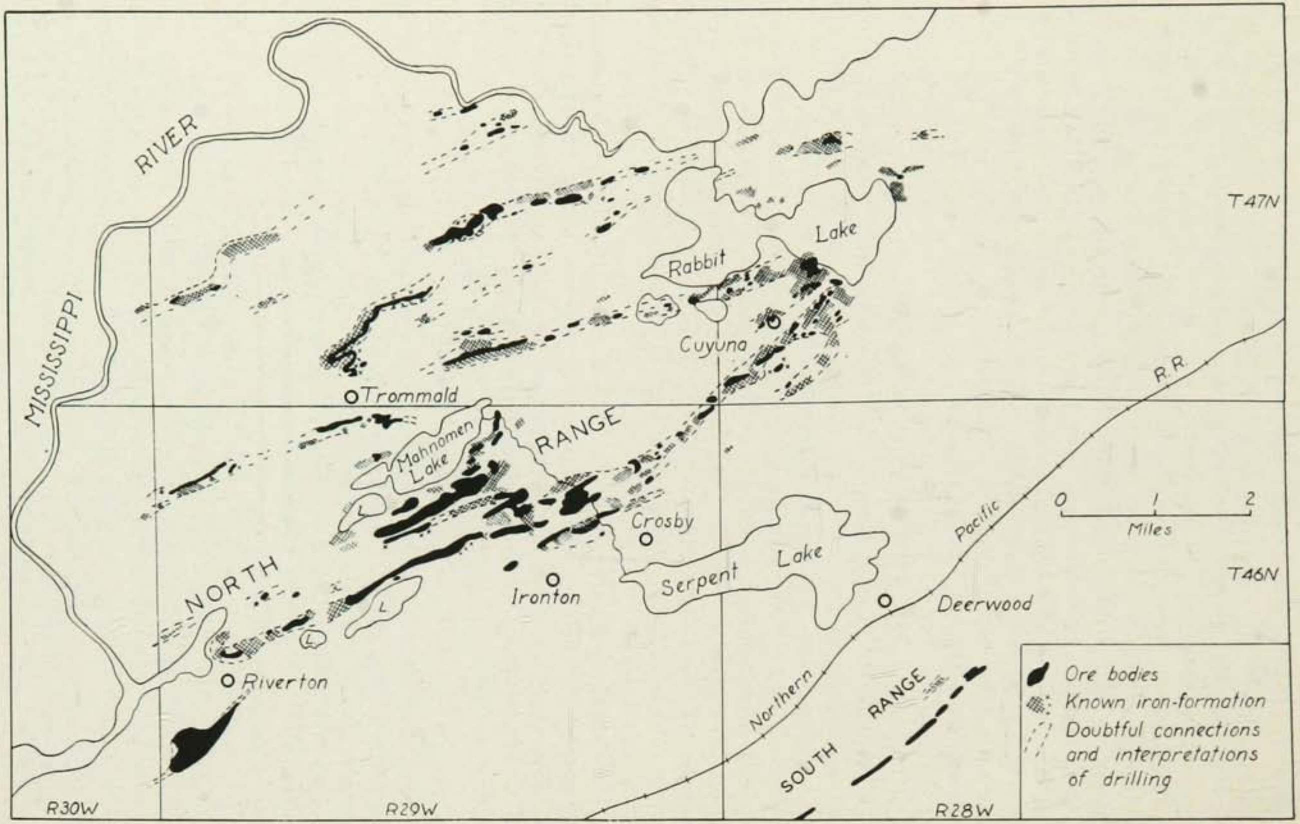

FIGURE 10. — Map of the northern part of the Cuyuna iron range, Minnesota.

GEOLOGIC SUCCESSION IN THE CUYUNA RANGE

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

which the iron ores of the Cuyuna range are largely derived, cherty and argillaceous beds alternate with beds rich in ferrous carbonates. Some have a banded or laminated appearance; others are thick bedded. Magnetite is a common constituent.

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

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

The North range includes a series of belts of the Deerwood member (fig. 10). The most northerly belt, south of the Mississippi River, is not well explored. South of this belt is one of more importance, containing the manganiferous iron ore bodies of the Merritt, Ferro, and Algoma mines. This belt appears to be more or less manganiferous throughout. Still farther south are a number of scattered occurrences of iron and manganese-bearing rocks in the region north and west of Mahnomen Lake and southwest of Rabbit Lake. South of these scattered bodies and almost connecting with them on the eastern end near Rabbit Lake is the main productive belt of the Cuyuna range, extending for a distance of about eight miles (fig. 10). It contains many important iron and manganiferous iron ores. North of the central portion of this main belt and southeast of Mahnomen Lake is a manganiferous iron-bearing area. South of this area is the Croft-Armour No. 2-Pennington belt, which is rather narrow but contains important ore bodies, mostly of iron, though some manganiferous ores appear locally. South of these are local occurrences of manganiferous and nonmanganiferous iron-bearing formation and ore in the southernmost areas of the North range.

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

Structure of the Deerwood Member.—All the rocks of the Deerwood and older formations have been folded into a complex series of close folds with steep dips to the northwest and southeast, those to the southeast predominating. The fact that the pitch of the folds is commonly almost horizontal causes the formation to appear on the erosion surface as approximately parallel northeast-southwest belts.

Ore Deposits.—The iron ore has been derived largely from banded cherty or slaty ferruginous carbonate rock. The ore bodies are roughly tabular in shape, the longer axes being parallel to the bedding of the enclosing rock. Their widths range up to several hundred feet and their lengths to possibly a mile. Some are shallow; others are 700 feet deep or even more. Most of the ore is soft. Some of it is hard, but this hard ore is more or less associated with the soft ore. The Cuyuna ore probably shows a greater variety of texture, composition, and color than the ore from any of the other Minnesota ranges.

Manganiferous ores are common in the North range, especially in the northern part. Nodules and small bodies rich in manganese commonly occur scattered in low-grade manganiferous iron ore and manganiferous iron-bearing rock, but they are too small to be mined separately. The chief manganese minerals are manganite, pyrolusite, and psilomelane, two or more commonly being associated in the same ore body.

The manganiferous ores [16] commonly follow definite stratigraphic horizons because more manganese was originally deposited in certain layers than in the beds on either side of them. (See also pp. 56–59.)

THE VERMILION RANGE

The iron ore of the Vermilion [17] district was first mentioned in 1850, but it was not until 1875, a decade after the fruitless quest for gold in this district, that exploration for iron became active. In 1884 the first ore was shipped from the Vermilion range.

[16] Harder, E. C., and Johnston, A. W., Preliminary report on the geology of East Central Minnesota, including the Cuyuna iron ore district: Minn. Geol. Survey Bull. 15, p. 135, 1918.

[17] Clements, J. M., The Vermilion iron-bearing district of Minnesota: U. S. Geol. Survey Mon. 45, 1903. Gruner, J. W., The Soudan formation and a new suggestion as to the origin of the Vermilion iron ores: Econ. Geol., vol. 21, pp. 629–644, 1926.

This district lies in northeastern Minnesota, in St. Louis, Lake, and Cook counties. It is from 5 to 15 miles wide, and the main production has been from St. Louis County. The topography is characterized by ridges, many with steep bluffs, and by lakes in the intervening depressions. As a whole there are no great differences in elevation in the area.

Stratigraphy

The geologic succession of rocks in the Vermilion district is shown in the following table.

Geologic Succession of Rocks in Vermilion District

Cenozoic	
Pleistocene series	Drift
Unconformity	
Proterozoic	
Keweenawan series	Duluth gabbro and Logan sills
Huronian (Animikie) series	Rove slate Gunflint formation
Unconformity	
Algoman granite	Vermilion granite and other intrusives
Knife Lake series	Slates, graywackes, conglomerates, and lenses of iron formation; also tuffs and porphyries
Unconformity	
Archeozoic	
Laurentian series	Granite of Saganaga Lake and other intrusive rocks
Keewatin series	Soudan formation (iron bearing) Ely greenstone

Archeozoic System. — The Ely greenstone is a basic igneous and largely volcanic rock. The original lavas issued from the earth probably under water, and it was upon this greenstone that the iron-bearing formation was deposited. The contact between the two is commonly quite sharp, but in some outcrops there may be thin layers of other material only a foot thick, such as breccia or conglomerate, mechanical sediments, greenstone conglomerate, or a graphitic black slate. The larger masses of the Soudan iron-bearing formation were formed as lenses during and probably after the outpouring of the lavas of the Ely greenstone. The details of the ores of the Soudan formation are given below.

The igneous rocks of the Laurentian series were intruded into the Ely greenstone and the Soudan formation. The granite of Saganaga Lake is of this period.

Proterozoic System. — The Proterozoic rocks, beginning with the Knife Lake series, lie upon the Archean unconformably. The Knife Lake series crops out chiefly in two large areas, one in the western part of the district and the other in the central and eastern parts. It occupies much of the shore and many of the islands of Vermilion Lake, extending westward from the lake to areas where the rocks are covered by the Pleistocene drift. The series has undergone complex folding so that it is impossible to determine its exact thickness, but it is many thousands of feet. The

Knife Lake rocks consist of interstratified slates, graywackes, and conglomerates, with a few small lenses of iron-bearing formation. The older classification into Ogishke conglomerate, Agawa iron formation, and Knife Lake slates is not applicable.

Certain porphyries and related igneous rocks were extruded during the sedimentation of the Knife Lake series. Later intrusive rocks of Algoman age, such as granites, granite porphyries, and others, were intruded along the range, the most extensive of these masses being the Giants range granite, the Vermilion granite, the Snowbank granite, and the Kekekabic (also spelled Cacaquabic) granite south of Kekekabic Lake.

The Animikie group occurs in a small area in the eastern part of the district just west of Gunflint Lake and in a few patches as far west as Gabimichigami Lake. It has been described under the heading of Gunflint range.

Nature of the Soudan Formation

The Soudan iron-bearing formation consists of well-banded ferruginous cherts, commonly called jaspilites. Portions of the formation are highly magnetic, the magnetite occurring in distinct bands between other bands of gray, black, or red extremely fine-grained chert or quartz. Where hematite replaces the magnetite the formation shows little magnetism and may be bright red. Small lenses of slaty material are associated with the ferruginous cherts. The Soudan formation is not a single large extensive iron-bearing formation like that of the Mesabi range but consists of lenses of relatively small dimensions. The largest ones are several miles long, but their very close and complex folding makes it difficult to estimate their widths.

Structures

The lenses of the Soudan formation are infolded in the Ely greenstone and dip steeply at many places. The conspicuously banded character of the formation makes it easy to observe the folding, which is very intense in some localities. In fact, the folding is so close and complicated that it is difficult to interpret with any degree of certainty.

The origin of the formation is sedimentary, and there is reason to believe that the rock in the Soudan formation is derived from siliceous iron-bearing carbonate in a manner similar to that in other Lake Superior ranges.

Ore Deposits

Ores are mined at Tower and at Ely. The ore bodies are as irregular in shape as the formation itself. The ores are mostly hard and dense bluish hematite and yield an exceptionally fine material for the blast furnace.

The principal iron minerals of the ores are dark red and blue hematites, with minor amounts of magnetite and siderite. In addition, there are small quantities of quartz, chlorite, calcite, kaolinite, and pyrite.

After deposition of the original iron-bearing formation, the ores were formed by processes similar to those forming ores in the other ranges: first, the alteration of the original formation to ferruginous chert, and second, the removal of the silica.

TITANIFEROUS MAGNETITE DEPOSITS

All prospects of titaniferous magnetite are in or at the border of the large intrusive mass known as the Duluth gabbro. This rock is exposed in the steep bluffs and ridges which extend from central Duluth southwest to Short Line Park. From there it can be traced as a belt many miles wide for about 150 miles northeast. Although magnetite in sedimentary iron-bearing formations contains very little titanium, the magnetite deposits locally abundant in the gabbro are all relatively high in titanium. Titanium occurs in the mineral ilmenite ($FeTiO_3$) which resembles magnetite in general appearance. A few bands of gabbro richer in magnetite than average gabbro are known near Duluth, but they are thin and have been given little attention. To the northeast, in Lake and Cook counties, there are many larger outcrops and shallow pits, and many diamond-drill holes have been put down to explore possible deposits. In the last fifty years hardly a summer has passed without some party of explorers or investors going into the region to look at the outcrops.

After the Gunflint Trail was opened to the Paulson mine a program of drilling was conducted by the Johnson Nickel Mining Company on one of the largest groups of outcrops, that near Iron and Tucker lakes. Other extensive showings are known near Little Saganaga Lake, near Poplar Lake, and near Jack Lake on the Temperance River.

The titaniferous ores are classified into four kinds: [18] (1) inclusions of banded Gunflint formation to which titanium has been added by the gabbro, (2) irregular bodies, possibly of the same origin but more altered and no longer recognizable as iron formation, (3) banded segregations in the gabbro, and (4) dikes rich in titaniferous magnetite. Each kind has been prospected, and many samples have been assayed for iron, titanium, nickel, and other metals.

The largest and most promising bodies of magnetite are the segregations. In most of these the chief gangue mineral is feldspar, but in some there is olivine. The deposits are not long, continuous belts but occur in zones in the gabbro in which there are overlapping lenses of ore. Most of these lenses are thin and many are lean, but some are as much as 15 feet thick, and the zone can be followed by outcrops and magnetic mapping for some miles. There is a wide range in the quality of samples from test pits and outcrops, but few lenses have more than 50 percent iron. Several carry more than 20 percent titanium oxide (TiO_2). The inclusions of Gunflint formation have an iron content varying from 12 to 56 percent, and

[18] Broderick, T. M., Relation of the titaniferous magnetites of northeastern Minnesota to the Duluth gabbro: Econ. Geol., vol. 12, pp. 663–696, 1917.

though most of them are low in titania, some contain from 10 to 20 percent. The dikes and irregular bodies have about the same range of composition.

There has been little or no demand for such ores because blast-furnace men object to the presence of titanium in furnace charges. Within recent years the demand for titanium compounds for paint and smoke screens has greatly increased, and it may be that when high-grade titanium ores become scarce the use of titaniferous magnetite will receive serious consideration. The ores are being tested with this possibility in mind. If two concentrates can be produced by selected methods, one rich in iron and low in titanium and the other rich in titanium, both might find a market. Microscopic examination of the ores shows that in some of the prospects the two minerals magnetite and ilmenite are so intimately intergrown that such concentration could not be accomplished. Other prospects are worthy of further testing. Prices to be expected may be estimated from the sales of ilmenite concentrates carrying more than 50 percent TiO_2. A few thousand tons produced annually sold for $10 and $15 a short ton.[19]

Interest in these titaniferous ores has recently increased because they contain vanadium, valuable in making steel alloys with special toughness and resistance to fatigue. It has long been known that some old and perhaps inaccurate assays of the ores showed as much as 2.74 percent vanadium oxide, V_2O_5, but its occurrence and the methods by which it might be extracted were not well studied because it was not supposed to be of any importance.

A recent study by J. R. Balsley[20] of the United States Geological Survey indicates that (1) titaniferous magnetites commonly carry more vanadium than the magnetites with low titanium but that (2) in case of magnetic concentration the vanadium in the ore is concentrated with the magnetite fraction of the ore, not with the ilmenite or titaniferous fraction. The metallurgical process of recovery is being actively studied. Careful assays show up to 0.43 percent metallic vanadium in some of the best Minnesota titaniferous magnetites. Several of the highly magnetic concentrates from lean ore contain 0.50 percent V_2O_5.

IRON IN SOUTHEASTERN MINNESOTA

In southeastern Minnesota[21] the old erosion surface of the Maquoketa and Cedar valley formations is in places covered by a residual deposit of limonite. The best examples are probably in Olmsted, Mower, and Fillmore counties, particularly in Bloomfield and York townships of Fillmore County, where test-pitting shows up to 18 feet of a low-grade ore that grades downward into the limestone and still carries the fossils characteristic of the beds from which it was formed. Apparently part of the iron has been concentrated in such regions from a large weathering surface,

[19] Minerals Yearbooks, U. S. Bureau of Mines.
[20] Reported in a personal communication.
[21] Data from Dr. C. R. Stauffer and Dr. J. W. Gruner.

and in some localities, such as Mankato, Rushford, and Osceola Bridge, the transporting solutions have carried the iron downward into the lower formations, such as the Oneota dolomite and the Jordan sandstone, where thick iron crusts now occur in cracks and cavities. Arenaceous ores three to five feet thick have thus been formed in porous beds. During the summer of 1941 an experimental carload of the ore was shipped from Spring Valley to a beneficiation plant at Crosby for treatment, and in 1942 more than 1,100 carloads were shipped to St. Louis by rail. The better parts of the deposit run about 50 percent iron; the silica content is usually rather high, but the ore is comparatively free from other objectionable elements.

MAGNETIC LINES

The geologic map of the state of Minnesota [22] shows a series of lines of abnormal magnetic attraction. Certain belts of these lines are shown roughly in figure 6. They are partly based on surveys by the United States Land Office, showing abnormal compass readings, and partly on more accurate magnetic surveys by the Minnesota Geological Survey and by commercial companies. Such lines are scattered widely from the east end of the Gunflint range westward and southwestward almost across the state. Near the productive ranges some of these have been carefully mapped and at a few places along the lines holes have been drilled in exploration for ore. Much of the development of the Cuyuna range was guided by such lines. Elsewhere the results of drilling have not been very encouraging, and some of the lines have never been explored. Ores may yet be discovered, but exploration is costly, and magnetic lines do not necessarily indicate iron-rich formations.

Several different rocks may cause similar abnormal magnetic fields. In north St. Louis County one area of attraction was carefully mapped and found to be related to a syenite rock of no value. Other rocks, such as the Keweenawan flows and dikes of basalt, have been followed because they have similar magnetic attraction, some of them very strong. Furthermore, experience on the productive ranges shows that some of the best ores are less magnetic than the lean iron-bearing formations, so that the lines of strongest attraction are not likely to indicate the best ore. It is important that many of the lines are in a region very deeply covered with glacial drift. Nevertheless, some of the lines are known to be caused by belts of iron-bearing rocks like those of the Soudan formation and the exploration of several may be justified if the explorer clearly recognizes that the odds are not necessarily favorable to him.

MISCELLANEOUS PROSPECTS FOR IRON

Since Minnesota produces more iron ore than any other state it is only natural that the whole region should have been prospected for possible iron ore bodies, even where the surface indications are poor. From 1890

[22] Geologic Map of the State of Minnesota; Minn. Geol. Survey, University of Minnesota, 1932.

to 1927 persistent prospecting was conducted on some magnetites north of the Mesabi range. A few such prospected rocks are related to the Giants range granite lying directly north of the iron-bearing rocks in many places, but most of those actively prospected are related to the Vermilion granite extending from Vermilion Lake to the Ontario boundary. This great granite batholith intrudes the Knife Lake slates and schists and at a few places the greenstones of the Vermilion range. Inclusions and roof pendants of these rocks are numerous and widespread in the area of the batholith, especially in the southern half.

These iron prospects are of two kinds.[23] In Section 4, T. 63 N., R. 12 W. there are a series of test pits in a belt of rock high in magnetite. A specimen from the dump contains 55.39 percent iron and 5.97 percent TiO_2. The band is opened for a width of 4 feet and a length of about 100 yards, but no large tonnage is indicated. The early prospectors and geologists were in some doubt as to whether the magnetite originated from alteration of the Soudan formation or from segregation in the borders of the granite batholith. Recent studies favor segregation.

The deposits in the second group are more widely scattered and have been opened at more places. They are in pegmatite dikes of irregular sizes in the granite and enclosed schist. What might be called the best prospects show a large tonnage of very lean rock but only a very small tonnage that could supply, by hand-sorting, ore containing over 20 percent iron. The sizes of magnetite grains in pegmatites range up to that of a hen's egg and can easily be concentrated without fine grinding to a product with 60 to 70 per cent iron content. Prolonged prospecting, however, has not revealed any area of as much as ten acres in which the rock has more than 10 percent iron in a form that can be concentrated magnetically.

RELATION OF IRON ORES TO IRON FORMATION

Iron-Bearing Materials

Explanatory Statements.—Iron is the fourth most common element in the crust of the earth.[24] Like nearly all the other elements, iron came from igneous rocks or from sources that originally produced these rocks. In some cases the concentration of iron as oxides in the original igneous rocks is high enough to constitute an iron ore. In most cases, however, later processes of a different nature, such as the decomposition of other rocks, produced iron ores. The origin of the Minnesota iron-bearing formations and ores has been shown to be connected with these secondary processes. The composition and physical characteristics of the taconite and ores will now be considered, with regard to their classifications and their uses. A few definitions will facilitate this discussion.

[23] Grout, F. F., The geology and magnetite deposits of northern St. Louis County, Minnesota: Minn. Geol. Survey Bull. 21, 1926.

[24] Clarke, F. W., Data of geochemistry: U. S. Geol. Survey Bull. 770, p. 36, 1924.

Iron ore has been defined as mineral matter that can be mined for the manufacture of iron with profit.

High-grade iron ore (direct-shipping ore) is an iron ore that, after mining, can be smelted economically without prior concentration or mixing with ore of better quality.

Low-grade iron ore is an iron-bearing material that, after mining, must be concentrated or mixed with ore of better quality before it can be smelted economically.

Taconite is a term for the rock of which the Biwabik iron-bearing formation consists. The name may be applied to any part of the formation except the ore.

A *unit* is 1 percent of the total weight; for the short ton it is 20 pounds.

To *beneficiate* ore is to improve its chemical quality or physical structure by processing after mining. This is done by such operations as crushing, screening, washing, drying, jigging, and flotation.

To *concentrate* an ore is to reduce its bulk and improve its chemical quality. This term excludes crushing and screening when such processes do not reduce the bulk of the material treated. A *concentrate* is an ore-bearing material which has been concentrated after mining.

Iron ores are mainly oxides and carbonates. Iron is contained in large amounts in silicates and sulphides, and under special conditions these also are ores. In Minnesota the ores now mined are oxides. These are chemical combinations of iron and oxygen in varying amounts.

The important minerals of iron mined in Minnesota are hematite and limonite. A small tonnage of magnetite has been mined in the past but is not mined at present except in very small amounts with other ores. Some siderite or iron carbonate is found intermingled with the ores.

Magnetite has the chemical formula Fe_3O_4 and is a compound of the ferrous oxide, FeO, and the ferric oxide, Fe_2O_3. Magnetite contains 72.4 percent of the element iron. This mineral is steel gray to black in color. It is attracted by a magnet.

Hematite is ferric oxide, Fe_2O_3, and contains 70 percent iron.

Goethite contains combined water and has the chemical formula $Fe_2O_3.H_2O$. Hydrous iron oxide commonly contains more water than is indicated by the formula above (10.1 percent), and the mixture is called limonite.

Siderite is an iron carbonate, the chemical formula of which is $FeCO_3$, and theoretically it contains 48.3 percent iron. Heating the siderite will drive off carbon-dioxide gas, leaving magnetic iron oxide. Some siderite occurs in Minnesota, mixed with hematites and limonites in small amounts, but it is not mined separately as siderite.

Classes of Iron-Bearing Materials.—The iron-bearing formation and ore of the Mesabi range are of major importance not only because of the great tonnages of high-grade ore, but also because of the enormous bodies of rock from which iron may be concentrated in the future. The unaltered iron-bearing formations of the Vermilion and Cuyuna ranges dip more steeply and are not as uniform as the immense tonnages of taconite on the Mesabi range. Therefore the taconite deserves most consideration.

The classification of the Biwabik iron formation into four divisions (page 18 and fig. 8) is a stratigraphic or geological one, but it indicates the type of ore likely to be found in certain parts of a mine.

Another method of classifying iron-bearing materials has been adopted by the University of Minnesota Mines Experiment Station, for the Mesabi range in particular. These classes are three: Class I, high-grade ore; Class II, low-grade intermediate ore material; and Class III, low-grade iron-bearing rock.

Class I ores contain between 50 and 60 percent iron and from 3 to 10 percent silica and are good enough to be shipped directly to the blast furnace without concentration, though some may be beneficiated. From 75 to 86 percent of all the ore shipped from Minnesota each year during the ten-year period 1929–39 was of this class. Approximately a billion tons of Class I ore have been shipped from Minnesota since the beginning of mining on the Mesabi range. About a billion tons of this class remain on the tax rolls. Undoubtedly some additional high-grade tonnages will be found and developed in the future, but most of the promising areas have been rather fully explored.

Class II low-grade intermediate ore material is partly altered rock assaying from 40 to 50 percent iron, which is not marketed without concentration or mixing with high-grade ores. The leaching of silica from the original taconite has not been complete, but in portions of the Class II material enough of the silica has been removed or freed from the iron oxides so that further removal in concentration plants becomes a profitable operation. The better portions of Class II material grade into Class I material, or taconite.

The ores in Class II have been classified according to percentages of silica in the material. Some portions of these ores (decomposed taconite and thin layers of unaltered taconite) when separated from the ore particles by the jigging process are as poor in iron content as the original Class III iron-bearing rock.

The Minnesota Tax Commission assessed 1,149,873,000 tons of Classes I and II ore on the Mesabi as of May 1, 1939, nearly a billion tons of which were Class I ores. On the Cuyuna range the total of Classes I and II ore was 62,077,000 tons, and on the Vermilion range the total tonnage assessed was only 14,235,000 tons — all Class I ore.

Class III is low-grade iron-bearing rock called taconite on the Mesabi range. For every ton of high-grade concentrate that could ultimately be obtained from Class III material, about three tons of this taconite must be mined. It is believed that for each man required to mine a certain tonnage of direct-shipping ore seven men will be required to mine and produce an equal amount of Class III concentrate of the same grade. According to the Mines Experiment Station of the University of Minnesota, for every ton of direct-shipping ore still in the ground, there might be made 50 tons of high-grade concentrates from Class III taconite if mining could be carried to a depth of 400 feet. (See pages 21, 22, 42, and 43.)

The Class I and II ores may be direct-shipping or beneficiated ores; their further classification is based upon their suitability for the various grades of pig iron to be used in the steel furnaces. The Lake Superior Iron Ore Association of Cleveland, Ohio, recognizes five classes of ore: Bessemer; low phosphorus, non-Bessemer; high phosphorus, non-Bessemer; siliceous; manganiferous. During recent years another class, the high alumina ore, has been recognized, but it is such a special ore that its position is not yet assured.

Bessemer iron ores are distinguished from non-Bessemer ores by their low phosphorus content. The percentage of phosphorus in Bessemer ores must average 0.045 or less because of the necessity of keeping the phosphorus content in the finished steel below 0.100 percent. Phosphorus cannot be removed in the acid Bessemer converter.

Low phosphorus non-Bessemer iron ores range in phosphorus content between 0.045 and 0.180 percent. In the early days of the Mesabi range the Bessemer ores were in great demand because the acid Bessemer converter produced steel very cheaply. With the continued increase in the production of a low phosphorus non-Bessemer ore on the Mesabi range, however, the basic open-hearth furnace gained in favor for the making of steel. In 1929 about 10 million tons of pig iron were produced in the United States by the Bessemer process, as compared with almost 25 million tons of pig iron by the basic open-hearth furnace. The differential in price between the Bessemer and non-Bessemer ores has decreased to only 15 cents a ton.

High phosphorus non-Bessemer ores contain more than 0.180 percent phosphorus. Special types of foundry pig iron require an especially high content of phosphorus with 0.400 percent phosphorus as a minimum.

Siliceous iron ores contain from 18 to 20 percent silica or more. They are used under certain conditions in blast furnaces to increase the slag volume and to aid in the smelting of the ore.

Compositions of Iron Ores

Occurring with the oxides of iron and manganese are many impurities in the average iron ore. These impurities are silica, phosphorus, alumina, magnesia, sulphur, volatile impurities, and "intimate impurities." Manganese is an impurity only when present in excess of the amount desired in a particular grade.

Manganese is needed in steelmaking, especially to desulphurize the steel, but it also deoxidizes and makes the steel tough and resistant to abrasion. Ninety-five percent of all the manganese produced is used in the making of steel. See pages 58–59.

Manganiferous iron ores of the Lake Superior region have been classified by the Lake Superior Iron Ore Association as those analyzing over 2 percent manganese. The Minerals Yearbook of the United States Bureau of Mines records all tonnages of shipments of material over 5 percent manganese in the chapter on manganiferous ores, thus separating all such tonnages from tonnages of iron ore proper. The present classification of the bureau recognizes three types of manganese-bearing material: from 5 to 10 percent, manganiferous iron ore; from 10 to 35 percent, ferruginous manganese ore; and 35 percent or above, manganese ore. These three classes are based on the products they are supposed to produce: manganiferous pig iron, spiegeleisen (spiegel), and ferro-manganese (ferro), respectively.

The classification of the manganiferous iron ores of Minnesota as brown and black ores (see page 58) takes into consideration their silica and phosphorus content as well as the manganese.

Silica is an oxide of silicon of the same chemical composition as quartz. Originally much of the iron of the iron formation on the Mesabi range was combined chemically with the silica to form a silicate called greenalite. In that form it would have been impossible to separate the iron from the silica without a chemical process; but this chemical work was widely accomplished by nature when the mineral greenalite was changed to iron oxides and quartz (silica).

The average analysis of all the ores shipped from the Mesabi range in recent years shows between 8 and 9 percent silica. When the silica exceeds 10 percent there is usually a penalty for each unit (page 33) in excess of that amount.

The main problem in concentration methods, therefore, is the reduction of the silica content to a suitable amount by washing, jigging, or other processes. This removal of excessive amounts of silica from low-grade ores must be accomplished before shipment of such ores to the furnaces.

Phosphorus usually occurs with the iron ore minerals. Practically none of the phosphorus is removed in the blast furnace. Some phosphorus is actually picked up by the molten iron from the fuel and flux in the blast furnace. It can be removed, however, in the open-hearth steel furnace. Phosphorus in excess of 0.100 percent in steel causes it to break under shock when it is cold. It is thus very detrimental to such products as steel rails.

Alumina, or aluminum oxide, occurs as an impurity in the high-grade ores of Minnesota in the amount of about 2 percent. As a result the ratio of alumina to silica is approximately one to three, which is about the proper proportion to fill the requirements of the blast furnace slag.

Lime and *magnesia* occur in only trifling amounts in most Minnesota ores.

Sulphur is an impurity that causes steel to crack and break during rolling at high temperatures. It occurs in such steel in the form of iron sulphide. Since manganese sulphide does not have this detrimental effect, manganese is added to steel to produce a change from the one sulphide to the other. One and a half times as much manganese as sulphur is theoretically enough to accomplish this beneficial result; practically, it is much safer to have at least eight times as much manganese as sulphur. The sulphur content in Minnesota ores is usually very low, but when a higher content is encountered locally the ore can generally be mixed with low-sulphur ores to reduce the average sulphur content. There is little demand for ores containing more than a few tenths of one percent sulphur.

Volatile impurities include ordinary moisture, combined water, organic matter, and carbon dioxide. Drying at 212° F. removes most of the moisture, and ignition removes the combined water, organic matter, and carbon dioxide.

Intimate impurities include those impurities which are practically unremovable in ordinary commercial furnace practice — for example, virtually all titanium and parts of the phosphorus and sulphur. Titanium is not present in amounts sufficient to be harmful in the iron ores now being mined on the three Minnesota ranges. The so-called titaniferous iron ores of the state have not been merchantable.

Chemical Data on Taconite. — The ferruginous chert, or taconite, of the Mesabi range has not been analyzed so carefully or often as the ores. Nevertheless, attempts have been made to estimate its average composition. Van Hise and Leith give the following analysis of the formation,[25] (a

COMPOSITION OF TACONITE

	Supposedly Typical	*Average of Nine*	*Selected Eastern Mesabi*
SiO_2	60.51	58.71	45.17
Al_2O_3	1.20	.54	.67
Fe	25.22	25.71	33.80
MgO	.52	...	2.39
CaO	.67	...	3.02
Ignition	Small	1.96	...
CO_2	...	...	.58
TiO_2	None	...	Trace
Mn	...	...	.61
P	(.05 P_2O_5)	.021	.049
S	.59	...	...

sample probably from the Gunflint area) which is here tabulated beside the average of nine typical taconites of the main Mesabi and a selected typical sample of the magnetite rocks of the eastern Mesabi.[26]

The possibility of making a high-grade concentrate from such material is discussed on pages 42–44.

[25] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, pp. 181, 185, 204, 1911.

[26] Grout, F. F., and Broderick, T. M., The magnetite deposits of the eastern Mesabi range, Minnesota: Minn. Geol. Survey Bull. 17, p. 29, 1919.

Chemical Data on Ores.—The Lake Superior Iron Ore Association of Cleveland issues an annual pamphlet giving analyses of ores, from which the data in the table on "Analyses of Shipments" are taken.[27]

ANALYSES OF SHIPMENTS IN RECENT YEARS

	Mesabi			Vermilion			Cuyuna		
	Average 1930–39	1940	1941	Average 1930–39	1940	1941	Average 1930–39	1940	1941
Fe Natural	51.48	52.23	52.07	58.14	58.12	57.40	43.09	42.09	41.85
P	.064	.059	.060	.060	.069	.073	.257	.306	.232
SiO_2	8.09	7.56	7.64	6.90	7.38	7.93	9.97	10.50	10.32
Mn	.71	.65	.64	.10	.10	.10	6.02	6.66	6.75
Moisture	11.59	11.39	11.45	5.91	5.08	5.35	11.23	11.45	11.53

More complete estimates were made by Hart,[28] showing compositions of ores shipped before 1929. There have been few changes of importance in the general compositions. Shipments from the Cuyuna are higher in manganese and silica than in the early years. The grade of shipments from the Mesabi since 1920 has kept pace with the demands of the blast furnaces by processes of concentration. The grade of ore mined has not been as high as that shipped in recent years, because the shipped ore included so much concentrate. Some Mesabi shipments before 1920 had a high iron content. The average in 1902 was 56.07 percent iron natural and 4.35 percent silica.[29]

ESTIMATES OF COMPOSITION OF ORE SHIPPED BEFORE 1929

	Mesabi	*Vermilion*	*Cuyuna*
Fe	58.09	61.47	52.21
P	.064	.041	.233
SiO_2	8.13	7.44	7.40
Mn	.61	.08	3.89
Al_2O_3	2.12	2.86	3.14
MgO	.20	.14	.24
CaO	.25	.21	.53
S	...	...	...
Loss on ignition	5.20	1.26	7.64
Moisture natural	11.06	6.08	11.51
Iron natural	51.67	57.73	46.20

PHYSICAL CHARACTERISTICS OF ORES

The ores of the Vermilion range are partly red hematites and partly hard to soft blue granular hematites. At the Soudan mine the ore is very hard, but the ore from the mines at Ely grades from hard to soft. The Mesabi range ores are chiefly soft hematites and limonites, varying in texture from very fine to coarse and granular. The ores from the four divisions of the formation show different characteristics. The Cuyuna range

[27] Craig, J. J., Annual volumes, Mining Directory of Minnesota.
[28] Hart, Charles, Foreign iron ores: Trans. Am. Inst. Min. Eng., vol. 84, pp. 7–38, 1929.
[29] Swart, W. G., Min. Cong. Jour., vol. 12, p. 269, 1926.

ores are mostly medium-soft hematites and limonites, though some hard ores are found. Their color ranges from black to red, blue, brown, and brownish yellow.

The specific gravities of the Vermilion ores range from 5.10 for pure hematites to 4.40 for the lower grade ores. The hematite ores on the Mesabi range have a specific gravity of about 4.5, the limonite ores about 3.6, and the ferruginous chert or taconite about 3.3. The specific gravity of the hard ores of the Cuyuna range is 4.2 and that of the soft ores about 4.1.

The number of cubic feet per long ton of ore in place in the ground varies from about 9, for certain types of the Vermilion range ores, to 16 and even 18 cubic feet per ton for the lighter ores of the Mesabi and Cuyuna ranges.

The porosity of the ores of the Vermilion district ranges from less than 10 percent for the hard ores of the Soudan mine to 20 to 28 percent for those at Ely. The Mesabi range ores show an average porosity of approximately 40 percent. The hard ores of the Cuyuna range vary from 9 to 20 percent with an average of about 13 percent, and the softer ores from 33 to 36 percent.

Size preparation of iron ores for the furnaces has been given much attention in recent years, especially the ratio of the fine ores to the coarse material. The conclusion has been reached that such fine material should be converted into a porous coarse agglomerate for effective smelting. The sizes of the lumps should have a definite relationship to the porosity, which has been shown to have a direct bearing on the time required for reduction in the blast furnace.[30]

TECHNOLOGY AND ECONOMICS

Mining

Exploration and Development. — In unopened areas exploratory work is often conducted by means of magnetic surveys, to give some idea of the location and structure of the formation; by test pits, where the ores are near the surface; by churn and diamond drilling, where the ores are deeper; and by other underground methods.

Diamond drilling was first employed in Minnesota on the Vermilion range. In the soft ores of the Mesabi range churn drilling is the common method, diamond drilling being used only for taconite. "Structure drilling" for large blocks of formation is a recent development. Both diamond and churn drilling are used on the Cuyuna range.

Estimating. — From the exploratory data, the ore tonnages and methods of mining the ore body are determined. The tonnages are estimated by one of two methods: the average thickness and area method and the cross-section method. The former is applicable to ore bodies like those of

[30] Joseph, T. L., Porosity, reducibility, and size preparation of iron ores: Am. Inst. Min. and Met. Eng. Trans., vol. 120, p. 86, 1936.

the Mesabi range, most of which are much wider than they are deep. The cross-section method is very generally used.[31]

Mining Methods.—Three types of mining are in use in Minnesota: open pit, underground, and milling. In the open-pit method, the surface, or overburden, of glacial drift or other material is stripped from the ore and the ore is mined in the open pit by power shovels or other means. In underground mining a shaft is sunk through the overburden and down to a point usually below the bottom of the ore body. Drifts are driven under the ore, which is mined and hauled through these drifts to the shaft, where it is hoisted to the surface. Milling is a combination of open-pit and underground mining. The ore in the open pit is put into "mills" through which it is dropped to underground drifts, where it is hauled to the shaft and hoisted, as in underground mining.

About 90 percent of the ore from the Mesabi range is mined from open pits. The greater portion of the ore is less than 300 feet below the surface, and the overburden seldom exceeds 100 feet. After the overburden is removed, the ore body can be opened up for power-shovel mining. This method affords a low-cost mining operation, with great flexibility as to production. During periods of great activity it is possible to produce large quantities of ore in a short time; during periods of enforced idleness the maintenance costs are small. If the idle period is prolonged, however, the interest costs on the large open-pit development investments become burdensome.

An ore body may be mined by all three methods: the open-pit method for the more accessible portions; the underground method for the deeper portions and around the edges of the open pit where the ore is shallow; and the milling method for ore in the open pit which is below the levels which can be reached by the railroad or truck grades. Belt conveyors reach some ore not reached by railroads.

More than 400,000,000 cubic yards of cover had been stripped from the Mesabi range ore bodies up to 1929,[32] or nearly twice the amount of material excavated in the construction of the Panama Canal. The total material, stripping and ore combined, removed from one pit alone (consisting of the Hull-Rust, Mahoning, Sellers, Susquehanna, Webb, and Agnew mines), has approximately the same yardage as the material excavated from the Panama Canal.

Beneficiation

Ore may be beneficiated by crushing, screening, washing, drying, and other processes. The increasing importance of beneficiation is shown by the increasing percentage which beneficiated ores have made of the total shipments of iron ores from Minnesota. From 1906 to 1936 the percentage

[31] Methods of sampling ore bodies by test pits, drilling, open-pit, and underground workings, as well as by sampling of shipments, are described in *The Iron Ores of Lake Superior* (Cleveland: The Penton Press, 1930), by the metallurgists Crowell and Murray.

[32] The Mesabi iron range: Min. Cong. Jour., vol. 15, p. 790, 1929.

rose in 5-year periods as follows: 0.6, 8.9, 9.6, 18.3, 36.3, 35.0, and 42.0.[33] In 1940 the beneficiated ore was more than half the total.

Crushing and Screening. — In the operation of blast furnaces it has been found that large lumps of ore are reduced to metallic iron very slowly. Consequently, except for special purposes, the present practice is to limit the size of the coarsest pieces of ore that are shipped, and it is necessary to crush the oversized pieces. The treatment consists of passing the ore over a stationary or movable grizzly (grate), which divides the material into coarse and fine products. The oversize material is then crushed and combined with the grizzly undersize material. This kind of beneficiation has been in use for many years. It may be used in combination with other beneficiation processes.

Washing. — Large deposits of iron-bearing material have been encountered, especially in the western part of the Mesabi range, which are low in iron content and high in fine silica, or "sand." The ore formation has been softened and leached to such an extent that the particles of iron ore and those of silica are mechanically freed from one another. In order to produce a high-grade concentrate from this material it is necessary only to remove the fine, sandlike grains. Any method that will remove the material finer than 65 mesh will leave a high-grade concentrate. The simplest method is to wash the fine sand away from the coarser particles of ore. It may be accomplished with different types of machines, including washing screens or trommels, log washers, Dorr washers, and classifiers of various kinds. The total amount of washed concentrate produced in Minnesota up to 1939 is about 120 million tons.

Jigging. — In mining wash ores, deposits of low-grade material are frequently encountered in which the silica is too coarse to be removed by the washing operation. When this kind of material is passed through the washing plants, the fine silica is removed, but the resulting product contains so much coarse silica that the concentrate is not rich enough to ship. In 1924 a process of jigging this material was started in Minnesota, and up to 1939 about 6,500,000 tons of jig concentrate had been shipped. As ordinarily used, the jigging operation follows the washing operation. The ore is agitated by rapidly pulsating water through a screen upon which the ore is supported. This agitation causes the material of higher specific gravity to collect near the bottom at the surface of the screen, and the material of lower specific gravity to move toward the top of the ore bed. The operation is similar to shaking a pan of popcorn, which causes the hard grains — in this case the particles of good ore — to settle to the bottom. The operation in itself is very simple, but considerable auxiliary equipment is required for crushing, washing, and sizing the ore and drying the products.

Drying. — All iron ore as mined contains water. This water is not an especially undesirable constituent in the blast furnace charge, but if the

[33] Craig, John J., Mining Directory of Minnesota, 1941, p. 210.

ore is very wet, transportation costs may be unnecessarily increased by the weight of the water. For this reason it is desirable to dry certain ores. The dryers are long cylindrical tubes or kilns through which hot gases are passed countercurrent to the movement of the ore, the heat being produced by the combustion of coal on grates or by pulverized fuel. The first drying operation was started in Minnesota in 1912, and by 1929 about 5,500,000 tons of dried ore had been shipped. Just how much of the moisture should be removed from the ore depends upon the nature of the material. Some ores become very dusty if the drying operation is carried too far.

Sintering.—Some of the ores encountered in considerable quantities are not only high in moisture but also have a high ignition loss. Drying such ores produces an excessive amount of finely divided material, but by sintering ore of this kind a very desirable product can be secured. Sintering is accomplished by thoroughly mixing the ore with from 6 to 10 percent of coke breeze or other fuel and burning this mixture on a grate provided with a strong down draft of air produced by a suction fan. The ore particles are fused together by this process into a hard porous product.

Magnetic Separation.—As already mentioned, there are large quantities of iron-bearing rock known as taconite on the Mesabi range. This material contains only about 20 to 35 percent iron, much of which occurs in very small particles or narrow bands of magnetite and hematite disseminated throughout the rock. This taconite must be crushed very fine in order to separate the iron oxide from the rock. That part of the iron oxide which is in the form of magnetite may be concentrated by the use of magnetic separation. The usual procedure consists of crushing the rock to 100 mesh or finer, removing the magnetic oxide with magnetic separators, and then sintering the fine iron concentrate to produce a desirable product.

In exploration of the taconite formation as material for concentration, the University of Minnesota Mines Experiment Station sampled a series of sections from the Siphon (Spring) Mine to Coleraine. There were 55 samples of Upper Cherty and Lower Slaty horizons containing an average of 33.33 percent iron and 55 samples of Lower Cherty horizon containing an average of 32.51 percent iron. The concentration of some samples magnetically was possible by simple grinding, but about half the samples had so much hematite that they were given a reducing roast at 600° C. to make the oxide more magnetic (pages 43f.). The magnetic concentration was regulated to determine how much concentrate containing more than 60 percent iron could be recovered by different grinding.

Clearly it is necessary to grind to 100 mesh in order to recover 40 percent of the original material in the form of high-grade concentrate. At 100 mesh about 80 percent of the total iron in the rock is recoverable magnetically in high-grade concentrate. An example may illustrate this point:

THE PERCENTAGE OF HIGH-GRADE (MORE THAN 60 PERCENT IRON) CONCENTRATE RECOVERABLE FROM TACONITE OF GIVEN SIZES

Horizon	Percentage of Concentrate after Grinding to Mesh Size			
	8 mesh	28 mesh	65 mesh	100 mesh
55 samples Upper Cherty and Lower Slaty mixed	13.92	19.99	29.70	41.09
55 samples Lower Cherty	10.52	19.22	34.77	46.08

Samples of the Lower Cherty taconite crushed to pass a 65-mesh screen gave an average recovery of high-grade concentrate that weighed 34.77 percent of the original weight. Therefore 100 pounds of taconite containing 32.51 pounds of iron yielded 34.77 pounds of concentrate that assayed at least 60 percent iron; thus $.60 \times 34.77 = 20.86$ pounds of iron. When crushed to pass 100 mesh, the recovery was $.60 \times 46.08 = 27.65$ pounds of iron, or about 85 percent of the iron originally contained in the taconite.

Magnetic Roasting.—Much of the taconite on the Mesabi range contains iron oxide that is not magnetic, but the rock is otherwise similar to the magnetite taconite. This material, after being crushed to one-inch pieces, can be passed through a magnetic roasting furnace at a temperature of about 600° C.; if oil gas is then passed through it, the resulting product has iron oxide in the form of magnetite. After being crushed to the proper size, this product can be concentrated on magnetic separators. Since this is a complicated and expensive process the plants that have been in experimental operation may be considerably modified as experience shows what treatments are best.

At Cooley, Minnesota, a magnetic roasting and concentration plant was built in which taconite that cannot be concentrated by washing or jigging was roasted to the magnetic state and concentrated on magnetic separators. This plant was built through an arrangement with Butler Brothers of St. Paul whereby the University of Minnesota erected a 250-ton roasting furnace and Butler Brothers constructed the ore-handling equipment and the magnetic concentration plant. It was operated in 1934 and 1935 under the direction of the staff of the Mines Experiment Station of the university. During this period 29,074 tons of tailings rejected from two nearby jigging plants were roasted and concentrated magnetically, resulting in the recovery of 15,870 tons of merchantable ore. The university's interest in the plant was then sold to Butler Brothers, who put it into commercial operation in the spring of 1936.[34]

The Cooley plant was the first in this country to attempt to produce any considerable amount of iron ore by magnetic roasting, but at Anshan, Manchukuo, half a million tons of pig iron per year are being produced by

[34] Davis, E. W., Beneficiating low-grade iron ores: Steel, vol. 100, nos. 19 and 21, May 10 and May 27, 1937.

the use of sintered ore produced by the magnetic roasting and concentration process. In 1921, before any attempt had been made to concentrate the Anshan ores, large samples were sent to the University of Minnesota Mines Experiment Station, where the concentration characteristics of this material were studied thoroughly. It is similar in many ways to the taconites of the Mesabi range. This similarity shows that the low-grade ores of the Mesabi can be concentrated by the same process that has been in use commercially in Manchukuo for twelve years.[35]

Transportation

From the mines on the three Minnesota iron ranges the iron ore is shipped by train to Lake Superior, where by far the greater part of it is loaded into boats and transported down the Great Lakes.

The Duluth, Missabe, and Iron Range Railway hauls ore from the Vermilion and Mesabi ranges; the Great Northern from the Mesabi range; and the Northern Pacific and the Minneapolis, St. Paul, and Sault Ste Marie (the Soo Line) from the Cuyuna range.

With the exception of a few hundred thousand tons of all-rail shipments, the total shipment from the mines of Minnesota in 1941 — 64,061,000 gross tons — was loaded into boats at Duluth and Two Harbors in Minnesota and at Superior in Wisconsin, and was shipped down the Great Lakes. The Duluth, Missabe, and Iron Range Railway supplies the Duluth and Two Harbors docks, and the Great Northern, Northern Pacific, and Soo Line supply the Superior docks. The ore is shipped in steel cars of 50 to 75 tons' capacity.

At Duluth two elaborate docks, each 2,304 feet in length, handle the ore, which is dumped from the ore cars directly into a sufficient number of pockets in the dock to load a boat. Each pocket holds six to eight cars of ore, depending on the size of the cars. The ore may be of uniform grade, or it may be of different grades, which will mix during the loading and the unloading at the Lower Lake Ports, to yield a cargo of the desired composition.

The capacity of the ore boats averages about 8,500 gross tons and ranges from 6,000 to 14,000 tons. The boats are usually built with 18 hatches placed at 24-foot centers. Since the pockets of the ore docks are constructed with 12-foot centers, alternate pockets are emptied one at a time; then the boat is moved forward 12 feet and the other pockets are unloaded. About 40 pockets of ore make a cargo. Four boats may be loaded simultaneously from one dock — two on a side. Each dock has a capacity sufficient to load 12 or 13 average-sized boats. The peak year at the docks in Duluth was 1916, when 21,837,949 gross tons were shipped. The largest day's shipment was 266,176 tons. In 1941, 20,498,781 gross tons were shipped. (A "gross ton" is a Lake Superior term for a long ton.)

[35] Davis, E. W., Magnetic roasting of iron ore: University of Minnesota Mines Experiment Station Bulletin 13, pp. 72–87, 1927.

There are three docks at Two Harbors, the longest of which measures 1,400 feet; the next, 1,376 feet; and the shortest, 920 feet. Each of the larger docks has a capacity sufficient to load six average-sized boats, and four boats may be loaded simultaneously from one dock, two on each side. The largest volume of ore, amounting to 15,011,066 gross tons, was loaded in 1941.

At Superior, Wisconsin, are located the Great Northern and Northern Pacific ore docks. The Great Northern Railway has four docks ranging from 1,812 feet to 2,244 feet in length, and the Northern Pacific Railway has one dock with two extensions, making a total of 1,960 feet. The maximum shipment from Superior was in 1941, when 27,745,737 gross tons were loaded. The Soo Line dock in Superior burned in 1929, and the ore carried by the Soo Line is now handled by other docks.

In 1937 there were 304 American ore carriers on the lakes, with a total capacity of 2,594,600 gross tons, each boat averaging 18 to 20 trips per season. The average time for a boat to make a trip from Duluth to the Lower Lake Ports and to return is approximately seven days.

A small part of the ore remains in Duluth and is smelted by the American Steel and Wire Company, a subsidiary of the U. S. Steel Corporation, and by the Zenith Furnace Company of the Interlake Iron Corporation.

The steel and wire plant manufactures fence posts, wire fences, nails, rods, and bars. It was established in 1909 as the Minnesota Steel Plant, but since 1930 it has been known as the American Steel and Wire Company. Capacity production is approximately 2,000 tons per 24-hour day, and as many as 20 carloads are shipped in a day from the mill. Their steel fence posts are shipped all over the United States and even to South America.

The Zenith Furnace Company has made coke, coal, gas, and pig iron since 1904. Since 1930 it has been owned and operated by the Interlake Iron Corporation. Of the 160,000 tons of ore consumed annually by this company, about 90 percent comes from the Mesabi range and 10 percent from the Cuyuna range. Limestone is shipped from northern Michigan rather than from southern Minnesota because Michigan stone can be landed more cheaply in Duluth by lake transportation. About 80,000 tons of pig iron are produced yearly, of which about 50 percent is sold in the Duluth market and the remaining 50 percent shipped to Chicago. The peak year was 1929, when about 220,000 tons of ore were consumed to produce about 110,000 tons of pig iron. When the iron furnaces are operating, the excess coke from the coke ovens amounts to about 80,000 tons; when the furnaces are not operating, the excess coke is approximately 130,000 tons a year. The coke is shipped to points in Minnesota and the Dakotas and to Winnipeg. The gas from the coking process is sold in Duluth and Superior.

Taxation of the Iron Mining Industry

The mineral industry in Minnesota is taxed by the federal government on net income, as are other federal taxpayers. The State of Minnesota levies three types of taxes: ad valorem, occupation, and royalty.

Ad Valorem Tax. — Iron ore is taxed as real and personal property under the general property tax.[36] Real property upon which there is a mine or quarry is valued at the price that such property, including the mine or quarry, would sell for at a fair, voluntary sale for cash.[37] All property in Minnesota that is subject to a general property tax and not subject to any gross earnings tax or other tax in lieu of it is classified for taxation purposes.[38] This classification law became effective January 1, 1914.

The Minnesota Tax Commission reviews and equalizes mineral assessments every year because of the constantly changing conditions resulting from new tonnage estimates, shipments, changes from inactive to active status, or vice versa, and numerous other factors.[39]

The valuation of an iron ore deposit might be based upon the same statutory rule as that applied to other property; namely, the price for which it will sell at private sale, but while the "sales" method has been used successfully with urban and rural property as a basis for equalizing values, it is difficult to apply in the valuation of iron mines because a direct sale is seldom made, the ore usually being sold on a royalty basis. It is therefore necessary to use some other method in valuing iron ore.

The value of a mine for purposes of taxation is estimated by the following five steps: [40]

1. Estimate of the available ore supply.
2. Estimate of annual ore production, which with (1) makes it possible to determine the life of the mine.
3. Estimate of the selling price at the Lower Lake Ports, of the product in terms of the proper "unit" and analyses of the ore.
4. Estimate of the unit cost of production, which with (3) makes it possible to determine the profit per unit. Cost estimates in different cases involve mining, beneficiation, development, plant, rail and lake freight, insurance, marketing, social security, ad valorem taxes, occupation tax, federal income taxes, etc.
5. Computation of present value with reasonable rates of interest.

The Vermilion, Mesabi, and Cuyuna ranges are considered as separate units because of the different conditions — such as the types of the ore deposits, structures of the ores, and costs of mining — prevailing in each.

The valuation system for iron ore used six classes when it was adopted in 1907. Since 1920 there have been nine classes, the first eight ranging from 40.1 cents to 9.8 cents as the assessed value per gross ton. These figures represent 50 percent of the true value of the ore, which is estimated according to the kind of mining, grade of the ore, and the status of development of the property. Class 9 has no specified rates and is desig-

[36] Mason's Minnesota Statutes of 1927, Sections 1977 and 1979.

[37] *Idem,* Section 1992.

[38] *Idem,* Section 1993.

[39] Biennial Reports of the Minnesota Tax Commission, 1938–40.

[40] Comstock, E. H., The taxation of the mining industry in Minnesota, 34th Ann. Conference National Tax Association, St. Paul, Minn., October, 1941; Skillings Mining Review, November 1, 1941.

nated as *Special Classifications*. The rates of all these classes are broadly divided into two divisions: mine and reserves.[41]

Chapter 161, Laws of Minnesota, 1905, provides that whenever any mineral, gas, coal, oil, or other similar interests in real estate are owned separately from the surface rights, they may be assessed and taxed separately from such surface rights and may be sold for taxes in the same manner and with the same effect as other interests in real estate are sold for taxes.

Chapter 170, Laws of Minnesota, 1925, as it relates to minerals, provides that mineral rights or interests in lands conveyed to the United States, to the State of Minnesota, or to any governmental subdivision of either, for national or state park purposes, or for any other purposes, which the owner reserves, shall be assessed and taxed as minerals, separately from the surface of the land, and such interests may be sold in the same manner and effect as other interests in real estate are sold for taxes.

Chapter 364, Laws of Minnesota, 1937, reduces the basis of assessed value from 50 percent of the true and full value for those unmined tonnages that require beneficiation and have an ore recovery below 50 percent. For each drop of 1 percent in the ore recovery, a reduction of 1 1/2 percent is made in the percentage of assessed value to true and full value, which percentage shall never drop below 30.

Chapter 365, Laws of Minnesota, 1937, amended Mason's Minnesota Statutes of 1927, Section 1993, Class 1, relating to the classification of real and personal property. The amendment affects ore, mined by underground methods after August 1 of a calendar year, which requires concentration other than crushing or screening or both to make it suitable for commercial blast furnace use, and in stock pile on the first assessment date after being mined. For such taxable year only it is taxed as if it were unmined iron ore. Thereafter it is assessed as mined iron ore.

Occupation Tax. — Under the provisions of Chapter 223, Laws of Minnesota, 1921,[42] as amended by Chapter 307, Laws of Minnesota, 1925, and Chapter 85, Extra Session Laws of Minnesota, 1937, every person engaged in the business of mining or producing iron ore or other ores in the state is subject to an occupation tax upon the value of all such ore mined or produced annually, the tax thereon at a specified percentage being based on the value of the ore produced at the place where mined, less the deductions specified in Section 2 of the statute.

Since most of the ore is sold at the Lower Lake Ports, it is difficult to ascertain the value at the place where it is mined. Accordingly, in the calculation of the tax certain non-statutory deductions, such as stock pile loading, beneficiation, marketing, and transportation are deducted from the value at the Lower Lake Ports to determine the value at the mouth of the mine. From this value the statutory deductions are subtracted to

[41] Biennial Report of the Minnesota Tax Commission, 1936, pp. 95–97.
[42] Biennial Report of the Minnesota Tax Commission, 1936, pp. 99–103.

TAXES LEVIED ON THE MINING INDUSTRY OF MINNESOTA, 1914 TO 1941 [1]

	Ad Valorem Taxes				Occupation Taxes	Royalty Taxes	Total Taxes
	State	County	Local	Total			
1914	$ 1,314,538	$ 1,091,052	$ 4,318,887	$ 6,724,477	....	....	$ 6,724,477
1915	1,107,878	1,558,370	4,544,477	7,210,725	....	....	7,210,725
1916	1,033,435	1,435,123	5,791,702	8,260,260	....	....	8,260,260
1917	1,499,875	1,893,147	6,996,085	10,389,107	....	....	10,389,107
1918	1,056,441	2,330,623	9,715,429	13,102,493	....	....	13,102,493
1919	2,328,322	2,876,204	12,371,521	17,576,047	....	....	17,576,047
1920	1,607,491	3,208,335	16,024,401	20,840,227	....	....	20,840,227
1921	1,203,473	3,040,145	13,941,538	18,185,156	$ 2,238,328	....	20,423,484
1922	1,161,288	2,951,031	14,299,181	18,411,500	3,440,597	....	21,852,097
1923	2,298,710	3,300,036	14,056,522	19,655,268	6,126,443	$ 1,027,847	26,809,558
1924	1,682,383	3,143,135	13,910,838	18,736,356	2,859,735	895,825	22,491,916
1925	2,149,882	2,984,651	13,436,296	18,570,829	2,316,432	845,072	21,732,333
1926	1,458,007	2,912,173	12,897,499	17,267,679	2,725,312	910,636	20,903,627
1927	1,972,268	3,167,651	12,202,463	17,342,382	2,183,308	916,825	20,442,515
1928	1,347,033	3,129,570	12,367,746	16,844,349	2,466,257	879,520	20,190,126
1929	1,592,537	3,290,144	12,369,019	17,251,700	3,786,352	1,044,696	22,082,748
1930	1,366,684	3,262,329	12,456,632	17,085,645	2,782,361	921,167	20,789,173
1931	1,883,194	3,382,985	11,351,038	16,617,217	1,383,145	649,804	18,650,166
1932	1,959,006	3,201,138	10,697,346	15,857,490	260,604	415,793	16,533,887
1933	2,643,812	3,247,220	10,691,097	16,582,129	958,388	335,600	17,876,117
1934	2,762,996	4,059,152	10,843,984	17,666,132	1,228,626	364,129	19,258,887
1935	3,062,746	3,931,227	10,329,856	17,323,829	1,387,546	459,951	19,171,326
1936	2,798,071	4,459,946	10,754,161	18,012,178	2,637,977	547,048	21,197,203
1937	2,024,419	4,009,528	11,235,619	17,269,566	9,033,930	1,305,385	27,608,881
1938	2,004,850	4,123,766	10,126,596	16,255,212	1,618,439	607,988	18,481,639
1939	1,953,413	4,601,422	9,876,487	16,431,322	4,888,964	865,926	22,186,212
1940	1,843,693	4,305,838	10,205,338	16,354,869	6,387,220	1,107,548	23,849,637
1941	1,507,775	3,951,242	9,105,236	14,564,253	8,399,387	1,823,592	24,787,232
Total	$50,624,220	$88,847,183	$306,916,994	$446,388,397	$69,109,351	$15,924,352	$531,422,100

[1] Authority: Minnesota Department of Taxation.

obtain the amount on which the tax is based. These deductions at the mouth of the mine include a reasonable cost of labor and supplies, the cost either of removing the overburden or of underground development, the royalties paid on the ore mined or produced during the year, and a percentage of the ad valorem taxes levied for said year against the realty in which the ore is deposited equal to the percentage that the tons mined or produced during such year bears to the total tonnage in the mine — all such amounts to be determined by the Minnesota Tax Commission. Upon this calculated amount the tax is based.

Up to and including the year 1936, the tax was 6 percent of this calculated amount. The 1937 Legislature raised the tax for the year 1937 to 10 percent, and for 1938 and thereafter to 8 percent. (Chapter 85, Extra Session Laws of Minnesota, 1937, July 23, 1937.)

Royalty Tax. — The Royalty Tax Law was enacted by the 1923 Legislature as a complement to the occupation tax. Under Chapter 226, Laws of Minnesota, 1923,[43] as amended by Chapter 361, Laws of Minnesota, 1925, Chapter 234, Laws of Minnesota, 1931, and Chapter 84, Extra Session Laws of Minnesota, 1937 (July 23, 1937), a tax of specified percentage is levied upon all royalty received annually by any persons for permission to "explore, mine, take out and remove ore from land in this state." The percentage is the same as that of the occupation tax in each year.

Taxes Levied. — The table on page 48 shows the approximate amount of taxes levied on the mining industry in Minnesota for the period from 1914 to 1941, inclusive.

Past and Future of Minnesota Iron Mining

The future of the mining of iron ores and manganiferous iron ores in Minnesota is intricately interlocked with the fact that they are used almost entirely for the production of pig iron in blast furnaces. Small amounts are used in open-hearth furnaces and puddling furnaces to assist in these operations. Even smaller amounts are used in the manufacture of paint.

The geographical location of an iron and steel industry must take into account its accessibility to raw materials and the market for steel. When either or both change the industry may require relocation. The source from which the iron ore is drawn will depend upon the cost of delivering a unit of iron at a properly located steel plant and the cost of smelting this iron. Thus other than physical factors play a part in the mining of iron ore. Such factors are tariffs, taxation, and the freedom of the seas — the last named an important consideration in modern economy, and particularly in the making of steel.

Production of Iron Ore. — Since the beginning of mining on the Vermilion range in 1884, and up to December 31, 1941, the three iron ranges

[43] Biennial Report of the Minnesota Tax Commission.

of Minnesota have shipped about 1,295,000,000 tons of ore. Of this total the Mesabi range has shipped more than a billion tons. Shipments as recorded by the Lake Superior Iron Ore Association of Cleveland, Ohio, are given in the following table.

TOTAL SHIPMENTS OF IRON ORE IN GROSS TONS FROM MINNESOTA RANGES, AND FROM THE LAKE SUPERIOR REGION [1]

Years	Mesabi Range	Vermilion Range	Cuyuna Range	Total Lake Superior Region (U. S.)
Unknown	....	....	....	273,553
1854–60	....	....	....	242,994
1861–70	....	....	....	3,597,014
1871–80	....	....	....	11,246,045
1881–90	....	3,223,005	....	42,378,390
1891–1900	31,389,888	11,968,274	....	114,237,008
1901–10	193,495,975	15,138,295	....	321,661,102
1911–20	332,927,885	13,859,858	13,849,779	513,896,362
1921	16,349,935	869,354	489,500	22,798,728
1922	28,064,247	1,211,559	1,496,356	44,001,066
1923	41,806,230	1,278,684	2,220,733	60,771,348
1924	29,142,247	978,163	1,469,054	43,896,318
1925	35,890,174	1,437,741	1,514,053	55,534,812
1926	38,250,856	1,586,030	2,082,689	59,970,009
1927	32,975,506	1,547,847	1,981,501	52,344,099
1928	35,398,660	1,671,466	2,097,716	54,855,641
1929	43,008,239	1,873,742	2,596,186	66,157,359
1930	31,067,292	1,884,529	1,929,189	47,187,661
1931	15,270,411	1,140,710	898,090	23,496,228
1932	1,934,719	216,744	98,737	3,588,608
1933	13,471,625	740,404	741,139	21,672,410
1934	14,650,099	785,149	532,571	22,063,824
1935	18,876,642	857,099	798,481	28,502,606
1936	31,459,429	1,064,473	1,305,439	45,251,250
1937	45,932,539	1,453,080	1,775,445	63,219,208
1938	13,304,036	929,952	581,823	19,549,909
1939	30,314,857	1,417,360	1,290,673	45,436,667
1940	45,667,677	1,547,469	1,734,176	63,948,846
1941	59,772,543	1,847,094	2,441,042	80,747,859[2]
Total	1,180,421,711	70,528,081	43,924,372	1,932,526,924[2]

[1] Authority: The Lake Superior Iron Ore Association.

[2] The total in 1941 includes 47 tons from Fillmore County. Preliminary figures for 1942 are: Mesabi, 70,280,087 tons; Vermilion, 1,924,877 tons; Cuyuna, 3,035,532 tons; Fillmore County, 59,171 tons.

Up to the end of 1937 Canadian mines of the Lake Superior district had shipped 3,935,450 tons.

The production of iron ore in Minnesota and the United States is shown graphically in figure 11. The table and the graph do not tell the whole story, however, for the Lake Superior iron ores now average 51 percent iron, whereas the ores from Alabama, for example, contain only about 35 percent iron.

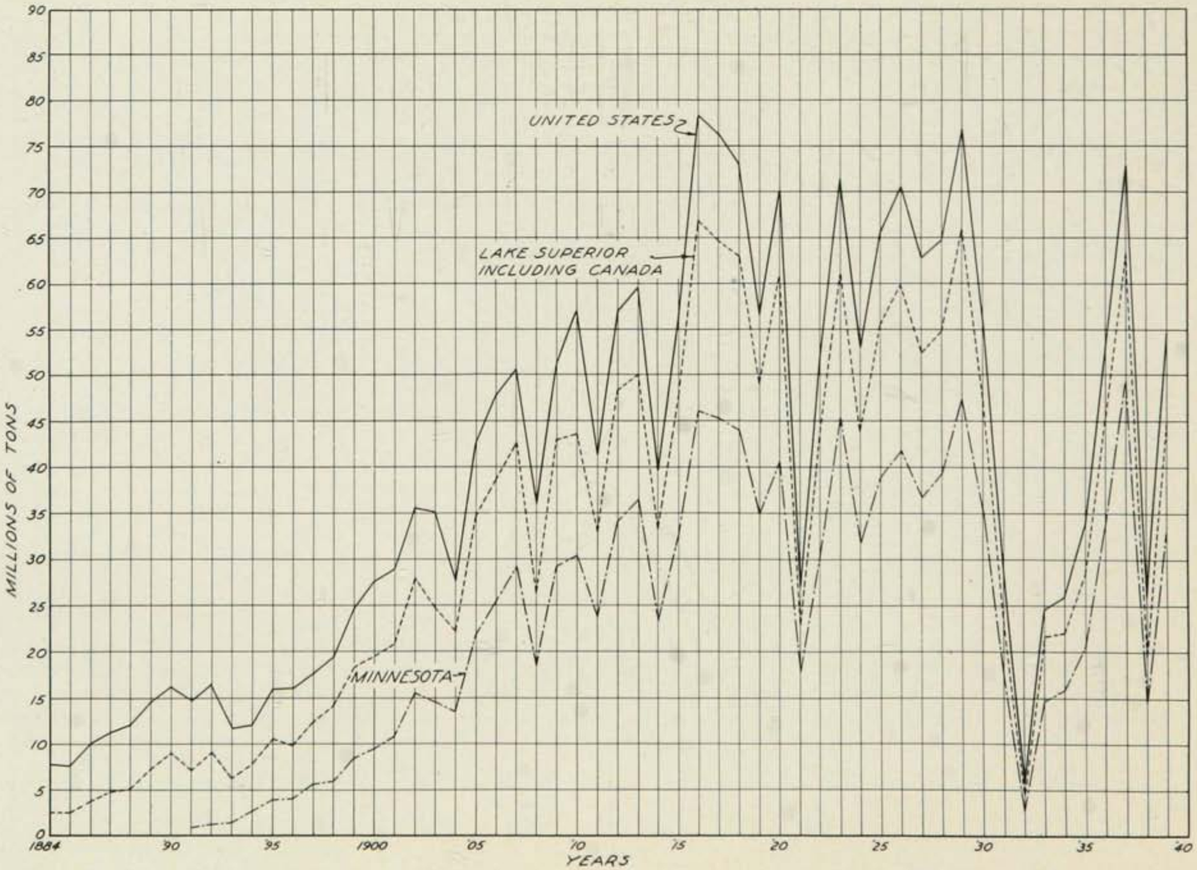

FIGURE 11. — Annual shipments of iron ores of Minnesota, of the Lake Superior region, and of the United States, since 1884. Records are in gross (long) tons.

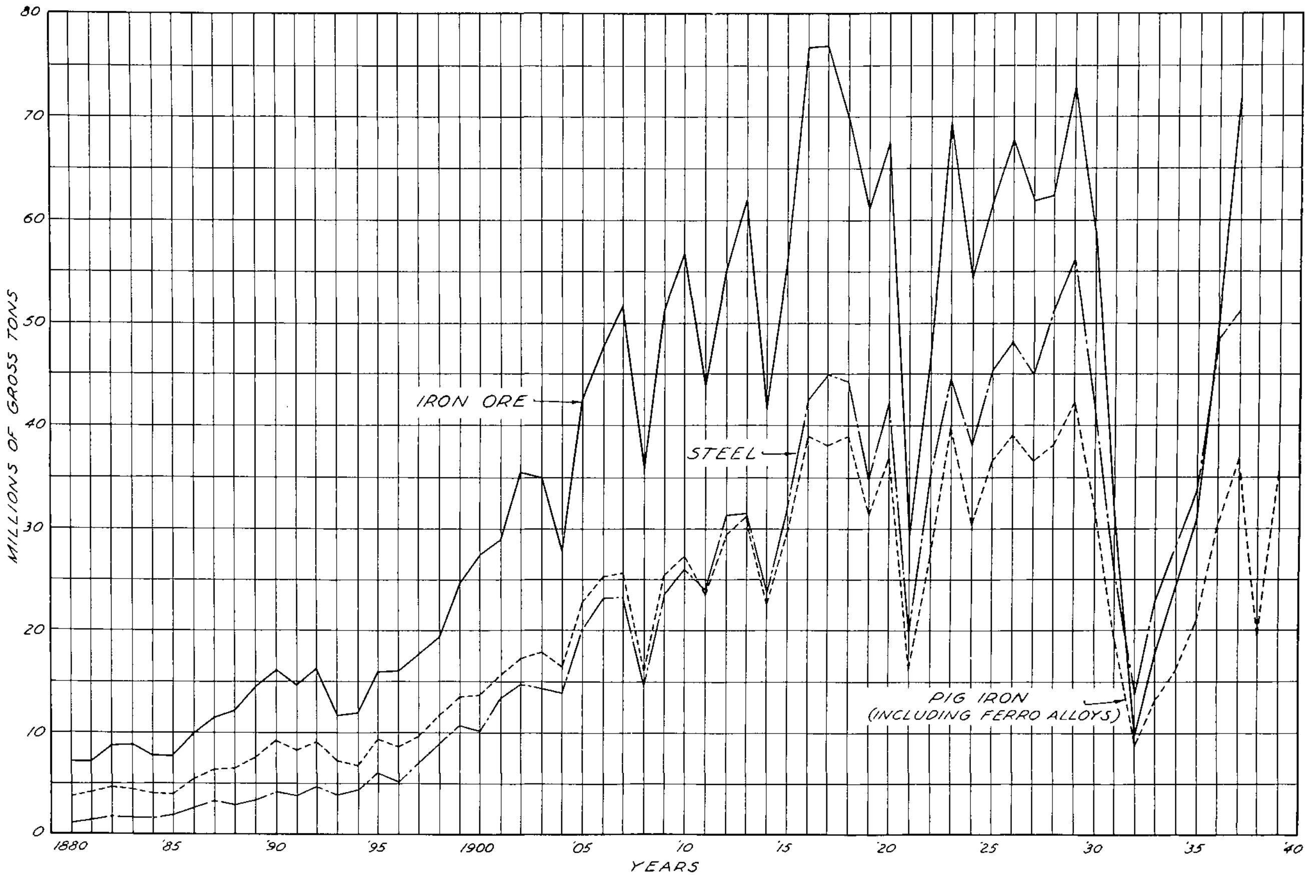

FIGURE 12.—Production of iron ore, pig iron, and steel in the United States since 1880.

Iron ore production reached a peak during the years 1916 and 1917. On the other hand, steel production reached a maximum in 1937, as may be seen in figure 12. The reason for this apparent discrepancy is that much scrap iron has been used for the making of steel in the last two decades. This fact, true not only in the United States but also throughout the world, greatly modifies the impression derived from tables of ore tonnages.

In the years 1935 to 1938, for example, France mined very large amounts of ore, in two of these years more than was mined in the United States. That ore, however, assays only about two-thirds as much iron as the ores of the Lake Superior region, so that France actually mined less iron. Germany during the same period mined relatively small amounts of iron ore but produced very large quantities of steel, in one year exceeding the production of the United States. Evidently she imported large quantities of French and Swedish ores for her steel industry. Another distortion of the picture results from the fact that countries like the United States export scrap iron, and Japan, on the other hand, imports it to make steel. For these reasons it is obviously impossible to show accurately the sources, grades, and ultimate distribution and uses of iron ores by simply listing annual ore tonnage figures.

Manganese-bearing iron ores have not been differentiated in these tables. Usually their tonnages are too small, in comparison, to list separately. The following table shows the quantities of manganiferous iron ores mined in Minnesota and the United States from 1926 through 1935.

MANGANIFEROUS IRON ORES MINED IN THE YEARS 1926–35, INCLUSIVE

Manganese Content	*Minnesota*	*United States*
2 to 5 percent	2,710,000 gross tons	not available
5 to 10 per cent	5,463,000 gross tons	6,084,000 gross tons
10 to 35 per cent	285,000 gross tons	968,000 gross tons

These figures were compiled by the Lake Superior Iron Ore Association and the United States Bureau of Mines. Most of the Minnesota ore was from the Cuyuna range.

Reserves of High-Grade Ores. — Reserves of ore may be classified into three classes from the point of view of their future availability: proven, probable, and possible.

Proven iron ore is ore that is now known to exist and that can be mined at a profit unless unforeseen circumstances should occur; *probable* ore is ore that explorations show in all probability exists and can be mined; and *possible* ore is material such as taconite that is indicated by the distribution of geological formations, but that cannot be profitably mined and concentrated by present methods.

The proven ore in Minnesota as of May 1, 1941, shown by the records of the Minnesota Tax Commission,[44] is about 1,196,184,000 tons in the ground and in stock piles. This total tonnage is largely on the Mesabi range — 1,115,951,000 tons. The Cuyuna total is more than 66,000,000 tons, and the Vermilion, 14,000,000 tons.

[44] Craig, J. J., Mining Directory of Minnesota, Mines Exp. Station, 1942.

These tonnages do not include ore which may later be developed or may be used as the high-grade ore becomes exhausted. This probable ore may increase the high-grade tonnages by as much as 15 percent. The tonnages in the wash-ore areas are difficult to determine before actual operations, but they also may be increased.

Reserves of Low-Grade Ores. — It is thus obvious that the reserves of high-grade ores are being depleted much more rapidly than the reserves of lower grades.

Marketing the high-grade ores presents no particular problem, but marketing the lower grades depends on many factors. Such ore has been mentioned as Class II on page 34. It is the material that must be concentrated by one or more processes or mixed with Class I ores before it becomes merchantable.

From 100 to 200 million tons of estimated ore of Class II are now merchantable. The remainder of the estimated total tonnage in this class — possibly 1.1 to 1.2 billion tons of concentrates after beneficiation, according to the Minnesota Mines Experiment Station — is at present marginal material, and it is here that the effects of high cost of operation and marketing are more noticeable. An increase of only a few cents in the cost of producing a ton of ore from such marginal material may keep large tonnages of this class from being used. Large-scale production of such material should be commenced before the high-grade ore has been exhausted in order to have sufficient time to perfect the processes of mining and beneficiation.

Taconite — Possible Ore. — The taconites of the Mesabi range are worthy of serious consideration as a possible source of iron ore [45] after the greater part of the high-grade ore has been mined and deep inroads have been made into the low-grade Class II material. Undoubtedly during the next 10 to 20 years the depletion of the high-grade ores will present a serious problem, and strenuous efforts will probably be made before that time to supplement the tonnage by concentration of low-grade material. If parts of this large reserve of taconite can be mined in competition with foreign ores, there is no question but that many of the operators of Minnesota, given proper encouragement, will be willing to spend large sums on research and operating equipment.

During the early twenties a large plant designed to treat such material was built at Babbitt [46] (page 21). It was operated for several months, but business conditions made it unprofitable to continue. It may be that the enterprise, possibly somewhat modified, will be given a new start, and similar developments may be expected farther west. There is even a possibility of a magnetizing roast and magnetic separation, as described on pages 42–44.

[45] Davis, E. W., Concentration of Mesabi hematites: Am. Inst. Min. Met. Eng. Trans. Iron and Steel Division, 1930, pp. 358–364.

[46] Swart, W. G., The Mesabi Iron Company enterprise: Min. Cong. Jour., vol. 12, pp. 267–272, April, 1926.

The University of Minnesota Mines Experiment Station has made certain estimates of available tonnages of taconite, based partly on data gathered by the Minnesota Geological Survey.[47] They believe that there is enough taconite to a depth of 400 feet (disregarding glacial drift) to make 57 billion tons of 60 percent iron concentrates. This tonnage would come from a belt 106 miles long and of varying width. Several factors may reduce this estimate considerably: (1) The taconite ranges widely in percentages of iron and portions containing 15 percent iron could hardly be mined profitably. (2) The slaty divisions are so fine in grain that, even after reduction of their iron to the magnetic state, concentration would be difficult. (3) These lean and slaty portions overlie the richer cherty portions in a great many areas, making the open-pit mining of these richer parts expensive. (4) The glacial drift cover is 200 feet thick at certain places and is commonly from 50 to 100 feet thick.

The best taconite prospects from the standpoint of uniformity of beds contain 25 to 32 percent iron as magnetite and have a thin drift cover near the east end of the Mesabi range.[48] The first attempt to mine taconite was made at Babbitt, because there it was not necessary to reduce the iron to the magnetic state, since most of it was already in the form of magnetite. In the central and western parts of the range much of the iron occurs as the less magnetic hematite, limonite, siderite, and silicates.

The competitive position of the low-grade iron-bearing formation, or taconite, cannot be predicted at present. Too many unknown factors enter into the situation, such as the probable construction of the St. Lawrence Waterway, the movement of the center of population of the United States, fuel supplies, rail and water transportation costs, investments in the Lake Superior region both for iron ore and for steel production, and the grade and availability of foreign ores as yet undeveloped.

Alabama contains about two billion tons of probable iron ore, some in open pits but most of it underground. Since the brown ores that can be concentrated by washing are nearing exhaustion, the possibility of concentrating the red ores is receiving much attention from the steel companies. The grade of the ore is the greatest obstacle in the use of Alabama ores, but ore, coke, and the limestone needed for smelting are all closely associated in the Birmingham district. Iron ores in New Jersey, New York, Pensylvania, and other parts of the country contribute important tonnages, but the real competitor of Lake Superior ores is the Alabama ore.

There are large tonnages of low-grade material in Michigan and Wisconsin, and the ores from these states have the advantage of lower freight rates to the furnaces. On the other hand, the ore formations dip steeply in contrast to the low dips of the formations of the Mesabi range. This structure of the Mesabi, added to the immense known tonnages, gives the Minnesota ores a decided advantage in lower mining costs.

If the St. Lawrence Waterway were built or if the steel industry moved to Atlan-

[47] Gruner, J. W., Contributions to the geology of the Mesabi range: Minn. Geol. Survey Bull. 19, 1924.

[48] Grout, F. F., and Broderick, T. M., The magnetite deposits of the Eastern Mesabi range, Minnesota: Minn. Geol. Survey Bull. 17, 1919.

tic ports, foreign ores would compete with our high-grade ores, at least on a small scale. If only the high-grade ores were involved, this competition would amount to little; but efforts to use the low-grade ores in the Lake Superior region to supplement the high-grade ores would drive ore prices high enough to allow the importation of high-grade foreign ore, especially if it could be brought in ships that would otherwise be empty. It is thought that 10 to 15 million tons could enter annually in prosperous years after the completion of the waterway. Undoubtedly some would enter.

On Bell Island near the mouth of the St. Lawrence River in Newfoundland is the Wabana district, with a large deposit of from 45 to 57 percent iron content extending out under the sea from Bell Island. The deposit is large — some billions of tons. It is ideally located for transportation to the Lake Ports if the waterway were completed. There are two disadvantages: it must be mined by underground methods under the sea, and the phosphorus content of the ore is too high for most of our present steelmaking facilities. This deposit has no advantage over the high-grade ores of Minnesota, but if our furnaces accommodated their smelting methods to the high-phosphorus ore, Wabana ore would compete with low-grade material from Minnesota.

Nodulized ore from Cuba must also be considered. When the Minnesota high-grade ore becomes scarce, and particularly if the waterway is built, Cuban ore might come into serious competition with Minnesota low-grade ore and taconite.

Ore from Chile, 5,000 miles away, is being imported into the United States for the plant at Sparrows Point near Baltimore. In recent years more ore has come from Chile than from Cuba, because of the high iron content and good structure of the Chilean ore.

Other deposits of sufficient size to be available for large-scale use in the lake furnaces are those in Brazil. Small deposits occur in the West Indies other than Cuba, others in Mexico, and still others in South America, in Venezuela, Colombia, the Guianas, Ecuador, and Peru. Brazil, however, may possibly become the chief competitor of the Lake Superior region. Brazilian ores are estimated to range from 60 to 70 percent in iron content and are very low in phosphorus. The deposits may possibly contain 7 to 8 billion tons, part of which can be mined by open-pit methods. On the other hand, Brazil has little coal and most of the ores will probably be smelted elsewhere. The distance from the mines to the coast is more than 300 miles by rail, and from there to the Lower Lake Ports via the St. Lawrence almost 7,000 miles. Transportation costs might be high.

Manganiferous Reserves. — Reserves of manganiferous iron ore are included without distinction in the figures already given for reserves of iron ore, because they make a very small part of the whole. Zapffe[49] in 1927 estimated the Minnesota reserves of manganiferous iron ores with more than 5 percent manganese at 44 million tons. Other estimates range from 20 million to 54 million tons, most of which is on the Cuyuna range. The Mesabi range may have from 2 to 10 million tons, but few of these ore bodies carry more than 5 percent manganese.

Conservative estimates of the tonnages and analyses of the Cuyuna reserves in 1927 were made by Joseph and Kinney,[50] but about 6 million

[49] Zapffe, Carl, Reserves of Lake Superior manganiferous iron ores: Trans. Am. Inst. Min. Eng., vol. 75, pp. 346–371, 1927.

[50] Joseph, T. L., and Kinney, S. P., Minnesota manganese ore in relation to the iron and steel industry: Univ. of Minn. Mines Experiment Station Bull. 12, pp. 13–17, 1927.

tons of brown ore (see page 58) have been mined out since this estimate was made. Brown ores constituted 20,435,122 gross tons and black ores 3,403,206 gross tons. There are also lean ores estimated at 4,589,785 gross tons.

Another type of manganiferous material, not merchantable from 1930 to 1940, is the so-called "high silica black oxide" material, with more than 20 percent silica. Only 362,828 tons of this material were included in the black ore reserves, but estimates range from 16 million to more than 50 million tons of material containing more than 15 percent manganese.[51] These ores were not used for making spiegel in normal times, but they can be used if the demand for manganese becomes urgent. They add to the reserves an enormous tonnage of possible future ore.

The lean ore and original formation that are not merchantable in normal times are also the basis of experiments on concentration. It is possible to produce a concentrate with more than 50 percent manganese.

[51] Manganese for National Defense, Report of Subcommittee on Manganese, A.I.M.M.E. Committee on Industrial Preparedness: A.I.M.M.E. Contribution No. 48, p. 25, 1933.

MANGANESE RESOURCES OF MINNESOTA

In Minnesota there is very little high-grade manganese [52] ore (containing more than 45 percent manganese), but, as indicated in the descriptions of iron ores, there are several grades of ore and rock that contain noteworthy amounts of manganese. Details of the manganiferous iron ores are given in the preceding sections of this bulletin and need not be repeated here. A few notes about the general situation of the country and the manganese resources of Minnesota are given here.

The principal use of manganese is in making steel. It desulphurizes and deoxidizes the steel to which it is added, making it tough and resistant to abrasion. Since sulphur in steel tends to make it brittle when hot, the addition of manganese results in a great improvement in its hot-working qualities. No satisfactory substitute has been found for manganese in desulphurizing steel, and for a number of years about 14 pounds of manganese metal have been consumed for each ton of steel produced in the United States. Normally a million tons of high-grade ore (containing 45 percent manganese) are needed each year, and more when the demand for steel is abnormally large.

Much of the manganese needed for steel has been added as alloys rich in manganese, but since 1918 some steel plants have added manganiferous iron ore to the blast furnace ore mixture so that less of the rich alloy is needed. In normal times a large part of the demand for this manganiferous iron ore is supplied by the Cuyuna range in Minnesota.

Manganiferous iron ore, however, furnishes only a small part of the total manganese metal needed by the steel industry. In fact, production of manganese in the whole of the United States in normal times supplies only 5 or 10 percent of the amount needed by the steel industry of the country. Manganese is classed as a "strategic mineral." If and when foreign supplies are not available, the resources of the country should be known and made available, even if they cannot be produced in normal times at a profit in competition with foreign ores. The resources of the Cuyuna range may prove to be a large factor in the national problem of manganese supplies.

The Cuyuna manganiferous iron ores produced since about 1917 are of two general grades: (1) black ores in moderate amounts, with about 15 percent Mn, 15 percent SiO_2, and 0.09 percent P, and 37 percent Fe; (2) brown ores in larger amounts with about 9 percent Mn, 6 percent SiO_2, 0.27 percent P, and 44 percent Fe. In addition there are (3) enriched oxide deposits that have not been marketable because of high silica content (more than 20 percent), and (4) fresh rock carrying carbonates of iron and manganese.

[52] Data on manganese supplied chiefly by Dr. F. F. Grout.

It is probable that the two grades of ore, black and brown, will continue to be produced and used as in the past, with fluctuations depending on the demands of the steel industry. It is hardly wise to consider them as a resource to be drawn upon heavily as a substitute for foreign ores when imports are stopped. The other two manganiferous materials appear to occur in much larger tonnages and are now being investigated as potential sources of high-grade concentrates. A recent writer reports estimates[53] of 44 million tons of ore of 15 percent or more manganese, and there are very large reserves of lower grade.

Two methods of making use of Cuyuna manganiferous rock have been tested by the Minnesota Mines Experiment Station and the Minnesota Station of the U. S. Bureau of Mines, one using a blast furnace and the other a leaching process, the Bradley process. Several other methods of concentration have been tested by the U. S. Bureau of Mines.[54] These methods proved practicable for making high-grade concentrate if current prices were, for example, doubled. The whole plan, however, depends on the uncertainty of obtaining foreign supplies and the possibility of government support or guarantees. The work was done, at least in part, on high silica deposits that have not been marketable in recent years.

Tests on the carbonate slates have not been carried far, but there are known to be enormous reserves[55] assaying 3 to 8 percent manganese and about 25 percent iron. Much of it can be steam-shoveled from open pits and so does not require preliminary treatment, such as the washing required to recover manganese nodules from low-grade shales.

[53] Mining and Metallurgy, vol. 21, p. 453, 1940.

[54] Shelton, S. M., and Fine, M. M., Ferromanganese-grade concentrates from the Cuyuna range: U. S. Bureau of Mines, Report of Investigations 3582, 1941.

Fine, M. M., Shelton, S. M., and Zadrs, J. B., Manganese Investigations, 9: U. S. Bureau of Mines, Report of Investigations 3624, 1942.

Dean, R. S., Fox, A. L., and Beck, A. E., Manganese Investigations, 7: U. S. Bureau of Mines, Report of Investigations 3626, 1942.

[55] Grout, F. F., Manganese for emergency use on the Cuyuna range, Engineering and Mining Journal, July, 1942.

BUILDING STONES OF MINNESOTA

INTRODUCTION

Some of the facts regarding the building stones[56] of Minnesota are summarized in this section, in order to acquaint architects, building contractors, real-estate firms, and monument dealers with the merits of the various structural and ornamental stones quarried and fabricated in the state. Details are available in Bulletin 25 of the Minnesota Geological Survey.[57]

Until recent years our stone products have been used more extensively in distant states than in our own communities. Minnesota stones enjoyed a national reputation for beauty and adaptability long before their merits were recognized by local builders. Even today many architects and structural contractors do not realize that more than fifty varieties of architectural stone are quarried and fabricated in Minnesota.

Monument dealers also should familiarize themselves with Minnesota stones. The extent to which a certain type of stone is used for monuments is influenced very largely by the reputation it establishes. In Minnesota the red and gray granites of the St. Cloud and Ortonville districts and the variegated granite of the Morton district have long been favorites. Other stones in the state, however, are equally attractive. Notwithstanding the excellence of the monument stones quarried in Minnesota, many monuments are shipped here from quarries in New England and from Scotland, Scandinavia, and other European countries. There are various reasons for the importation of monuments, and probably one of the most important is the desire of the friends and relatives of a person who has immigrated from another country to mark his grave with a monument of stone from his native land. Another reason is the established reputation of such stones as those from Quincy, Massachusetts, and Barre, Vermont. Increased publicity for the granites of Minnesota would tend to offset the extravagant claims made by some dealers for foreign stones. The pink and red granites of Minnesota, whether brilliant or subdued in color, are unsurpassed in beauty, and the dark gray granites (diorites and monzonites) are as fine in every respect as those quarried elsewhere.

In 1939 about 1,405,740 short tons of stone, valued at $2,239,774, were produced in Minnesota. Even in 1942, when war restricted the industry, production was 1,451,210 short tons, valued at $1,858,631. This stone came from widely scattered districts, and still other districts have considerable stone resources. Recently productive quarries, with their locations, are as follows:

[56] The section on building stones was compiled chiefly by Dr. G. A. Thiel.

[57] Thiel, G. A., and Dutton, C. E., The architectural, structural, and monumental stones of Minnesota: Minn. Geol. Survey Bull. 25, pp. 1–160. 1935.

MINNESOTA QUARRIES

Location (County)	*Stone*	*Location (County)*	*Stone*
Benton	Granite	Pipestone	Quartzite
Big Stone	Granite	Ramsey	Limestone
Blue Earth	Limestone	Redwood	Granite
Chippewa	Granite	Renville	Granite
Dakota	Limestone	Rice	Limestone
Fillmore	Limestone	Rock	Quartzite
Goodhue	Limestone	Scott	Limestone
Hennepin	Limestone	Sherburne	Granite
Houston	Limestone	St. Louis	Basalt and Gabbro
Lac Qui Parle	Granite	Stearns	Granite
Lake	Gabbro	Steele	Limestone
Le Sueur	Limestone	Wabasha	Limestone
Mille Lacs	Granite	Washington	Limestone
Mower	Limestone	Winona	Limestone
Olmsted	Limestone	Yellow Medicine	Granite
Pine	Sandstone		

EARLY HISTORY

The stone industry in Minnesota began more than a century ago, when limestone was quarried to build part of Fort Snelling. From this small beginning the industry has progressed, with periods of fluctuation, until today it is second in value in the mineral production of the state. Even early geological surveys demonstrated that Minnesota was endowed with an unlimited supply and a great variety of building materials. The results of these studies have been published by the Minnesota Geological Survey and the United States Geological Survey. (See figure 13.)

The granite industry of the Northwest began in the St. Cloud area as early as 1867. The first quarry was opened in the village of Sauk Rapids. In 1868 Breen and Young opened a quarry in East St. Cloud which supplied stone for the United States Custom House and Post Office in St. Paul. By the year 1870 both red and gray granites were being developed in the region. The granite industry has grown steadily since 1900, and more than fifty plants for cutting, shaping, and polishing stone have been established in the area.[58] St. Cloud has earned the title of the "Granite City" of the Northwest.

The quarrying of sandstone along the Kettle River at Sandstone, Minnesota, was begun in 1885. For a number of years the rock was hauled by team up the steep, rocky road out of the valley and more than ten miles to Hinckley, where it was loaded upon flatcars for shipment to St. Paul and Minneapolis. The rock was used exclusively for paving, curbing, and bridge stone. With the advent of direct railroad connections, stone was shipped to Minneapolis, Omaha, Duluth, and elsewhere. In 1893–94 the Wing Dam at St. Anthony Falls was built of this stone. In 1894 the disastrous Hinckley fire destroyed the entire equipment of the plant. The Minnesota Sandstone Company was organized in 1895, the name being changed later to the Kettle River Quarries Company. This

[58] Biennial Census of Manufactures, 1937, Part I, pp. 1374–1375.

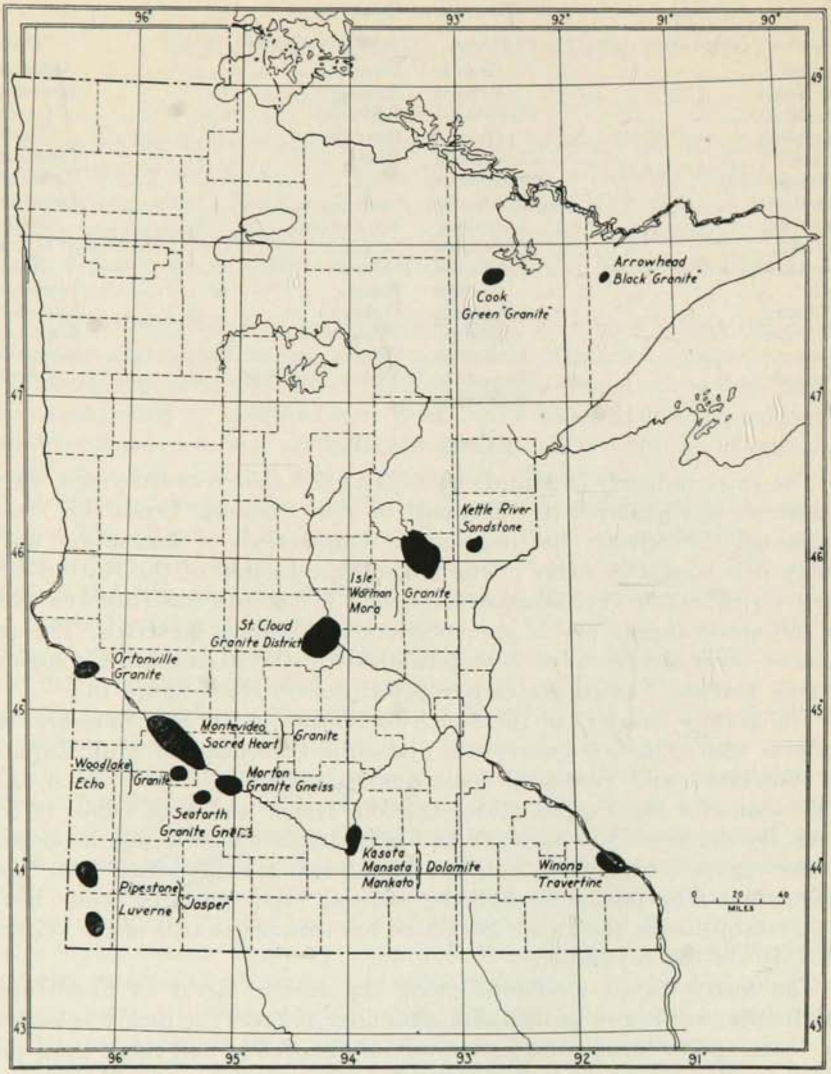

FIGURE 13. — Outline map of Minnesota showing the locations of the most active stone-producing areas. After Thiel and Dutton.

firm was recently reorganized and now operates as the Sandstone Quarries Company, which is associated with the William Penn Stone Company. The equipment has been greatly improved and increased, and the available stone will supply all demands for many generations. Most of the stone is fabricated in the company's plant at Sandstone.

The quarrying of limestone began at Fort Snelling in 1820. A few years later a quarry was opened at Mendota to obtain stone for the construction of a house for General Sibley. At Stillwater the Carli quarry began operation in 1847 and was later taken over by the city. In the southeastern counties the first quarry was opened at Winona in 1854. A few years later quarrying operations began at Mantorville, Red Wing, and other points along the Mississippi River and its major tributaries. The first quarry at Mankato was opened in 1853, and by 1868 the region near Kasota was also producing building stone.

The quartzite that crops out in south central and southwestern Minnesota was first quarried in 1859 near Courtland, on the north wall of the Minnesota Valley. Later the same type of stone was used in New Ulm under the trade name "Redstone." The red quartzites of Rock and Pipestone counties were quarried at an early period of the state's stone industry. The thin beds and closely spaced joints yielded small blocks of stone suitable for paving. Many of the paving blocks were shipped to Omaha, where they were sold under the trade name "Sioux Falls Granite."

PHYSICAL PROPERTIES OF BUILDING STONE

The essential qualities of building stone are strength, durability, workability, color, and beauty. Depending upon the type of structure for which the stone is to be employed, the properties required range widely. For bridge spans, great strength is essential; for monuments and outdoor structures, appearance and resistance to weathering are required; and for interior decoration, pleasing color and adaptability to carving and polishing are important.

When new types of stone are placed on the market, tests are of value in helping to determine the comparative quality of the product. Furthermore, the stones from different levels in the same quarry may show different properties. To arrive at a trustworthy knowledge of any deposit,

TESTS OF STONE

I. Tests to determine strength	Compression Transverse Tensile Shear Elasticity Flexibility Hardness Impact
II. Tests to determine durability	Absorption Freezing Heat Efflorescence Resistance to acids
III. Tests to determine density	Specific gravity Porosity
IV. Tests to determine composition and structure	Chemical analysis Microscopic study

separate tests should be made on the rock at various horizons within the formation.

The various tests are grouped according to the kind of information they give regarding the specimen that is being tested.

Such tests are made at the United States Bureau of Standards. Many of the properties referred to above have been determined for Minnesota stones.[59]

One of the chief considerations in selecting stone for exterior work is durability. The weathering of any rock depends primarily upon its mineral composition, texture, structure, and, to some extent, upon the conditions under which it is used.

COMPOSITION

Some minerals are very stable under all ordinary conditions of use; others are very unstable, and the presence of even a small percentage of them may be sufficient to affect seriously the durability of the rock in which they occur. Certain minerals are injurious under all circumstances, whereas others are to be avoided only when they occur abundantly in certain types of rocks. The following paragraphs discuss the most common impurities in building stone.

Mica is an objectionable impurity in limestones and marbles. It may occur in scattered grains, isolated blotches, or bands. When it occurs in appreciable amounts it interferes with the continuity of the polish and it may yield to the attacks of weathering agents and thus lead to the development of pits or spalled spots on the polished surface. Mica is not harmful in most crystalline rocks such as granite and gabbro. In certain granites of inferior quality large tabular crystals of mica an eighth of an inch or more in diameter have been known to swell during prolonged exposure and finally to "pop" out, leaving a pitted surface. In gneissic rocks mica is seldom injurious.

Pyrite and other sulphides of iron such as marcasite and pyrrhotite are to be avoided. On exposure to the weather these minerals are oxidized and hydrated to a yellow or brown iron oxide, which may wash down over the surface of the rock and produce an unsightly stain. Furthermore, in the oxidation of pyrite some sulphuric acid is generated, which will attack and dissolve several other minerals that may be in the rock. Under certain conditions iron sulphate is formed from pyrite. This salt is very soluble and is brought to the surface as evaporation takes place. If it is abundant a whitish scum is deposited on the surface of the stone. Iron sulphides do not occur in most of the building stones quarried in the state, and in none do they occur in objectionable quantities.

Flint or *chert* nodules are objectionable features in many limestones and marbles. The flint is much harder than the rock that encases it and therefore interferes with cutting and polishing.

[59] See Thiel and Dutton, *op. cit.*

Minerals of the clay group, if abundant, decrease the desirability of a rock. The granites quarried in the state are fresh and contain little or no clay minerals. The same is true of the sandstones, and the long service rendered by the limestones in many walls shows that the clay minerals they contain are not harmful.

QUARRY METHODS

Stripping.—Although many quarries in Minnesota are begun on outcrop surfaces, the area of operation gradually increases so as to necessitate removing the mantle above the bedrock. This mantle, or overburden, is usually gravel, sand, or clay of the glacial drift, but at one quarry in the Morton area and one in the St. Cloud area the overburden is decayed bedrock.

The removal of such valueless material from the bedrock is known as stripping. The operation is usually performed by teams and scrapers but is sometimes done by hand loading into large iron trays, which are then lifted from the pit by a hoisting derrick. In the Kasota-Mankato district, power shovels are used for stripping operations. The overburden should be moved far enough from the quarry not to interfere with its future expansion.

Plan of Operation.—If sufficient rock is exposed, consideration should be given to joints, sheets, and rock imperfections before the quarry site is opened. For the most efficient operation there should be only two nearly vertical joint systems, intersecting at approximately 90 degrees. Such a relation yields blocks that require a minimum amount of trimming.

Excavating.—Hammer drills of various types operated by compressed air are now used almost exclusively in quarrying operations. In some quarries a method known as broaching, or channeling, is used. It consists of drilling straight parallel rows of holes by a so-called drifter drill mounted on a quarry bar. The holes are from 1 5/8 to 2 inches in diameter and are so spaced as to leave approximately 3/4 of an inch of rock between the holes. This rock between the holes, known as the web, is then cut out by means of channel bars. Quarry blocks of the desired length and width are outlined by such a method.

In some quarries, rows of holes for blasting are drilled with pneumatic, hand-held, jackhammer drills. The distance between holes and the depth of the holes are determined by the character of the rock and the size of the stock desired.

In some of the limestone and dolomite quarries large blocks of raw stone are loosened by channeling machines. The cut is made by the impact of five steel bars so fastened by clamps and activated by an eccentric drive wheel as to be successively raised and then dropped upon the stone. The machine moves back and forth automatically on steel rails.

Wire saws, in use in some districts, have not been adopted by Minnesota quarrymen. They should prove successful in extracting and shaping limestone if a good cutting abrasive, such as silicon carbide or steel shot, is used.

USES OF STONE

Building stone used for walls is of four main types: cut or finished stone, rough building stone, ashlar, and rubble.

Cut or finished stone includes columns and plain rectangular blocks for walls, as well as special and carved pieces for corners, window and door sills and caps, steps, and many other forms. In interiors it is used for flooring, fireplaces, wainscoting, stairways, columns, and so on. Obviously this type of stone is the most expensive.

Rough building stone is employed for walls, chimneys, basements, and elsewhere. It consists of rock-faced pieces of stone of various shapes and sizes, which are laid into walls having irregular joints.

Small rectangular blocks with sawed or rock-faced surfaces are called ashlar. There are two varieties — even-course ashlar, consisting of blocks of uniform height for each course in a wall, and random ashlar, consisting of blocks of several sizes. Ashlar is a by-product in that it represents a way of using stone fragments that would otherwise be cast on the waste heap.

Rubble is the name commonly applied to irregular fragments with one good face. It may be used for basements, retaining walls, and elsewhere, but it has been largely supplanted by concrete.

Monument stone, made up in the form of headstones and more elaborate memorials, is familiar to everyone.

Paving, curbing, and flagging production in Minnesota is negligible; concrete is used at present for these purposes.

Riprap consists of heavy fragments of stone which are used in the construction of piers, breakwaters, etc.

The use of crushed stone is discussed later. (Pages 111–12.)

FABRICATION METHODS

Certain types of stone are ready for use as soon as they are quarried; others require special preparation. Building stone is dressed or given the required form and surface by machines that cut stone as precisely as saws and planes cut lumber. Mallets and hard chisels are still used in very delicate carving operations.

The machines are driven by electric power, and most of them are operated by push-button controls. Such machines include travelling cranes, gang saws, rotary saws, planers, lathes, and complicated machines for cutting twisted and curved forms like handrails for stairways. The operators are guided by patterns prepared by draftsmen directly from the architects' plans. Carvers use plaster casts of the designs they are preparing.

Different types of finish produce differences in texture and color in the natural surface of stone. Finishes may be adjusted to various types of architectural specifications. Those commonly used are:

Seam Face.—A seam-face finish is the natural surface produced by splitting sedimentary rock along the bedding planes.

Rock Face.—The natural rough, broken surface is a rock-face finish. This surface is popular for large houses, churches, and schools.

Picked Finish.—The picked finish surface is produced by smoothing the rough rock face to an approximate plane by means of picks.

Bush-Hammered Finish.—The bush-hammered finish is produced by pneumatic hammers, which pound sharp pyramidal points into the smooth surface of the stone. The surface is thus covered with many tiny dots.

Sand-Sawed Finish.—A sand-sawed surface is one that has been sawed by gang saws, using sand as an abrasive.

Shot-Sawed Finish.—A shot-sawed rock shows a deep, rough, parallel scoring produced by the use of chilled steel shot as a cutting medium for straight-cut gang saws. It is a rough-textured finish that is desirable in combination with other finishes.

Diamond-Saw Finish.—A diamond-saw finish is distinguished from a shot-saw surface by the pattern of its scoring. Diamond teeth are most commonly used in rotary saws. A diamond saw, therefore, leaves shallow arclike grooves.

Planer Finish.—The planer produces a smooth, unpolished surface used for a great variety of purposes in stone structures.

Sand-Rubbed Finish.—A sand-rubbed finish is produced by placing the stone on a rubbing bed, where it is subjected to sandgrinding until it is smooth. It is generally smoother than a planer finish.

Carborundum Finish.—A carborundum wheel produces a semipolished surface. Such a surface approaches the color of the polished rock.

Honed Finish.—The surface of a honed stone is very smooth and resembles a polished surface. Such a finish is produced by means of fine-grained abrasive powders.

Polished Finish.—Rock is polished with abrasive powders and buffers. Different abrasives are used for different stones.

A polished finish emphasizes the beautiful patterns and colors of a stone and is the most durable of all finishes. The smooth surface serves to seal off avenues of attack open to weathering agents in rougher exteriors.

GRANITES

General Statement.—As stated in the introductory section, granite is an igneous rock formed by the crystallization of molten material in large subterranean chambers such as those forming batholiths. In places erosion has removed the overlying rocks and today many outcrops of granite may be seen. They possess a granular texture in which mineral grains, sufficiently large to be identified with the unaided eye, interlock with one another, forming a firm, strong rock. Granite may be fine grained, medium grained (mineral grains about an eighth to a quarter of an inch long), or coarse grained. Some may have a porphyritic texture, in which certain minerals occur as grains larger than those surrounding them.

The term "granite" as employed in this report and in the stone industry includes granites, gneisses, diorites, gabbros, and other igneous rocks. Geologically, however, granite is a rock containing relatively large amounts of the minerals orthoclase and quartz, with minor amounts of dark minerals, such as hornblende, mica, and magnetite. The so-called black granite quarried in northeastern Minnesota is not a granite; it is a gabbro. Gabbro is an igneous rock with the same texture as granite, but instead of orthoclase (a potash feldspar) it has plagioclase (a soda-lime feldspar); quartz is absent, and augite is usually the most abundant dark mineral. Some chemical analyses of granite are given below.

CHEMICAL ANALYSES OF MINNESOTA GRANITES

	1	2	3	4	5
SiO_2	69.63	71.17	64.40	71.54	69.55
Al_2O_3	13.85	13.30	14.93	14.62	15.52
Fe_2O_3	0.54	3.52	1.63	0.69	0.14
FeO	4.01	....	3.13	1.64	3.29
MgO	0.83	0.30	3.05	0.77	1.61
CaO	2.58	1.56	4.18	2.08	3.67
Na_2O	2.32	3.85	3.31	3.84	3.79
K_2O	4.33	4.33	3.95	3.92	2.12
H_2O+	0.23	0.64	0.15	0.30	0.40
H_2O-	0.10	....	0.07	0.02	0.10
TiO_2	0.33	0.23	0.57	0.26	0.44
P_2O_5	0.28	0.23	0.57	0.10	0.07
CO_2	....	0.21	0.18	0.14	....
ZrO_2	....	....	0.07	....	0.02
S	....	....	0.12	....	....
MnO	....	....	0.09	0.04	....
BaO	....	....	0.05	....	....
Cr_2O_3	....	....	....	....	0.01
	99.03	99.34	100.45	99.96	100.73

1. Rockville pink granite. F. F. Grout, analyst.
2. St. Cloud red granite, average of 3 analyses.
3. St. Cloud gray granite. F. F. Grout, analyst.
4. Morton granite. S. S. Goldich, analyst.
5. Warman Creek granite. F. F. Grout, analyst.

In average years Minnesota ranks third among the states in the production of granite, following Vermont and Massachusetts, the foremost producers. St. Cloud is the second largest monument stone center in the United States, exceeded only by Barre, Vermont. Granite for construction purposes, however, is much more important in Minnesota than in Vermont, for about 40 percent of the Minnesota output is used for building and 60 percent for monuments. Scattered throughout Minnesota are 111 retail monument stone dealers, 44 of whom finish all or part of the memorials they sell. In 1939 the granite sold or used by the producers in Minnesota, largely for monuments, was about 26,570 short tons, valued at $626,587.[60]

In the St. Cloud district there are 33 firms engaged in the fabrication of granites; many of them operate their own quarries. At Cold Springs, Minnesota, the Cold Springs Granite Company employs more than 400 men in the largest granite-finishing plant in the United States.[61] About 40 granite quarries are active in the state and approximately 50 others have been worked sometime in the past.

The granites of greatest economic value are found in three widely separated districts in the state (fig. 13): (1) central Minnesota, particularly in the vicinity of St. Cloud; (2) the upper Minnesota River valley from New Ulm to Ortonville; and (3) the Arrowhead district north of Duluth in St. Louis, Lake, and Cook counties. Stone quarried in these districts has enjoyed a wide distribution for use in buildings and monuments (fig. 14).

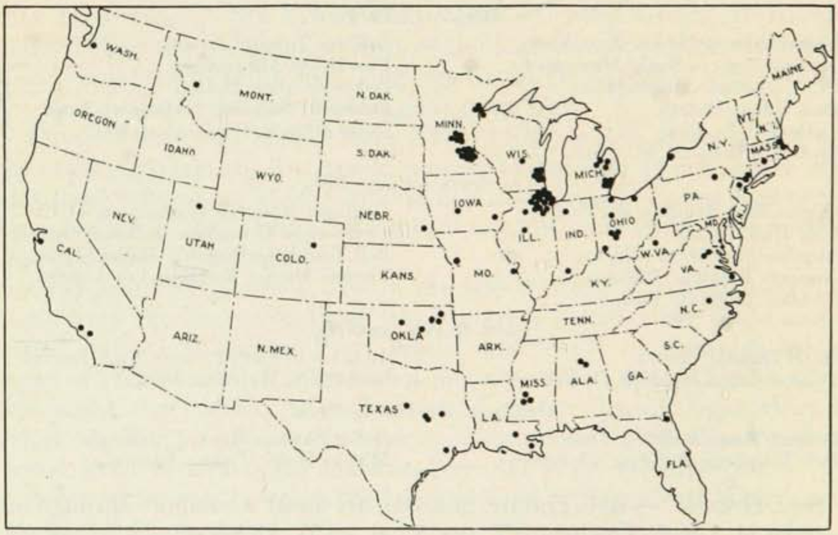

FIGURE 14. — Map of the United States showing by dots localities in which Minnesota granites have been used for one or more prominent buildings. After Thiel and Dutton.

Pink Granite. — Most of the pink granite used as building stone occurs southwest of St. Cloud in a zone extending from Sec. 2, T. 124 N., R. 29 W. in St. Joseph Township, southwestward to Rockville. This is best described as a stone with large pink crystals set in a finer grained matrix of black and white. The minerals are sufficiently uniform in distribution

[60] Bowles, O., and Jensen, M. S., Minerals Yearbook, 1940, p. 1167, 1941.

[61] See Thiel and Dutton, *op. cit.*, for lists of granite producers and locations of abandoned quarries.

to give the stone a very attractive appearance. The finished stone is marketed under the trade names "Rockville Pink," "Cold Springs Pearl Pink," "Original Minnesota Pink," and "Sauk Rapids Pink" granites.

Some pink granite, most of it used for monuments, is quarried in the Minnesota River valley south of Sacred Heart. A small quarry has been opened in the Giants range granite about two miles northwest of Mountain Iron; the stone is sold under the name "Mesabi Pink."

Analyses of typical Rockville Pink granite and physical tests are given on pages 68 and 72.

The Federal Court House in New York, the tallest granite structure in the world, has an exterior of Rockville Pink granite. The building consists of a tower of 38 stories rising from a square-columned base structure. The total freight cost from St. Cloud to New York on more than 600 carloads of finished stone was about $208,000, and the cost of stone, f.o.b. New York, was about $1,350,000.

Prominent buildings in which Minnesota pink granites have been used are:

ROCKVILLE PINK

Federal Court House, New York
Federal Reserve Bank, Minneapolis
Pro-Cathedral, Minneapolis
Post Office, Duluth
Cathedral, St. Paul
St. Cloud Hospital, St. Cloud
Tribune Tower, Chicago
Post Office, Milwaukee
Fisher Building, Detroit
Democrat Building, Davenport, Iowa
Capitol Plaza, Washington, D. C.

COLD SPRINGS PEARL PINK

State Office Building, St. Paul
City Hall, Duluth
Merchandise Mart, Chicago
Koppers Building, Pittsburgh
Cadillac Building, Boston
Gallinger Hospital, Washington, D. C.
Chamber of Commerce, Jacksonville, Fla
Bell Telephone Building, Dallas, Texas
Youngs Market Building, Los Angeles

SAUK RAPIDS GRANITE

Hotel Duluth, Duluth
Federal Office Building, Omaha
Addition to United States Mint, Denver
Post Office, Waterloo, Iowa

ORIGINAL MINNESOTA PINK

Detroit Times Building, Detroit
Bell Telephone Building, Cleveland
Dollar Savings Bank, Pittsburgh
Mincks Hotel, Tulsa, Oklahoma

Red Granite.—Red granite quarries are most abundant throughout western St. Cloud Township, T. 124 N., R. 28 W. In Sections 8, 17, 18, 19, and 20 the exposures are almost entirely of red granite, and in Sections 29, 30, and 32 they are of red granite associated more or less intimately with gray granite. Red granite crops out sparingly on the east side of the Mississippi River, the largest exposure being Section 17, Haven Township, Sherburne County. Other outcrops, some of considerable size, appear in western Benton County.

The red granite of the St. Cloud district is medium- to coarse-grained rock, the feldspar grains averaging about one-fourth inch in diameter. The chief minerals are feldspar and quartz, with minor amounts of black hornblende and biotite. Red feldspar constitutes about 75 percent of the rock and gives it its characteristic red color. The granite is marketed under a variety of trade names, such as "Indian Red," "Rose Red," "Melrose Red," "North Star Red," "Ruby Red," "Mahogany Red," and "Standard Red." Most of the rock is used for monument purposes, but architectural stone also is fabricated.

Some red granite is quarried for monument stone near Ortonville and Echo Lake.

Gray Granite.—The most extensive outcrops of gray granite are in St. Cloud Township, Stearns County, in Sections 21 and 28. There are a great number of smaller exposures in Sections 29, 30, 32, and 33 of the same township, but these are all more or less intimately associated with red granite. East of St. Cloud in Sherburne County numerous outcrops occur in Sections 6 and 7, and isolated outcrops appear in western Benton County from Sauk Rapids to Watab.

The gray granite of the St. Cloud district is marketed under a variety of trade names, such as "Reformatory," "Pioneer Dark Gray," "Minnesota Dark Gray," "St. Cloud Gray," and "Crystal Gray." It is finer grained than the red granite. Most of the feldspars are about one-eighth to three-sixteenths of an inch long. St. Cloud gray granite was used for the base course in the new Minneapolis post office.

Physical tests on a sample from NE 1/4 SE 1/4 Sec. 21 show that under crushing strain the first crack came at 15,080 pounds per square inch and final collapse at 21,000 pounds per square inch. Under transverse breaking stress the modulus of rupture is 2,979 pounds per square inch. (See also table on page 72.)

Gray granite is quarried also in the Isle-Warman Creek district. The stone from the quarry south of Isle is marketed under the trade names "Isle" and "Cold Springs Pearl White" granite. It is adaptable for all types of architectural and memorial purposes. The stone takes an excellent polish. Its porosity is low enough so that it is quite impervious to solutions that produce stains and discolorations. Cut finishes, such as sawed, axed, or hammered surfaces, leave the stone nearly white.

A few structures in which the Isle and Cold Springs Pearl White granites have been used are:

Gateway and office, Lakewood Cemetery, Minneapolis
Aviation Building, Fort Worth, Texas
Price Building, Kansas City, Missouri
Waite Phillips Building, Tulsa, Oklahoma

Variegated Granite.—From New Ulm to Ortonville a number of different types of granitic rocks crop out in or near the Minnesota Valley (fig. 15). Morton stone, perhaps the best known product of the group, is composed mainly of red feldspar and dark minerals arranged in streaks and bands. The feldspar constitutes the greater part of the rock, both red orthoclase and gray plagioclase being abundant. There is considerable

RESULTS OF PHYSICAL TESTS ON MINNESOTA GRANITES [1]

Rock No.	Compressive Strength Perpendicular (A) and Parallel (B) to the Rift				Absorption by Weight for Immersion Period of 1 Year (Percent)	Density		Porosity (Percent)	Computed wt. 1 cu. ft. (lbs.)
	Specimens Dry (lb. per square inch)		Specimens Wet (lb. per square inch)						
	A	B	A	B		Bulk	True		
1..........	18,300	17,400	16,800	17,200	.22	2.637	2.680	1.60	164
2..........	19.000	20,000	17,400	16,000	.15	2.684	2.710	.96	167
3..........	21,800	30,700	26,000	28,000	.24	2.659	2.688	1.08	166
4..........	29,400	24,200	23,100	20,400	.18	2.626	2.651	.94	164
5..........	26,900					2.70			168
6..........	20,700					2.62			163

1. Isle Gray granite
2. Rockville pink granite
3. Morton granite gneiss
4. Ortonville red granite
5. St. Cloud gray granite
6. St. Cloud pink granite

[1] Kesler, D. W., *et al.* Physical, mineralogical, and durability studies on the building and monumental granites of the United States: Journal of Research, National Bureau of Standards, vol. 25, p. 184, 1940.

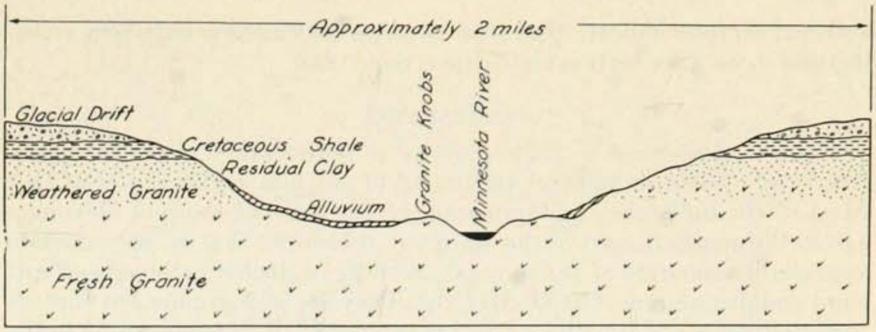

FIGURE 15. — Generalized cross section of the Minnesota River Valley at Morton, showing granite hills exposed by stream erosion. After Thiel and Dutton.

quartz. The chief dark minerals are hornblende, biotite, and a few grains of magnetite. Analyses and physical tests are given on pages 68 and 72.

Because of its attractive color tones and peculiar swirling figures, the granite has been given a number of trade names, such as "Oriental," "Rainbow," "Tapestry," "Antique," "Imperial," and "Variegated." Its variety of color and texture makes it especially desirable for facings, columns, and certain kinds of interior work. It is in demand as a facing for large buildings, for which its variegated coloring is well suited. For such purposes the stone is commonly sawed and placed in such a way that unique patterns and designs are formed.

A partial list of prominent buildings in which Morton granite gneiss has been used follows.

Northwestern Bell Telephone Building, Minneapolis
Baker Building, Minneapolis
Northwestern Bell Telephone Building, St. Paul
Adler Planetarium, Chicago
Hemenway Building, Boston
David Stott Building, Detroit
Hartford Gas Company, Hartford, Connecticut

Black Granite. — During the last few years there has been a growing demand for polished "black granite" as a structural and ornamental stone. Because of the increased interest in this kind of stone a number of new quarries have been opened in the area north of Duluth.

In this district the rock is dark gray or greenish gray to black. It owes its color to the dominance of gray-green feldspars and dark green to black ferromagnesian minerals such as hornblende and augite. The stone is sold under the name of "Arrowhead Black Granite," "Green Granite," and "Archean Green." Quarries supplying such rock are located near Cook and in the Superior National Forest southeast of Ely. A very black stone is quarried about one mile southwest of Beaver Bay.

ANORTHOSITE

Rocks called anorthosite, which are mainly light colored basic feldspar, occur at numerous easily accessible places in northeastern Minnesota.

Polished samples indicate that some of these may make satisfactory architectural stone. (See section on feldspar, page 125.)

LIMESTONES

General Statement.—Limestone is a sedimentary rock composed largely of calcite, a mineral consisting of calcium carbonate ($CaCO_3$). Most of the limestones in Minnesota, except some of those of Devonian age in the southern part of the state, are dolomitic; that is, they contain appreciable amounts of the mineral dolomite, a double carbonate of calcium and magnesium ($CaCO_3.MgCO_3$). They are seldom pure but contain various amounts of other minerals. Limestone usually owes its origin to the accumulation of calcareous shells and other hard parts of marine organisms and their fragments on the bottoms of seas of moderate depth, supplemented to some extent by chemical precipitation. Fossils may be observed in many of the limestones of the state.

In 1931 the limestone dimension stone sold or used by producers in Minnesota was approximately 284,960 short tons, valued at $816,484.[62]

Although some building stone has been quarried from each of the limestones in Minnesota (page 7), the Oneota dolomite of Ordovician age has yielded the greatest tonnage and the highest quality of stone. Mankato and Kasota stone and the "Winona Travertine," chosen by many architects for both interior and exterior work because of their interesting textures and pleasing warm colors, are quarried from ledges of this formation (figs. 13 and 16).

The Breen Stone and Marble Company, the Kasota Stone Quarries Corporation, and Babcock and Wilson of Kasota; the Fowler and Pay Stone Company and the T. R. Coughlan Company of Mankato; and the Biesanz Stone Company, Winona, are the principal producers of limestone in the state. In southeastern Minnesota there are more than 200 abandoned quarries in Paleozoic limestones, which at various times in the past have produced limestone for construction, lime burning, crushed rock, and other purposes.[63] Notable quarries were opened at Mantorville, Faribault, and in the Twin Cities area.

The Mankato-Kasota District.—The early settlers in the Minnesota River Valley from Shakopee to Mankato utilized the outcropping stone for building purposes. The strata are nearly horizontal and are continuous over large areas, so that the supplies are inexhaustible. However, the thick glacial drift conceals them except in the bottom lands and in the low parts of the bluffs along the river valleys. Many of these layers are suitable for high-grade building stone (fig. 17).

Much of this limestone is hard enough to take a polish and is sometimes called marble. "Kasota marble" has been quarried since 1868. Since the early eighties a similar stone has been quarried also at and near Man-

[62] Coons, A. T., Stone, Minerals Yearbook 1931, p. 313.
[63] Lists are given by Thiel and Dutton, *op. cit.*

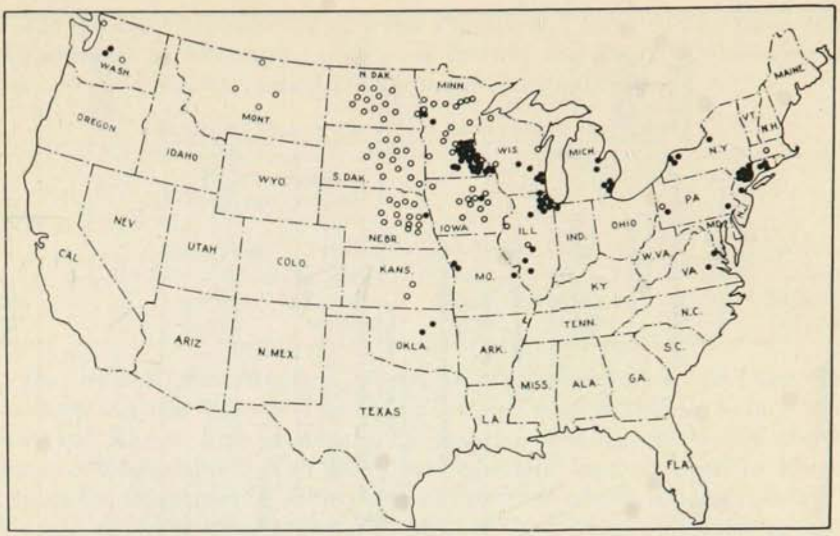

FIGURE 16. — Map of the United States showing the localities in which Minnesota limestones (dots) and sandstones (circles) have been used for one or more prominent buildings. After Thiel and Dutton.

kato. It is widely known in the United States and also in Canada and Mexico. Most of the stone is a medium-grained, buff to yellowish-pink, dolomitic limestone. The yellow is used extensively for decorative details because of its rich color with slightly darker markings. The following trade varieties are based on the color and texture of the stone:

Mankato Cream	Mankato Pink Buff
Mankato Yellow	Mankato Red
Mankato Coarse Yellow	Kasota Yellow
Mankato Gray	Kasota Pink
Mankato Silver Gray	Kasota Interior Pink Veine
Mankato Gray Buff	Kasota Interior Pink Fleuri
Mankato Gray Pink	Mansota Cream
Mankato Pink	Mansota Pink Buff

The following analyses were compiled by Thiel and Stauffer,[64] who give also a compilation of physical tests on limestones.

ANALYSES OF MANKATO AND KASOTA STONE

Sample	Insoluble Silica, etc.	Oxides (Iron, etc.)	Total Insoluble	CaO	$CaCO_3$	MgO	$MgCO_3$
78	10.4	1.1	11.50	27.4	48.9	18.9	39.5
79	30.5	1.2	31.70	21.6	38.6	14.2	29.7
80	26.5	1.8	28.20	22.0	39.3	15.2	31.8
81	21.8	1.1	22.90	23.5	42.0	16.3	34.1
82	13.5	1.4	14.90	26.2	46.8	18.0	37.7
83	12.4	1.3	13.70	26.5	47.3	18.4	38.5

[64] Thiel, G. A., and Stauffer, C. R. The limestones and marls of Minnesota: Minn. Geol. Survey Bull. 23, pp. 1–154, 1933. For physical tests see page 126.

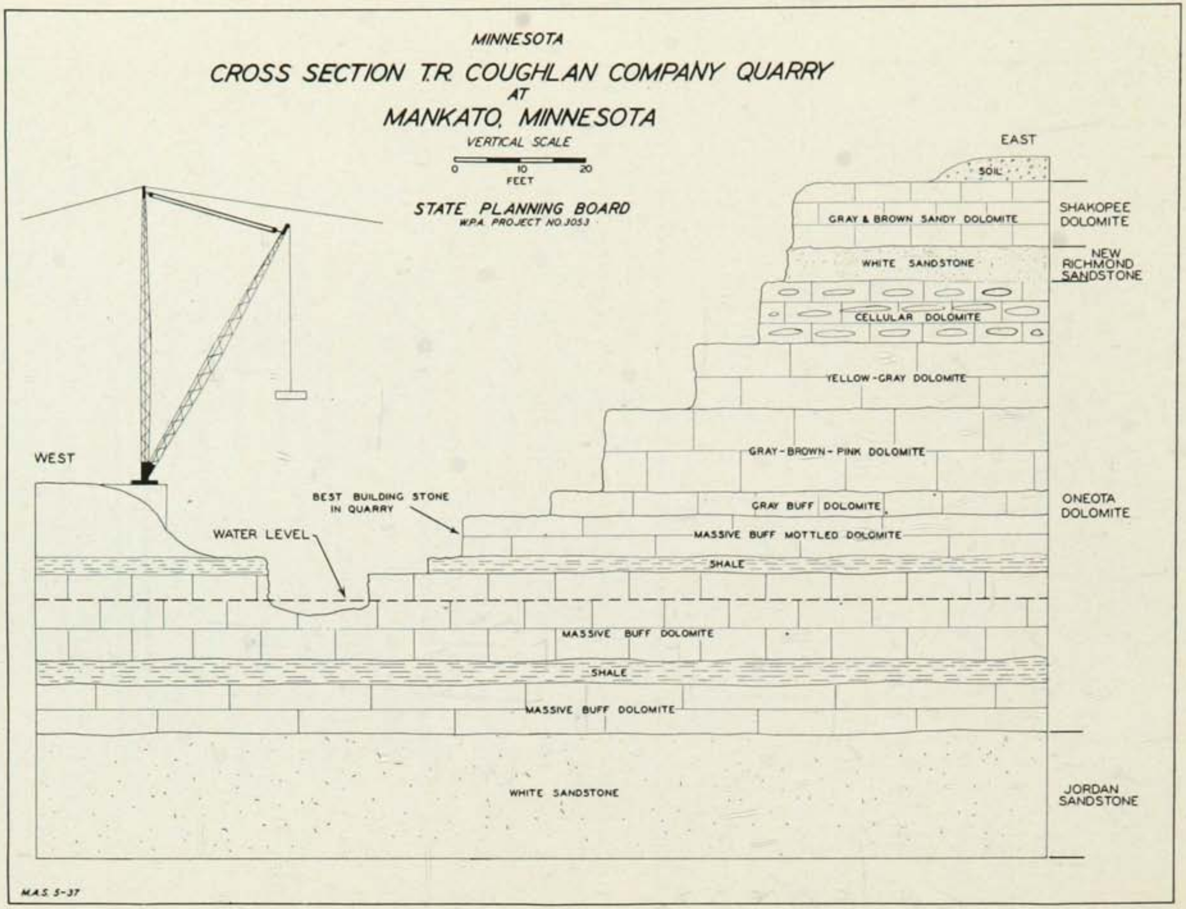

FIGURE 17. — Cross section through T. R. Coughlan quarry, Mankato, Minnesota.

The data tabulated below give the amount and value of limestone sold by producers at Mankato and Kasota in 1921 and 1931.[65] Production in more recent years has varied with commercial conditions.

LIMESTONE SOLD BY PRODUCERS AT MANKATO AND KASOTA

Year	Building Stone (rough and dressed)		Other		Total	
	Cubic Feet	Value	Short Tons	Value	Short Tons (approximate)	Value
1921	230,290	$495,895	38,410	$22,962	56,590	$518,857
1931	216,720	469,684	74,150	65,659	90,420	535,343

The Philadelphia Museum of Art is constructed of stone from the Mankato-Kasota district. The entire exterior is of Mankato Yellow and Gray and Kasota Pink stone, and the interior is of Kasota Yellow stone. About 350,000 cubic feet of stone (855 carloads) were shipped to Philadelphia for this structure. The value of the stone at the time of construction was approximately $1,500,000. Most of the cutting and finishing was done at the building site.

A few of the important buildings in which stone from Mankato and Kasota has been used are:

Northwestern Bell Telephone Building, Minneapolis
Post Office, Minneapolis
Municipal Auditorium (interior), Minneapolis
University Baptist Church, Minneapolis
Minnesota State Capitol (interior), St. Paul
Union Trust Building, Detroit
Union Depot, Kansas City, Missouri
Manufacturers Trust Building, New York
Eagles Club, Milwaukee

Winona Travertine.—Along the bluffs of the Mississippi River from Hastings southward the same dolomite layers that are quarried at Kasota crop out in the high bluffs. At Winona the rock is porous. Here the Biesanz Stone Company produces a picturesquely porous dolomite sold under the trade name "Winona Travertine." This stone is somewhat similar in structure to the celebrated travertine stone quarried in Italy and shipped to many parts of the world for building purposes. Perhaps the principal difference between the Italian Travertine and the product of the Biesanz Stone Company is that the Italian stone when first quarried is quite soft and easily worked but hardens on exposure, whereas Winona Travertine is moderately hard when quarried and remains so. It has been used for both interior and exterior construction. Notwithstanding its pitted surfaces, it is highly resistant to frost.

A number of different color and texture varieties are fabricated. Cream, buff, and gray are the common colors. The rock is also broken along the natural seams, or bedding planes, and sold as "seam-face" dolomite.

Stone chips for terrazzo floors are also made by the Biesanz Stone Company. The Winona stone is ideal for this purpose, for the fragments

[65] U. S. Bureau of Mines, Minerals Yearbook 1934.

grind down easily to a finished terrazzo without splintering, and yield a pleasing, durable surface. An example of this work may be seen in the Young-Quinlan Building, Minneapolis.

Representative installations of Winona Travertine may be seen in the following buildings:

Federal Reserve Bank Building, Minneapolis	Garment Center Capitol, New York
State Teachers College, Winona, Minnesota	Mayflower Hotel, Washington, D.C.
Belmont Hotel, Chicago	Dexter-Horton Bank Building, Seattle
Liggett Building, New York	

SANDSTONES AND QUARTZITES

Sandstone and Kettle River District. — A buff to salmon-colored sandstone is exposed along the Kettle River in Pine County. Precipitous bluffs more than 100 feet high form the walls of the valley. This Kettle River sandstone is strong and well cemented. The mineral matter forming the cement is mainly secondary quartz that has been deposited on the original quartz grains of the sand. Small amounts of iron oxide in the form of limonite and hematite give the rock its color. Where the limonite predominates it is buff to yellow, whereas hematite produces various reddish tints.

The Sandstone Quarries Company produces building stone, sawed slabs, flagstone, curbing, rubble and riprap, paving blocks, crushed stone, and silica sand. The finished building stone is sold under the trade names "Kettle River Standard," and "Kettle River Variegated." These architectural stones are very attractive. Beautiful effects may be produced with their red, pink, and buff tints.

Tests made by the United States Department of Agriculture on the Kettle River sandstone show its physical properties to be: specific gravity, 2.5; weight per cubic foot, 156 pounds; percentage of wear, 15.8; French coefficient, 2.9; coefficient of hardness, 14.8; toughness, 4.0; and crushing strength, 8,000 to 12,000 pounds per square inch.

Typical installations may be seen in the exterior of the Baker Building in Minneapolis and the interior of the Hill Reference Library in St. Paul.

Jasper-Pipestone Area. — In Pipestone and Rock counties in southwestern Minnesota there is a red quartzite, known as the Sioux quartzite, which extends into eastern South Dakota and northwestern Iowa. It was probably deposited as sand in the Huronian seas. The color of the rock varies from pale pink to deep purplish red. Interbedded with the quartzite layers are strata less indurated and in some places very clayey. One such clayey bed is noted in Indian tradition as a source rock for carved pipes and numerous other trinkets. This bed is the real "pipestone" from which the formation gets its name. The pipestone is a dense, red, indurated clay or shale, much softer than the quartzite beds above and below it.

North of the city of Pipestone the quartzite crops out extensively in two distinct varieties. One is an attractive deep red stone that occurs in beds rarely more than eight inches thick; the other is a pale grayish red of poorer quality. Owing to its uneven and irregularly spaced joints the rock is seldom cut into large blocks for structural purposes, but its attractive appearance and great strength make it desirable for ornamental trimming. The stone is used extensively for building blocks, roofing chips, and crushed stone. A typical installation may be seen in the Scottish Rite Temple, Minneapolis.

For grinding materials in which iron would be an objectionable contamination — feldspar, talc, whiting, and some kinds of cement and pigments — tube mills are lined with so-called "flint" blocks, and "flint" pebbles are used instead of steel balls. Most of the "flint" lining blocks and pebbles used in the United States are quarried and fabricated from the Sioux quartzite by the Jasper Stone Company at Jasper. In service the pebbles compare favorably with the famous Danish, Belgian, and French flint pebbles. Such pebbles are normally imported in amounts ranging from 15,000 to 20,000 tons per year. In wartime imports are greatly curtailed if not completely stopped. If the supply from Jasper is not sufficient to meet the demand, other American materials may be produced.[66] The quartzite pebbles on the shore of Lake Superior between Grand Portage and Pigeon Point have been used and found satisfactory in some mills. The Sioux quartzite has also been quarried at New Ulm, Minnesota, for crushed rock. (See page 111.)

KEEWATIN BASALT

Areas of ancient lava flows are exposed in northeastern Minnesota. The flows are principally of basaltic composition and of Keewatin age. The rock crops out abundantly at Ely, Minnesota, and is sometimes called Ely greenstone. It has been quarried to some extent for foundations, retaining walls, and crushed rock.

Since 1920 a somewhat massive phase of the Ely greenstone has been quarried about five miles southwest of Ely and used for the manufacture of roofing granules. The quarry and mill are operated by the Emeralite Rock Products Company.

The rock from the quarry is crushed by jaw crushers, gyratory crushers, and rolls. Fine material is discarded, and the granules used are those which pass a 10-mesh but are retained on a 35-mesh screen. These granules are colored variously by water-glass solutions, and shipped in bulk carload lots or in 120-pound bags to manufacturers of composition shingles. Before 1933 the granules, naturally green, were used uncolored.

SLATES

Various kinds of slaty rocks crop out in Carlton County along the valley of the St. Louis River, and in northern Cook County near the international boundary. Several quarries were opened before 1880 at Thomson, but none of the rock has proved to be suitable for commercial roofing.

[66] Metcalf, R. W., Grinding pebbles and tube-mill liners: U. S. Bureau of Mines, Information Circular 7139, 1940.

SAND AND GRAVEL[67]

GENERAL STATEMENT

Sand and gravel are used for many purposes, but the greatest use is for concrete mixtures in the building industry and in highway construction. Other commercial uses include molding sands for foundry practice; high silica sands for the manufacture of glass; sharp, abrasive sands for polishing and grinding; engine sands for rail traction; filter sands; coarse sand for poultry grit; and sands and gravels for railroad ballast.

As recently as 25 years ago the sand and gravel industry was relatively unimportant in Minnesota. Until the widespread use of automobiles made good roads a necessity, road building and road maintenance were often haphazard. Now highway engineering is highly developed, and standardized materials are required. They can best be supplied by organizations that specialize in the production of various types of crushed rock and sand or gravel mixtures. However, the growth of the sand and gravel industry in Minnesota is attributable not only to the surfacing of many hundreds of miles of highways in recent years, but also to an increase in other kinds of concrete construction in recent decades.

Sand and gravel are found in almost inexhaustible deposits throughout Minnesota, except in five minor areas. These are: (1) the central portion of the Red River Valley from Clay County north to the Canadian boundary; (2) the extensive swamplands in Beltrami, Lake of the Woods, and Koochiching counties; (3) the region along the Canadian border in northeastern Minnesota where the bedrocks crop out at the surface or are only thinly covered with soil; (4) the areas between streams in the southeastern corner of the state; and (5) the extreme southwestern corner of the state (fig. 18.)

GEOLOGY OF SAND AND GRAVEL

Formations containing sand and gravel in Minnesota may be classified as follows: (1) bedrock, (2) glacial deposits, and (3) post-glacial alluvium.

Bedrock Deposits

Little or no gravel is produced from bedrock in Minnesota. However, the Jordan sandstone of Cambrian age and the St. Peter sandstone of Ordovician age are exploited to some extent for sand; both are virtually flat-lying, sedimentary formations of marine origin.

The Jordan is commonly a white to yellowish, medium-grained, friable, high-silica sandstone. It ranges in thickness from about 100 to about 200 feet and is exposed at places in the southeastern quarter of the state, particularly along the St. Croix, Minnesota, and Mississippi rivers. Locally the grains are angular, and the material has been used for sand blasting, stone sawing, and other abrasive purposes. It has been used also

[67] Data on sand and gravel compiled chiefly by Dr. G. M. Schwartz.

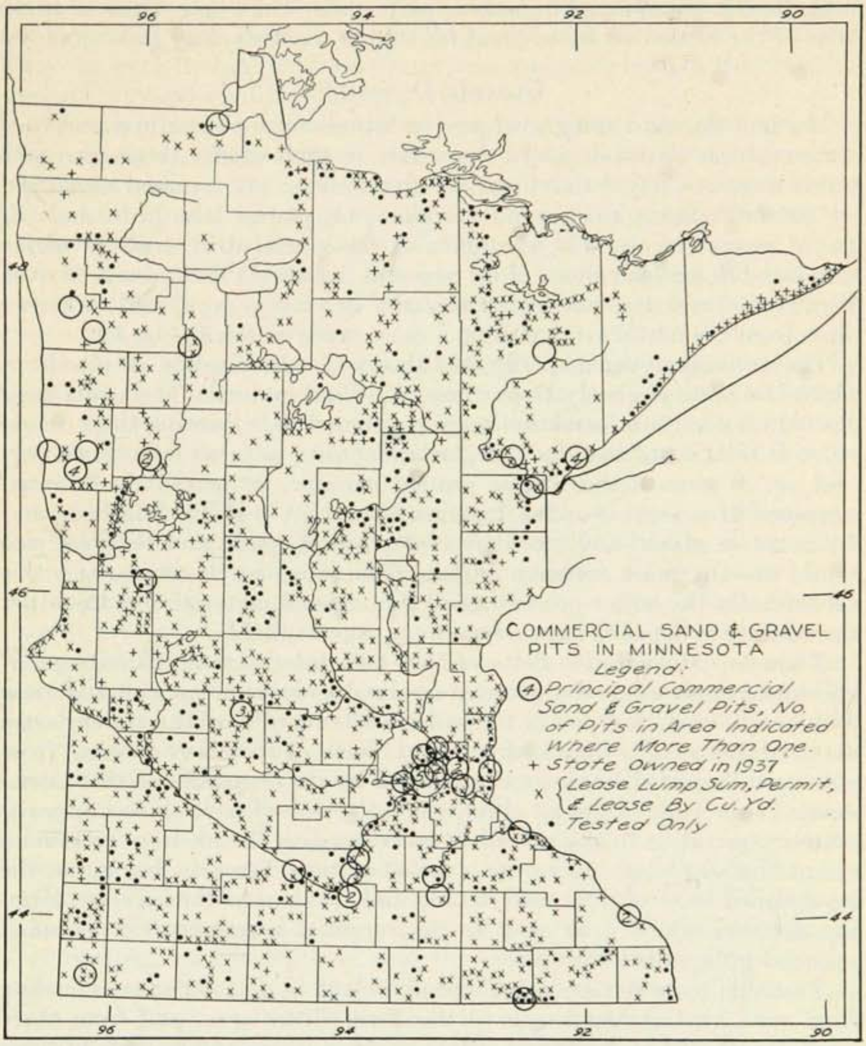

FIGURE 18. — Outline map of Minnesota showing commercial sand and gravel pits and state-owned pits, April 1937.

for foundry sand and for filter beds in municipal water plants, and it has produced some sand suitable for making glass.

The St. Peter is normally a white, incoherent sandstone with medium to fine, well-rounded, frosted grains of quartz. It crops out at many places in the southeastern portion of the state and is well exposed along the Mississippi River in the Twin Cities area. This material is used for rough finishing of stone and for core sand in foundry work. At the Ford Plant in St. Paul it is employed in making plate glass. The iron content of some parts of the formation is too great for that of a satisfactory glass sand.

Glacial Deposits

Much of the sand and gravel used in Minnesota for structural purposes is mined from glacial deposits. According to their origin, these sand and gravel deposits may be divided into five groups: (1) terminal moraines, (2) outwash plains, (3) ground moraines, (4) glacial lake beds, and (5) glacial river terraces. The character of the glacial drift deposits varies with the different directions of ice invasion. Ice sheets that advanced over Minnesota from the northwest brought in clayey gray drift, whereas those from the northeast deposited a more sandy red drift (fig. 5).

The accompanying map (fig. 18) shows the distribution of pits from which the State Highway Department has used material. These pits were plotted on a surface formation map of Minnesota,[68] showing their occurrence in relation to the kinds of glacial deposits to be as follows: 30 percent are in areas designated as ground moraine, 26 percent in terminal moraines, 21 percent in outwash plains, 16 percent in glacial lake beds, and 7 percent in glacial and recent river deposits. Ground and terminal moraines are the most common surface formations in the state, and this accounts for the larger percentage of pits in such material, but the other three kinds of deposits have a larger tonnage available.

Terminal Moraines. — Belts of low hills interspersed with irregular, undrained depressions characterize terminal moraine areas. Soil and loose rock became incorporated in the ice as it advanced over the region; some material was gouged from bedrock; and blocks of rock were plucked from outcrops. Terminal moraines were formed by the deposition of this glacial debris at the edge of the ice sheet, when the rate of melting was approximately equivalent to the rate of advance, causing the ice front to remain essentially stationary over a long period of time. Streams flowing on the ice dropped some of their load of sand and gravel near the ice edge, forming deposits which exist now in the terminal moraine areas as small rounded hills, called "kames."

Terminal moraines are thick and abundant in a broad zone extending from west central Minnesota to the Twin Cities area, and from there south to Albert Lea. Sand and gravel occur in lenses and pockets in these glacial hills. Kame-like ridges and hills have furnished much material of good grade.

Outwash Plains. — Streams and sheetfloods issued from the melting ice, forming outwash plains by depositing material transported by running water beyond the terminal moraine zone. This action of running water yielded deposits of more or less sorted gravels and sands. Topographically, outwash areas are broad, gently sloping plains. They do not

[68] Map of Minnesota showing surficial deposits, made by putting together the maps in Bulletins 12, 13, and 14 of the Minnesota Geological Survey.

cover as many square miles in Minnesota as terminal and ground moraines do, but large deposits of excellent sand and gravel occur in them. They are exploited in the Twin Cities area and elsewhere in the state for construction and road-building materials.

Ground Moraines.—Ground moraines and gently undulating plains of poorly sorted glacial drift were deposited over most of the region during the advance of the ice or during its final melting. They cover many thousands of square miles in the state. In the areas of gray drift from the northwest they are largely clay till, but much sand and gravel occur in drift from the northeast. There are some small pockets of sand and gravel even in the clay till, and they are mined locally where other types of deposits are not available.

Eskers or "serpent ridges" of sand and gravel, which were deposited by streams flowing in tunnels in the ice, or in channels eroded on the surface of the ice, are sometimes found in ground moraine areas. Although not very numerous, they are excellent sources of sand and gravel in the districts where they occur.

Glacial Lake Beds.—Two large glacial lakes existed in Minnesota during glacial time, Lake Agassiz and Lake Duluth. When ice blocked the normal easterly drainage of Lake Superior, much of the water from the melting ice was impounded; the lake was more than 500 feet higher than at present and extended over a larger area. This old lake, referred to as Lake Duluth, has sand and gravel deposits along its abandoned shore lines. In a similar manner Lake Agassiz was formed when the ice edge retreated within the Red River Valley. Near the shore of this ancient lake, waves reworked the glacial drift and built gravelly beach ridges. A series of these beaches exist, indicating the extent of the lake during various stages of its recession. The beaches are 5 to 20 feet high and are important sources of sand and gravel in the Red River Valley. Some of the beaches of Lake Superior have large amounts of quartzite pebbles.

Glacial River Channels.—The glacial river, Warren, which drained Lake Agassiz and flowed in the present Minnesota River Valley as far as Fort Snelling, and from there into the present Mississippi Valley, deposited much material along its course. Near New Ulm, St. Peter, Red Wing, and Winona considerable amounts of gravel and sand have been excavated from its alluvial terraces. Some of the gravel pits in and near St. Paul and Minneapolis are in similar deposits formed during the early stages in the development of the Upper Mississippi Valley.

Post-Glacial Alluvium

The principal reserves of sand and gravel formed since glacial time are the alluvial deposits along the Mississippi and Minnesota rivers and their tributaries. Most of this material, however, is of glacial origin and has been reworked by post-glacial streams. Large washing and screening plants at Winona and Mankato use material of this kind.

SAND AND GRAVEL INDUSTRY IN MINNESOTA

State Highway Department

On July 1, 1940, the State Highway Department owned 12,720,172 cubic yards of gravel and sand in 383 pits scattered through 64 counties in Minnesota. For maintenance and construction 2,048,650 cubic yards of sand and gravel were used in 1939 and 1940, about 53 percent of which came from state-owned pits. Most of it was pit-run material with low unit value. Nearly all large producers have had the quality of their product tested by the Highway Department before attempting large development.

It has been found that the cost of prospecting may be reduced as much as 50 percent by using geophysical methods to delineate a mass of sand and gravel before sinking test holes to prove and sample the deposit.

Commercial Producers

Pits and plants producing sand and gravel are so numerous throughout the state that a complete coverage of the industry would be impossible without an extensive survey. Locations of the principal plants are shown on the accompanying map (fig. 18). Some of them crush and screen boulders occurring in the deposit, in addition to washing and screening the pit-run material. Annual capacities range from a few thousand to many thousand tons.

The Minnesota Department of Highways at St. Paul issues nearly every year a mimeographed list of the producers of washed sand and gravel. It does not necessarily include all available sources of such material and does not pretend to be a guaranty that each producer can meet the specifications of all purchasers. The list is nevertheless a useful one. It may be obtained from the department.

Mining

Numerous methods of excavating sand and gravel are employed in Minnesota. Hand-shoveling is still the method used in small operations, but at the larger pits power equipment is used for digging and loading. Steam, gasoline, and Diesel shovels are the most used mining machines. At some establishments draglines, cranes, or cableway buckets are used, and at a few places where the gravel bank is under water the material is removed with pump dredges.

The table at the top of page 85 shows the quantity of sand and gravel excavated in Minnesota by types of equipment used in 1929.

Screening and Washing

Delivery of sand and gravel from pit to plant is usually made by dump cars drawn by steam or gasoline locomotives and by dump trucks. Belt conveyors are in use in a few plants.

Sand and Gravel Recovered in Minnesota in 1929 [1]

Types of Equipment	Short Tons	Percentage of Total
Power shovel only	1,243,381	42
Dragline only	678,303	23
Power shovel and dragline	482,247	16
Others	545,949	19
Total	2,949,880	100

[1] Statistics from the U. S. Bureau of the Census: Mines and Quarries, 1929.

The purpose of washing is to remove clay and soft stone. Screening grades the material according to size. A few firms use special scrubbing apparatus. Vibrating, shaking, and revolving screens are among the types employed. Some of the screen sizes sold by producers in the state are shown in the following table.

Screen Sizes for Sand and Gravel

Size	*Use*	*Approximate Price per Short Ton*
Less than 1/4 inch	Concrete sand	$ .35
1/4 to 1/2 inch	General construction gravel	.75
1/2 to 3/4 inch	General construction gravel	.75
3/4 to 1½ inches	General construction gravel	1.25
1½ to 2 inches	Paving gravel	1.25

Past Production and Employment

Minnesota normally ranks from eleventh to fifteenth among the states in the output of sand and gravel. The use of sand and gravel in government-aid projects accounted in part for the large production of over five million tons in 1934. The table on page 86 gives some of the details concerning the industry in Minnesota. Employment is seasonal because road building and construction are curtailed during the cold months.

In 1931 about 11,450 thousands of sand-lime brick, valued at $94,050, were produced in Minnesota. Approximately four pounds of washed sand with a grain size of one-fourth inch or smaller goes into each brick. The Belt Line Brick and Superior Brick companies of Minneapolis and the C. H. Klein Brick Company of South St. Paul manufacture sand-lime brick.

Gravel is used mainly for paving, general concrete construction, surfacing roads, and railroad ballast. Most of the so-called graveled roads are surfaced with ungraded, pit-run material. Gravel and sand are employed also in bituminous mixes on highways. The manufacture of pre-mixed concrete and such concrete products as building blocks, brick, cast stone, pipe, and vaults is an industry of considerable importance. Minnesota ranks tenth among the states in the production of these items. Sixty plants were operating in 1937.[69]

[69] Biennial Census of Manufactures, 1937, p. 855.

GRAVEL AND SAND SOLD OR USED BY PRODUCERS IN MINNESOTA IN 1929 AND 1939 [1]

	Gravel	1929	1939
Building	Short tons	629,310	960,962
	Value	$583,839	$663,993
Paving	Short tons	1,223,437	4,332,350
	Value	$919,314	$606,473
R. R. ballast	Short tons	1,482,348	745,637
	Value	$275,407	$126,051
Total gravel	Short tons	4,990,256	8,501,211
	Value	$2,412,776	$1,942,438
	Sand		
Molding	Short tons	27,919	12,791
	Value	$23,259	$14,480
Building	Short tons	968,369	1,666,018
	Value	$346,239	$356,418
Paving	Short tons	554,310	434,357
	Value	$219,604	$128,215
Engine	Short tons	64,323	29,946
	Value	$20,525	$5,867

[1] Mineral Resources for 1929 and Minerals Yearbook Review of 1939 (1940), U. S. Bureau of Mines. (See also Minerals Yearbook for 1941, page 36, giving statistical summary by states.)

MARKETING

Sand and gravel are transported by truck, rail, and barge. There are no statistics available regarding the relative amounts moved by these various methods, but probably most of the sand and gravel produced in Minnesota is delivered by truck. Shipments and sales in this industry are closely correlated with those of Portland cement.

NUMBER OF MINNESOTA SAND AND GRAVEL PLANTS AND AVERAGE PRODUCTION OF PLANTS, 1910–40 [1]

	Small Plants		Medium Plants		Large Plants		Minnesota Total	
	Number	Average Production (tons)	Number	Average Production (tons)	Number	Average Production (tons)	Number	Average Production (tons)
1910	27	3,588	9	42,760	..	......	36	13,381
1920	25	8,594	10	58,595	4	196,065	39	40,642
1930	59	6,930	13	62,469	9	248,446	81	42,679
1940	39	8,823	18	48,481	9	154,501	66	39,504

[1] Data from Colby, S. F., Development of the sand and gravel industry: U. S. Bureau of Mines, Information Circular 7203, 1942.

In recent years portable screening and washing plants have come into competition with the larger stationary ones. They offer the advantages of employing local labor and producing aggregate on the job, making long hauls unnecessary.

Sales of sand and gravel may be direct to consumers, government agencies, and contractors for government and private construction. Some sales are made through wholesalers and jobbers, others through agents or dealers on a commission basis. Other methods of disposal are direct sales to nonaffiliated, ready-mixed concrete companies and concrete products manufacturers, or sales or transfers to affiliated (or owned) organizations.

Evidently the business recession in 1933 so reduced the local industry that it has not yet come back to the tonnages of earlier years. The Minerals Yearbook data for 1941 show a general increase in production over 1940. A major change in the development of the industry is a decentralization based on the success of portable plant equipment.

FOUNDRY SANDS

Minnesota possesses an abundance of foundry sands and all materials commonly used for making molds in the founding of iron, steel, brass, and aluminum. For casting almost all metals and alloys, sands and loams found in the state are as good as and in some instances superior to those imported. The occurrence and uses, and the tests made to determine the suitability of foundry sands, clays, and loams in Minnesota are discussed in detail by Knapp.[70]

Founding, the art of casting metals, consists of preparing a pattern with the shape of the desired product, using this pattern to make a mold with suitable material, pouring molten metal into the mold, and allowing the casting thus formed to stand until the metal has set. Patterns are usually made of wood, but they may be fabricated also from wax or clay. Molding materials are sand, loam, and clay. They are supported by frames, known as "flasks," while they are being rammed around the pattern to make the mold, and during the casting and setting of the metal. According to the purpose for which they are used, foundry sands may be classified as (1) core sands and (2) molding sands.

Core sands are used in making the hollow spaces in metal castings. For this purpose a clean sand free from clay is desirable. Glue, resin, linseed oil, or molasses is added to bind the sand grains together during the molding processes. The heat of the metal destroys this bond, and the sand can be readily removed from the voids in the casting when it has cooled.

Molding sands contain sufficient clay to bind the sand, but not enough completely to clog the spaces between the grains. When slightly dampened they can be molded into any desired form, and they retain this form when dry. They should be sufficiently open textured to permit steam and other gases generated by the hot metal to escape, and thus to prevent disruption of the mold. If the temperature is high, as in casting steel, the sand must be a high-silica (quartz) sand containing as little as possible of such fluxing impurities as lime, alkalies, and iron oxides. The textures, tensile strength, and degree of refractoriness required differ at different foundries.

[70] Knapp, G. N., The foundry sands of Minnesota: Minn. Geol. Survey Bull. 18, pp. 1–105, 1923.

Distribution in Minnesota

The geology of Minnesota has been outlined in the section on general geology and in part in other sections of this report. In the following paragraphs only those formations which contain satisfactory sands for foundry use are discussed, beginning with the oldest and ending with the youngest.

Sioux Quartzite.—Sioux quartzite is a hard siliceous rock quarried at Pipestone, Jasper, and Luverne in the southwestern part of the state, and formerly at New Ulm. Screenings from rock-crushing plants at these localities furnish a valuable sand for refractory molds, and are used also to sandblast the castings.

Kettle River Sandstone.—At Sandstone, Minnesota, Kettle River or Hinckley sandstone is quarried for building stone and crushed rock. Screenings, a high-silica by-product of the crushing operations, have been sold for refractory material to foundries in Minneapolis and St. Paul and for use in the steel furnaces at Duluth.

Jordan Sandstone.—Jordan sandstone is a white, well-rounded quartz sand. It attains a maximum thickness of 200 feet and is exposed along the Minnesota River as far upstream as Mankato and also at some places along the Mississippi and St. Croix rivers. Much of the sand is incoherent and can be extracted by shoveling without blasting. It is a refractory sand and is used for steel casting, core work, and other foundry purposes. It is mined near Ottawa and Jordan, and at other localities along the Minnesota River. Material from Ottawa, Minnesota, sized to 20 mesh cannot be distinguished from the well-known standard sand from Ottawa, Illinois.

St. Peter Sandstone.—The St. Peter is a white, poorly-cemented, nearly pure quartz sandstone. It is somewhat finer grained than the Jordan sandstone and the clay and silt content is usually higher. It is the most exposed bedrock in the Minneapolis-St. Paul area, where it is used largely for core work.

Cretaceous Formation.—The Cretaceous formation contains some high-grade white sand, but there is such an abundance of better high-silica sands in the Jordan and St. Peter sandstones that it has not been exploited for foundry material.

Glacial Deposits.—Some of the red, sandy, morainic material scattered over the eastern side of the state from Minneapolis and St. Paul northward is used for foundry work. In northern Minnesota glacial sands are usually employed for core work. The drift in the western part of Minnesota has little material suitable for foundry use.

Much material was ground to rock flour in the moving ice. Since glacial time these deposits of rock flour have been weathered and leached and soluble substances have been removed, leaving a residue with a loamy consistency. In Minnesota these loams are erratic in distribution and character, but some are used for foundry work.[71]

[71] Knapp, G. N., *op. cit.*, page 27.

Outwash plains have supplied much foundry sand. Outwash areas and the flood plains of glacial streams furnish loams of better grade than those mentioned above.

Loess.—Loess, a windblown silt, covers many townships in the southeastern corner of the state from near Red Wing south to the Iowa line, and many in the southwestern corner of the state (fig. 18). Locally it may attain a depth of about 40 feet. It has a low fusion point, but since brass, other alloys of copper, and aluminum are cast at relatively low temperatures, it is a very satisfactory molding sand for these metals.

Recent Deposits.—Sand from Lake Superior is used in Duluth foundries for core work. Loams along the present drainage channels are likely to be variable in quality, but by careful selection good foundry material may be obtained from some of them.

Production of Foundry Sands

There are 43 foundries in Minneapolis and St. Paul, and perhaps as many more scattered through the state. They use many types of molding material.

Foundry sands are produced at the places mentioned in the foregoing paragraphs. Many foundry operators use material obtained locally, mined either by themselves or by contractors. Much of it, however, is excavated in or near Minneapolis, St. Paul, Duluth, Ottawa, and Jordan. Some is imported. Estimates of the quantity of foundry sands mined and sold in Minnesota vary, but the production in 1936 was approximately as follows:

Production of Foundry Sands in Minnesota, 1936

	Short Tons (approximate)	*Value (approximate)*
Steel sand	1,000	$2,000
Cast-iron sand	20,000	45,000
Brass and aluminum sand	300	1,500
Core sand	25,000	50,000

CLAYS AND SHALES

INTRODUCTION

Clays[72] in Minnesota were used for brick manufacture as early as 1862 and possibly earlier. By 1884 attempts had been made to employ Minnesota clays for making pottery, drain tile, and fire brick. Nearly every county in the state has clay from which someone has tried to make brick for local use. (See also the section on fuller's earth.)

Geologic formations bearing clays in the state were tested in detail and reported by the Minnesota Geological Survey;[73] the report was revised and reprinted by the United States Geological Survey.[74] These works may be referred to for more detailed information than is given here. Material for the following discussion is largely from these bulletins (fig. 19).

DEFINITIONS

Clay is a mixture of minerals composed essentially of hydrous aluminum silicates (predominantly kaolinite, $H_4Al_2Si_2O_9$) in particles which range in size from approximately 0.005 millimeter to submicroscopic. Clays are seldom pure, however, and they commonly contain various amounts of such minerals as quartz, calcite, and feldspars in a fine state of division or as silt, sand, and even gravel. Plasticity, the ability of moist clay to be fashioned into forms which the clay will retain until dried to rigidity, is a property of clay familiar to everyone.

Shale is a consolidated sedimentary rock composed of laminated clays. Shale beds are chiefly of marine origin and have been buried under other sediments.

PHYSICAL PROPERTIES

In addition to plasticity, the following properties have an important bearing on the behavior of clays.

Shrinkage.— Both air shrinkage and fire shrinkage differ in different clays. Air shrinkage occurs during drying of the molded ware. In Minnesota clays linear air shrinkage may range from 3 to more than 10 percent. Fire shrinkage occurs during firing. Linear fire shrinkage may amount to several percent. Cracked or distorted products may result from excessive shrinkage.

Tensile Strength.— The resistance of a mass of air-dried clay to rupture when subjected to a tensional force is its tensile strength. The tensile strength of Minnesota clays ranges from 30 to more than 170 pounds per square inch.

Fusibility.— Fusion of clays occurs gradually with increasing tempera-

[72] The section on clays and shales was compiled chiefly by Dr. F. F. Grout.

[73] Grout, Frank F., and Soper, E. K., Preliminary report on the clays and shales of Minnesota: Minn. Geol. Survey Bull. 11, pp. 1–172, 1914.

[74] Grout, Frank F., Clays and shales of Minnesota: U. S. Geol. Survey Bull. 678, pp. 1–259, 1919.

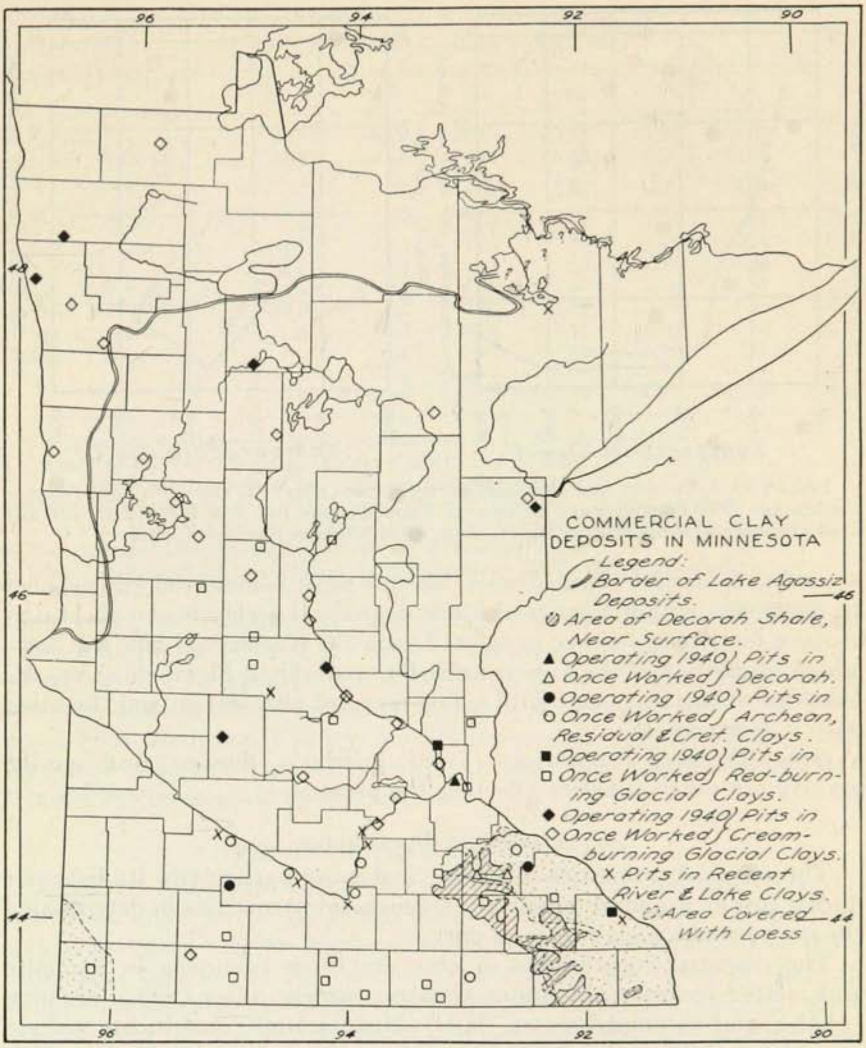

FIGURE 19. — Outline map of Minnesota showing commercial clay deposits.

ture and takes place in three stages; namely, incipient fusion, vitrification, and viscosity. Incipient fusion occurs in some Minnesota clays at temperatures as low as 1780° F., but in the more refractory clays it may be at a temperature over 2280° F. Viscosity, or the point at which the ware softens and flows as a viscous liquid, is reached between 2200° F. and 3200° F. in different clays. Incipient fusion, vitrification, and viscosity are not sharply separated, but the interval between incipient fusion and viscosity is known as the range of vitrification. Clays having a wide range

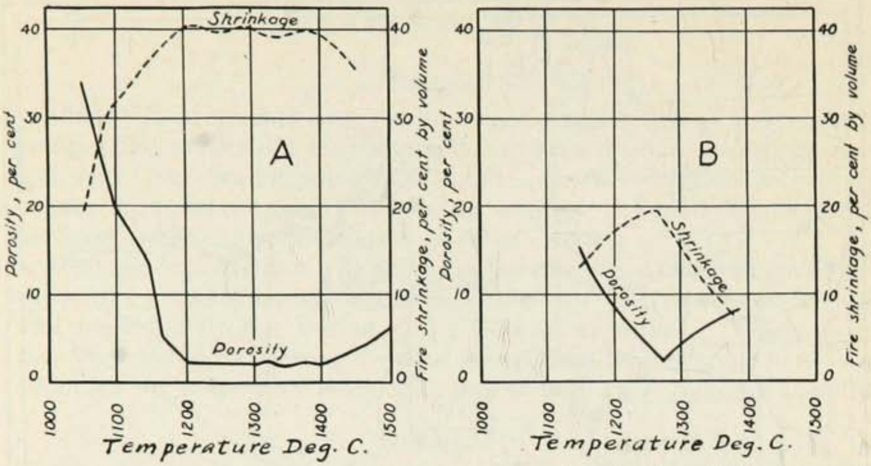

FIGURE 20. — Porosity and shrinkage curves for two clays. *A*, clay with large range of vitrification: after Bleininger and Loomis, Tr. Amer. Ceramic Soc., vol. 19, 1917. *B*, clay with short range of vitrification: after Brown, Jour. Amer. Ceramic Soc., vol. 1, 1918.

are safest to use for vitrified ware, because most commercial kilns cannot be controlled within a range of a few degrees. If a clay begins to lose its shape a few degrees above incipient fusion the commercial kiln will leave a high proportion of the ware overfired or underfired. Figure 20 shows the behavior of two clays, one with a long range of vitrification and the other with a short range.

Other Physical Properties. — Color, grittiness, fineness, and specific gravity are other qualities affecting the product.

Chemical Properties

The physical properties of a clay, and more particularly its behavior during fusion, are more important than chemical analysis in determining the use to which a clay may be put.

The essential constituents of clay are those occurring in kaolinite and related hydrous aluminum silicates; namely, silica (SiO_2), alumina (Al_2O_3), and combined water (H_2O). Nonessential constituents include lime compounds, especially $CaCO_3$, iron oxides, magnesia, alkalies (K_2O and Na_2O), and iron sulphides. Usually, the greater the percentage of such fluxing impurities as alkalies and lime, the less refractory the clay.

ORIGIN OF RESIDUAL CLAYS

Weathering of such rocks as granites, impure limestones, and feldspathic sandstones produces clay which, if it is not removed by erosion, remains behind in a residual deposit. Deposits of that kind, which resulted from the weathering of Archean granites, occur in southwestern Minnesota. There are probably locally some high-grade fire clays, some

Analyses of Some Minnesota Clays
(from U. S. Geological Survey Bulletin 678)

	1	2	3	4	5	6	7
Silica, SiO_2	41.71	69.92	63.65	56.35	58.85	50.51	47.70
Alumina, Al_2O_3	34.61	17.39	17.27	18.63	7.25	15.89	13.58
Ferric oxide, Fe_2O_3	4.58	1.68	4.75	6.19	4.97	8.21	6.51
Ferrous oxide, FeO	6.88						
Magnesia, MgO	.22	1.11	.06	2.97	3.45	5.14	3.13
Lime, CaO	1.16	.60	1.21	.96	9.42	7.10	11.70
Soda, Na_2O	.11	.07	.91	.25	1.37	1.66	1.05
Potash, K_2O	trace	2.25	2.47	7.37	1.76	1.87	2.34
Ignition, H_2O+	12.69	5.45	7.36	4.81	11.20	7.35	13.23
Moisture, H_2O-	....	1.10	2.03	2.41	2.10	2.44	1.79
Titania, TiO_2	....	.63	.62	.65	.36	.26	.31
	101.96	100.20	100.33	100.59	100.73	100.43	101.34

1. Kaolin of the weathered Archean, near Morton. A. D. Meade, analyst.
2. Cretaceous clay, as shipped to stoneware plant, Red Wing. F. F. Grout, analyst.
3. Cretaceous shale, Springfield brick clay. F. F. Grout, analyst.
4. Decorah shale, lower 10 feet, brick yard, West St. Paul. F. F. Grout, analyst.
5. Gray drift clay, Hutchinson; requires washing to remove pebbles. F. F. Grout, analyst.
6. Red waterlaid glacial moraine, Duluth. A. W. Gauger, analyst.
7. Glacial lake clay, gray, laminated, Littlefork River. A. W. Gauger, analyst.

paper clays, and possibly even china clays, but the deposits are not well exposed and most of them are not easy of access, because they are commonly covered by glacial drift to depths of 50 to 250 feet. These clays, however, do crop out along the Minnesota Valley in the vicinity of Redwood Falls, Redwood County, and at Richmond, Stearns County, and they are well known from well records. At many places light-colored clays attain a thickness of 50 to 100 feet.

ORIGIN OF TRANSPORTED CLAYS

Marine.— Clays are carried by rivers to the sea and are there deposited in quiet water. By burial beneath other sediments, compaction, and cementation they are hardened to shales. In Minnesota the two shale formations best suited for ceramic purposes are the Decorah shale of Ordovician age and the Cretaceous shales and clays. The Decorah shale extends from the Twin Cities south and southeast (fig. 19), and the Cretaceous shales are known at several widely scattered points from Brown County to Goodhue County. The adaptability of the shales is shown by the production at Springfield, West St. Paul, and Red Wing (pages 95–97).

Glacial.— Clays of glacial origin in Minnesota are of three kinds: (1) till, (2) lake clays, and (3) river clays.

(1) Glacial till deposited by the retreating ice is widely distributed through the state and ranges widely in character. The surface clays depend principally on the kind of glacial drift brought in from different directions.

The gray drift from the northwest has the greatest areal extent (fig. 5), but clays from this formation usually contain limestone pebbles, which burn to lime and later slake and expand, breaking the ware. Because of this serious defect perhaps nine-tenths of the pioneer attempts to use Minnesota clays were abandoned. Some of these surface clays have been reworked by running water and wave action and redeposited in lakes, and have thus been freed from pebbles. Attempts were made to duplicate this process artificially at Hutchinson, McLeod County, but the cost was considerable.

The red drift from the north and northeast is less limy, but it contains more sand and gravel.

(2) Around the west end of Lake Superior, in what was the bed of glacial Lake Duluth, are large deposits of red plastic clay. The clays have been reassorted there by stream and wave action and are good brick clays.

(3) Along the valleys of the Mississippi and Minnesota rivers and their tributaries are deposits of banded, gray, glacial clays laid down when these streams carried sediment-laden water from the melting ice. Clays of this origin have been used at Chaska and Jordan along the Minnesota River and along the Mississippi River from Minneapolis to Brainerd.

Stratified red glacial lake and river clays occur on the eastern border of Minnesota.

Post-Glacial River Clays. — Thick beds of banded clay occur along the Red River. They were probably deposited both during and after the glacial period. The principal recent river clays occur in alluvial terraces in the flood plains of the Minnesota, Mississippi, and St. Louis rivers and their tributaries. They are moderately plastic, but most of them are sandy and supply only common brick material.

Loess. — As pointed out in the discussion of the geology of Minnesota, loess is a fine-grained, windblown deposit derived chiefly from the glacial drift. Considerable loess is found in southeastern Minnesota and some is found in the southwestern corner of the state (fig. 19). It has low plasticity, but common brick can be made from it.

MINING

Clays in Minnesota are mined from open pits. Surface clays may usually be excavated with a scraper or dragline. At the Twin City Brick Company's quarry in St. Paul, shale is handled with a power shovel. At Springfield a five-yard road scraper attached to a caterpillar tractor is employed to strip about 35 feet of glacial drift and poor quality clay from a 55-foot bank of commercial Cretaceous shale. The shale, which is soft, is loaded into small, steel dump cars which are hoisted to a hopper above the grinding plant. In Goodhue County stoneware and sewer pipe clay is dug by hand and hoisted from the pit by a dragline. It is hauled by trucks to plants in Red Wing, about 13 miles north.

FABRICATION

Preparation of the Clay.—Much of the gray drift clay contains limestone pebbles which must be removed. At Hutchinson the drift was washed in open ponds, and the clay was used to make drain tile. Certain other plants, besides removing stone, find it necessary to employ disintegrators and crushers. Fine crushing is necessary to obtain a product of the proper plasticity from some hard shales. Many clays and shales adhere to machinery so strongly that rolls rather than jaw crushers are used in grinding.

At the Red Wing Potteries Company clay is prepared for the manufacture of stoneware by making it into a soupy mixture in blunger mills and passing it through rotary sieves to remove coarse sand. The slush is then pumped into filter presses to extract the surplus water. Steam is used in the blunger mills and in the washing process, keeping the mixture at the boiling point to increase the efficiency of the filter-pressing operation. Cakes of clay weighing approximately 40 pounds are removed from the filter press and are then ready to be tempered and molded.

Tempering.—To produce the degree of plasticity necessary for molding, clay is "tempered" by adding the required amount of water and by mixing in a machine, commonly a pug mill, which is essentially a trough in which a horizontal axis with arms or knives set at an angle rotates and mixes the clay. The axis with its arms acts like a screw conveyor and forces the clay out of the end of the mill.

Molding.—Bricks and structural tiles are usually molded by the extrusion method. The tempered clay is forced through a die, and as the ribbon of clay issues from the molding machine wires cut it to brick size.

In making sewer pipe the clay mass is forced through a die by a piston operated by steam pressure. Odd shapes are molded in plaster casts. In small brick-making operations clay may be molded by hand or pressed into molds by a plunger. Fabrication of pottery and stoneware is more complicated.

Drying.—Common brick plants in the state dry their ware out of doors. Face brick and tile are dried in tunnels by waste heat from the kilns. Pottery is dried in a room or tunnel with the humidity and temperature closely controlled.

Burning.—The clay is "burned" or "fired" in various types of kilns. At many common brick plants the kilns are temporary and must be built up for each batch of brick. Kilns may be either of the up-draft or down-draft type. The latter type is used for face brick and hard, vitrified products, and there is less loss from overburned and underburned ware.

CLAY PRODUCTS INDUSTRIES IN MINNESOTA

Face Brick and Tile

Twin City Brick Company, St. Paul.—Decorah shale is used by the Twin City Brick Company in the manufacture of its products. The bed is 74 feet thick at the plant site. The business was incorporated in 1892, and the annual production amounts to over 12,000,000 face brick. Some roofing, face, and back-up tile also are made. Thirty-three down-draft kilns are located on the property. The shale burns ordinarily to a buff or tan when vitrified; to red or brown at lower temperatures; and to a great variety of attractive colors when flashed (varying the amount of air and fuel gases during firing). Production continues throughout the year, giving employment to an average of 75 men. The company has furnished brick for residential and business buildings, schools, and other public structures in Minnesota and neighboring states. Some shipments are sent to the East, where they compete successfully with other high-grade face brick.

Important buildings in which this company's brick have been installed include:

Auditorium, St. Paul
Music Hall, University of Minnesota
Field House, University of Minnesota
Lowry Hotel, St. Paul
Schools at Anoka, Minnesota
North Dakota Agricultural College, Fargo
Homewood School, Milwaukee, Wisconsin
Dudgeon School, Madison, Wisconsin
Masonic Temple, Chicago
Daily News Building, New York City

A. C. Ochs Brick and Tile Company, Springfield, Brown County.—The owner started molding brick by hand at Springfield in 1892. The business was incorporated in 1916, when the owner associated his three sons with him. A bank of Cretaceous shale, which burns to a red and reddish-brown color, supplies raw material. The plant is conveniently located on the Chicago and Northwestern Railway, a short distance east of Springfield. Sixteen round, down-draft kilns were operated on the property at about 75 percent capacity in 1940.

About 70,000 to 80,000 tons of shale are mined yearly. During 1936 approximately 13,500,000 face brick and about 22,000 tons of hollow structural building tile for walls, barns, and silos were produced. About 80 to 90 men are employed throughout the year.

The Springfield firm sells its product both in Minnesota and elsewhere. It has furnished brick for about 150 schools in the Northwest. It is estimated that about 40 percent of the ware is hauled by truck and about 60 percent is shipped by rail.

The following buildings are examples of installations of the A. C. Ochs Company's product:

Nicollet Hotel, Minneapolis
Pioneer Hall, University of Minnesota
Veterans' Hospital, Fort Snelling
St. Cloud, Minnesota (49 buildings)
Mankato, Minnesota, Schools
Alex Johnson Hotel, Rapid City, South Dakota
First National Bank, Fargo, North Dakota

Sewer Pipe

Red Wing Sewer Pipe Corporation.—Clay is mined from deposits of Cretaceous age several miles south of Red Wing by the Red Wing Sewer Pipe Company. The deposits, which have been disturbed by glacial ice, are irregular and range up to 50 feet in thickness. From 10 to 70 feet of soil, sand, and gumbo are stripped to expose the commercial clay. About 25,000 tons of clay are excavated annually. Some of it is sold to the Red Wing Potteries Company.

Formerly sewer pipes were fabricated at Hopkins, Minnesota, by this company. Work has been discontinued there and the firm now operates only its Red Wing plant, where it gives employment to about 100 men. An average of 1,000 carloads of sewer pipe are shipped annually, and it is estimated that about 10 percent of the deliveries are by truck. Some drain tile also are made. A by-product is said to be useful for filter beds in "aero-filtration" of sewage and industrial wastes.

Stoneware and Pottery

Red Wing Potteries, Inc.—Stoneware products have been made in Red Wing since 1872. Today they are sold under the name of "The Red Wing Line," and include such articles as jars, jugs, flowerpots, filters, lavatory accessories, casseroles, and mixing bowls. Ornamental pottery, mainly vases, known as "The Run Rill Line," and colored dishes, called "The Gypsy Trail Line," are also manufactured, but foreign and out-of-state clays are used in their fabrication. This ornamental pottery constitutes about half their output.

About 10,000 to 20,000 tons of clay from the deposits in Goodhue County are consumed annually by the Red Wing Potteries in the manufacture of stoneware. The pottery furnishes steady employment during the year to about 200 men.

Nemadji Tile and Pottery Company.—Near Moose Lake in Carlton County there has been a noteworthy production of pottery by the Nemadji Tile and Pottery Company. Three varieties of glacial and lake clays in the district furnish material for the industry: first, a reddish-brown clay in the S 1/2 NW 1/4 Sec. 14, T. 46 N., R. 18 W.; second, a red clay in the SW 1/4 NW 1/4 Sec. 26, T. 47 N., R. 17 W.; and third, a gray clay in Sec. 28, T. 48 N., R. 16 W. All these varieties were apparently deposited in the lakes formed when glacial ice blocked the eastern outlet of Lake Superior. The enlarged Lake Superior at one stage is referred to as Lake Nemadji. Part of the clay may have been deposited as a moraine, dropped directly from the melting ice into the lake, but the gray clays were washed into the lake from the gray drift areas to the north. The deposits are thick and cover large areas, and supplies are therefore almost unlimited. The gray clay has been used many years at Wrenshall for light-colored building brick.

The three clays have different properties and are skillfully blended to make the products desired. The company has made red and brown floor tile since 1923, and since 1937 it has made an increasing amount of pottery in Indian styles and brilliant colors. The clay is prepared in a blunger to a slip to pour into molds. Chemicals are used to improve deflocculation and fluidity. The ware is fired without vitrification in a down-draft kiln and glazed in a muffle kiln.

Common Brick and Tile

Common brick and tile are produced at many plants and with a variety of equipment. In small operations soft mud machines and temporary drying sheds and kilns are used; in larger plants stiff mud and presses, continuous drying tunnels, and continuous kilns are employed. The large producers of common brick are the C. H. Klein Company of Chaska, the Wrenshall Brick Company of Duluth, the Red River Valley Brick Corporation of Grand Forks and Fertile near East Grand Forks, and the Bemidji Brick Company of Bemidji. These establishments, which produce light-colored brick for back-up purposes, operate principally in the summer, when the bricks are air-dried. Smaller plants make common brick at St. Cloud, Anoka, Willmar, Warren, and Winona. Of these only the Winona clay burns red. The Willmar plant makes mostly tile.

Rank of State in Production

Minnesota ranks about twenty-fifth in the production of clay products in the United States. The stoneware industry at Red Wing is unique in this whole region. It places Minnesota third among the states in the production of stoneware. Ohio and Illinois have greater production. The output of sewer pipe from the same clay deposit in Goodhue County is also important; it serves a large area north and northwest of Illinois.

Detailed statistics have not been compiled since 1918, but before that year Minnesota was third in the manufacture of stoneware, sixth in drain-tile production, and tenth in the production of face brick and sewer pipe.

Statistics concerning the clay industries of Minnesota have been compiled from the Biennial Census of Manufactures, and the United States Bureau of Mines Mineral Resources and Minerals Yearbooks, the annual statistical publication, where further details may be found. For many years there have been from 10 to 20 firms manufacturing clay products in the state, all together giving somewhat seasonal employment to about 500 or more men. The products are valued at $400,000 to $1,700,000 a year. Common brick are valued at about $9 to $11 a thousand.

USES OF CLAY

Minnesota clays are used largely for the manufacture of face brick, common brick, structural tile, drain tile, stoneware, and sewer pipe. Other uses of clay are for porcelain, earthenware, paint fillers, paper filling, china dishes, Portland cement, refractory wares, and ornamental pottery. Some plastic Minnesota clay has been ground, bagged, and sold for "mortar-mix," that is, mixed with cement in making concrete, to improve the workability of mortar. Drain tile in Minnesota are now made from concrete, and concrete construction has largely replaced construction making use of the fireproofing formerly made from clay in North Minneapolis. (See also the paragraph on fuller's earth, page 100.)

In the central portion of the Red River Valley, where gravel is scarce, there is a possibility that clay may be burnt in the future for use as a road metal.

MARKETING

Clay products are sold direct to consumers, through dealers and salesmen, and to contractors and jobbers.

Shipments to distant points are made principally by rail, but truck haulage is common for short distances. Long hauls are sometimes made by truck, especially if the truck would otherwise be empty on a return trip. Common brick producers cater largely to local trade, and trucking is the usual method of transportation.

The Clay Products Institute of Des Moines serves producers in the region as a sales agency, but not all the large producers in Minnesota are members. The only two manufacturers of face brick, those at Springfield and at St. Paul, compete with each other and with brick manufacturers in other states. St. Paul brick are shipped East in competition with fine face brick made in that section.

The Red Wing stoneware and sewer pipe companies supply most of the Minnesota market and sell some in adjacent states. The sewer pipe company has shipped as far west as Montana. Tile made at Mason City, Iowa, compete with Minnesota tile in Minnesota markets.

RESERVES

Minnesota has vast supplies of clay suitable for the manufacture of such products as face brick, common brick, structural tile, and drain tile. Reserves of lake clays for common brick are enormous, and if they were exhausted gray drift clays of the western half of the state could supply the demand. These gray drift clays are not much used at present because they contain limestone pebbles, but the work done at Hutchinson indicates that the pebbles can be removed at a moderate cost by washing, to yield a clay that is satisfactory for making brick and drain tile.

The quarry of the brick company in West St. Paul has enough Decorah shale to last for several decades. If the shale supply at the present quarry becomes depleted, operations could be expanded laterally within the limits imposed by the value of city property. Accessible and virtually inexhaustible reserves of Decorah shale exist over many square miles in southeastern Minnesota (fig. 19).

At the Springfield plant there is sufficient Cretaceous shale to last 75 years or more at the present rate of production. Other large deposits of the same shale are known to exist in the vicinity.

The stoneware clays in Goodhue County have been prospected in sufficient detail to assure a supply for several decades. Surface indications near the deposits are encouraging, and it is very likely that future prospecting will disclose additional reserves.

FULLER'S EARTH (BLEACHING EARTHS)

"Bleaching clay" is a term used for clays that clarify mineral and vegetable oils; it includes fuller's earth and bentonite. The bentonites need "activation" by acid treatment before they will absorb much of the color of oil, but there is no sharp distinction between the kinds of bleaching clay. Bentonite is derived largely from the alteration of volcanic ash and is composed chiefly of the minerals montmorillonite or beidellite. Fuller's earth is produced largely in Florida and Georgia and bentonite in Texas and Wyoming.

Several samples of supposed fuller's earth in Minnesota have come to the Geological Survey, but until recently none has proved satisfactory. After a series of preliminary tests it appears that at certain places the Decorah shale in Minnesota is a fuller's earth equal in bleaching power to the standard Florida-Georgia earths. The localities where Decorah shale crops out, roughly south and southeast of the Twin Cities area, are sketched in figure 19.

Tests made in 1940 show that the fresh Decorah shale, such as that exposed at the brick yard in West St. Paul, is not good bleaching clay; but the same formation near the surface where it has been affected by weathering is very promising. The preparation of the material for market requires care and standardized procedure. No one has yet undertaken to market the Minnesota product in a large way, but there are large reserves, and for the local market there would be a saving in freight in competition with products from Georgia.

LIMESTONES AND MARLS

The occurrence and uses of Minnesota limestones, dolomites, and marls[75] are discussed briefly in the following pages. For further information the reader is referred to a bulletin of the Minnesota Geological Survey.[76] The use of limestone as a building stone is noted on pages 74–78. (See also the use of dolomite for magnesium, in the later section on miscellaneous mineral deposits.)

GEOLOGY OF MINNESOTA LIMESTONES AND MARLS

As pointed out in the sections on general geology and on building stones, limestone is a sedimentary rock which owes its origin to the accumulation of calcium carbonate ($CaCO_3$) on the floors of seas and lakes of moderate depth. This material may be in the form of shells and other hard parts of marine animals and plants, or in the form of a calcareous mud, precipitated chemically, or by the grinding up of marine organisms and their deposition by water. Most limestones in Minnesota are dolomitic, and at certain points a few are almost pure dolomites, i.e., they contain a high percentage of the double carbonate of calcium and magnesium ($CaCO_3.MgCO_3$). Some contain an appreciable quantity of clay and are called argillaceous limestones.

Limestones and dolomites are scattered in the southeastern quarter of the state. They are particularly well exposed along the Mississippi River at places from Minneapolis to the Iowa boundary and along the Minnesota River from Fort Snelling to Mankato. They were deposited during the Paleozoic era, ranging in age from Cambrian to Devonian (fig. 4).

The geological column showing the rocks and their approximate thickness in Minnesota is given on page 7. The accompanying map (fig. 21) shows the distribution of marl deposits in Minnesota.

Marl is an unconsolidated earthy material composed essentially of calcium carbonate. It is grayish white or buff in color, but if it is contaminated with peaty material it may be a dark gray or brown.

It has been estimated that in Crow Wing County alone there are approximately 30 million cubic yards of wet marl. Stearns County also has several large deposits. Isolated large deposits occur in Aitkin and Wright counties and elsewhere. Although explorations have not been exhaustive it may be said that at least 50 million cubic yards of marl are available (fig. 21).

Since the glacial period, water percolating through the drift has leached calcium carbonate from the heterogeneous glacial deposits. Eventually much of this water entered the lakes, where the calcium carbonate was

[75] The section on limestones and marls was compiled chiefly by Dr. C. R. Stauffer and Dr. G. A. Thiel.

[76] Stauffer, Clinton R., and Thiel, George A., The limestones and marls of Minnesota: Minn. Geol. Survey Bull. 23, pp. 1–193, 1933.

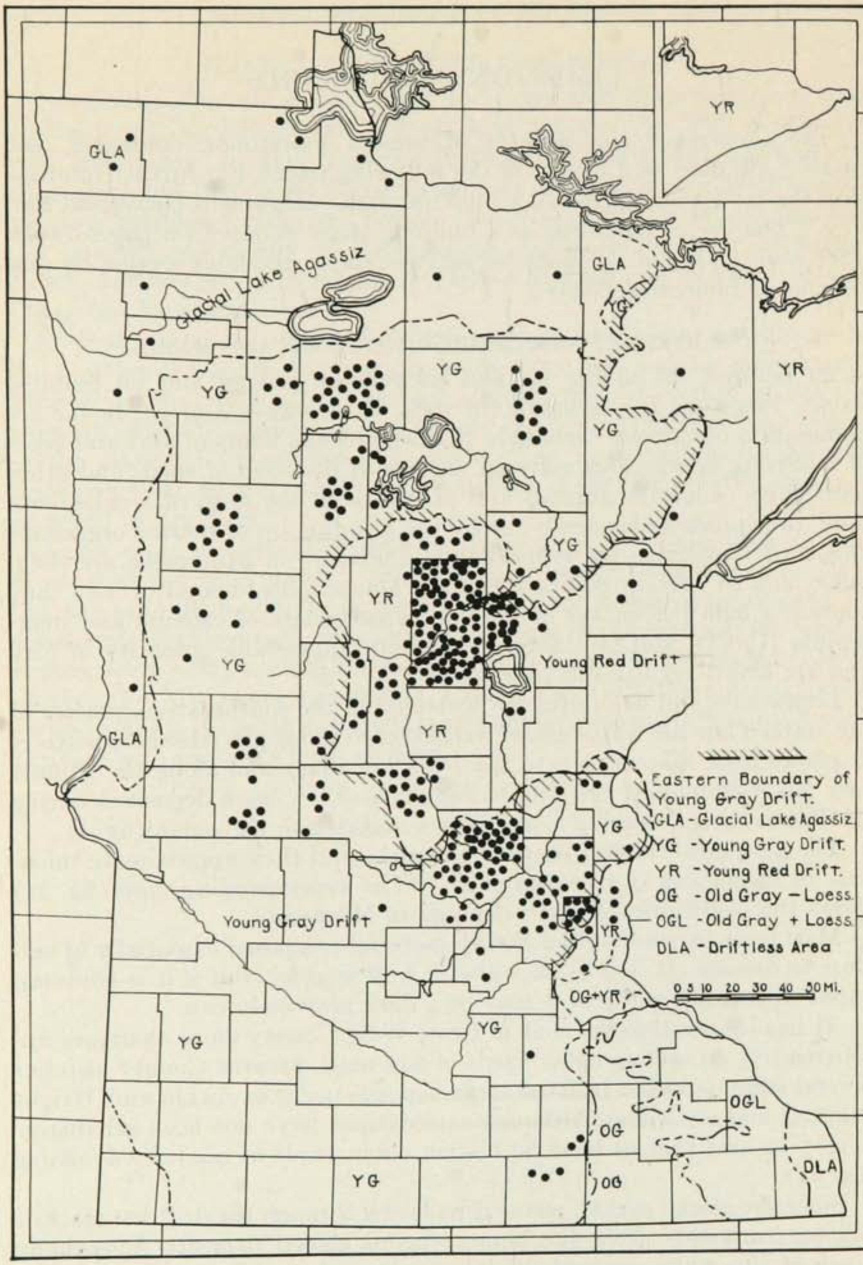

FIGURE 21. — Outline map of Minnesota showing the distribution of the principal marl deposits and their relations to different glacial drifts. After Stauffer and Thiel.

NUMBER OF MARL BEDS OCCURRING IN THE AREAS OF SEVERAL TYPES OF GLACIAL DEPOSITS IN MINNESOTA COUNTIES

County	Sandy Moraines	Clayey Moraines	Outwash	Till Plains	Total
Aitkin	18	..	5	1	24
Anoka	..	..	9	..	9
Becker	7	..	6	..	13
Beltrami	..	4	15	4	23
Benton	..	..	3	..	3
Carlton	1	1	..	..	2
Carver	..	2	..	..	2
Cass	5	..	..	2	7
Chisago	..	..	1	2	3
Clearwater	..	..	7	..	7
Crow Wing	5	..	76	..	81
Dakota	..	..	1	..	1
Douglas	1	4	..	..	5
Freeborn	..	1	1	1	3
Hennepin	5	..	5	2	12
Hubbard	5	..	5	1	11
Isanti	2	..	..	1	3
Itasca	..	7	6	..	13
Kandiyohi	..	..	1	..	1
Kittson	..	..	2	..	2
Meeker	..	..	1	..	1
Mille Lacs	..	1	2	..	3
Morrison	4	..	2	1	7
Otter Tail	5	1	2	..	8
Pine	..	..	..	1	1
Pope	5	..	2	..	7
Ramsey	..	1	8	..	9
Rice	..	1	..	..	1
St. Louis	2	1	..	..	3
Sherburne	1	..	22	2	25
Stearns	5	1	8	2	16
Steele	..	..	2	..	2
Todd	1	1	3	3	8
Wright	..	5	14	4	23
Washington	1	..	2	..	3

precipitated, either chemically, or biochemically by the life processes of such aquatic plants as chara and zonotrichia. In this manner thick beds of marl have been deposited in many of the lakes of Minnesota. Some of these lakes have been drained since the glacial period, and their marl beds may be found in bogs or on dry land above the present ground-water level.

After marl had partially filled some of the lake basins, or after the level of the water had been lowered, a luxuriant growth of aquatic plants gained a foothold and their remains formed a peat deposit over the marl. Some marl deposits in the state have an overburden of peat varying in thickness from a few inches to several feet. The accompanying diagram (fig. 22) shows this relationship. The material below the marl beds is usually glacial clay or sand.

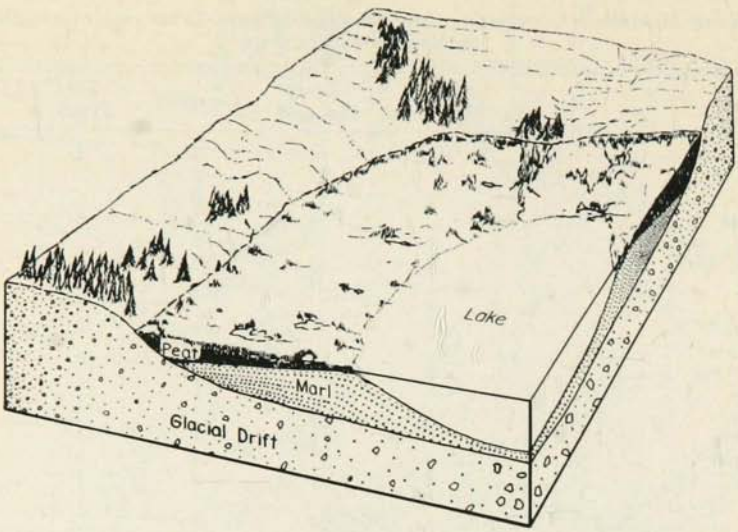

FIGURE 22. — Diagram of section of lake basin showing the relation of marl and peat in a growing deposit. After Stauffer and Thiel.

COMMERCIAL USES OF LIMESTONES AND MARLS

Broken, Crushed, and Ground Limestones and Marls

The use of Minnesota limestone for architectural purposes has been discussed in the chapter on building stones. Broken limestone is also used in different sizes for other types of construction. Large fragments (riprap) are used to construct retaining walls, piers, and breakwaters, and smaller blocks, called rubble, may be used for coarse concrete aggregate. Crushed limestone is employed chiefly for road metal and concrete aggregate, but partly for bituminous mixes, railroad ballast, and "soil sweeteners."

Marl has been used on roads in sandy regions in Minnesota as a binding material to prevent the formation of deep ruts.

Limestones, dolomites, and marls are used to neutralize acid soils and are known as "soil sweeteners." Marl is unconsolidated and can be spread on a field without preparation. Limestone and dolomite are usually ground to pass a 60-mesh screen before they are used for this purpose. Alfalfa and clover do not thrive on acid soil, and a single application of one of these sweeteners on acid soil will do much to promote their growth. Some crushed rock producers grind limestone for soil conditioning, but several portable crushers grind native limestone for local consumption. Crushed limestone and marl are used for poultry feed and as a filler in certain stock foods. The fine texture of marl makes it especially suitable for stock foods, but the difficulty of drying it for such food mixtures has restricted its use.

Pulverized limestone and a good grade of marl may be employed as whiting to mix with paint, or with linseed oil to form putty. They are also used as asphalt filler.

In 1939 the crushed and broken limestone used by producers or sold in Minnesota was 1,263,230 short tons, valued at $1,407,589.[77]

The principal plants producing crushed limestone in Minnesota are listed below by towns:

Faribault	Lieb Stone Company
Kasota	Breen Stone and Marble Company
Le Roy	Hickok Calcium White Rock Company
Mankato	F. R. Coughlan Company
Mankato	Fowler and Pay
Mankato	Mankato Lime Company
Mankato	Mankato Crushed Stone Company
Minneapolis	Minnesota Crushed Stone Company
St. Paul	J. L. Shiely Company
Winona	Biesanz Stone Company

Natural Cement

In 1936 there were 12 plants in the United States engaged in the manufacture of natural cement (including masonry cement of the natural cement class and hydraulic lime). Two of these, the Carney Cement Company of Mankato and the Austin Cement Company of Austin, are located in Minnesota. About 1,011,400 barrels (376 pounds per barrel) of cement were shipped from these plants in 1935.

Natural cement is used mainly in mortar for laying brick and stone. It sets more quickly and is cheaper than Portland cement. Clayey limestone is the raw material used. The usual practice is to mix the limestone in lump form with coal and burn it in a vertical kiln at temperatures between 900° and 1000° C. Carbon dioxide is liberated from the rock and incipient fusion takes place. The burned rock is ground to a fine powder and when mixed with water it will harden or set. If it is allowed to set in moist air it will harden under water, and for this reason it is sometimes called hydraulic cement. The Austin Cement Company plant has recently been dismantled. The Carney Cement Company operates a mill in Mankato with a capacity of about 3,000 barrels of cement a day. The industry was established in 1883 and was called the Standard Cement Company. From 1903 to about 1915 it was known as the Mankato Cement Works, but since then it has been owned and operated by the Carney Cement Company. Raw material is quarried from a ledge of Oneota dolomite, near Pilgrim Rest Cemetery, about two miles north of the city limits, and transported by rail to the plant. A small amount of gypsum is added to retard the setting time, and calcium stearate is used to make the cement more nearly impervious and to improve its workability. Thus improved, the product is sold under the name of "Carney Cement" and enjoys a wide market. It has been used for laying brick, stone, and tile in many American buildings, including:

[77] Bowles, O., and Jensen, M. S., Stone, Minerals Yearbook 1940, p. 1184, 1941.

Veterans' Hospital, Minneapolis
Post Office, Chicago
Roshek Building, Dubuque, Iowa
Indian School, Wahpeton, North Dakota
International Harvester Building, Salt Lake City
Immigration Building, Galveston, Texas

Lime

Limestones, dolomites, and marls are used for making lime. The magnesia present in dolomites and dolomitic limestones is not regarded as an impurity, except for the manufacture of high-calcium limes. The main impurities are silica, alumina, and iron. High-calcium limes are used largely for chemical purposes and for mortar. They can be spread more easily than magnesian limes, but the magnesian limes shrink and crack less on drying, and are therefore more desirable for finishing coats in plastering, provided the iron content is low enough to prevent a yellowish discoloration.

The conversion of limestone to lime requires the application of heat. Limestone in lump form is placed in a kiln, and the temperature is elevated to about 800° C. by burning some fuel, usually coal or wood. Carbon dioxide and water are expelled, leaving a residue composed essentially of lime when a high-calcium limestone is used and a mixture of lime and magnesia when a dolomite is employed. These products may be sold as quicklime for more or less immediate use, or they may be allowed to react with water in special hydrators, and are then sold as hydrated or slaked lime. Hydrated lime is more convenient to handle than quicklime. It does not deteriorate in storage, and the consumer is relieved of the necessity of providing labor and equipment for slaking.

Lime has been manufactured from almost all the limestone formations in Minnesota. For many years Red Wing was known as the lime center of the state. Kilns at Red Wing used Oneota dolomite, and their products were sold over a considerable area. These kilns have been abandoned as have those at or near Shakopee, Ottawa, Spring Valley, and elsewhere in the southeastern quarter of the state. The lime kilns at Mankato were inactive in 1940, but they could be put in operation under better market conditions. Marl was once used for the manufacture of lime at St. Cloud and at a point about midway between St. Cloud and Clearwater, but these projects have been abandoned for many years.

Fowler and Pay of Mankato and the Cutler-Magner Company of Duluth were the only firms in Minnesota engaged in making lime in 1940. The latter uses limestone shipped by boat from Michigan to Duluth. Fowler and Pay operate two vertical shaft kilns at Le Roy in Mower County. They employ about 12 men during the season. Capacity production amounts to approximately 200 barrels of lime a day. A pure, white, high-calcium lime is produced and is sold as quicklime, or, in the hydrated form, for chemical, building, and pharmaceutical purposes.

The Cedar Valley limestone of Devonian age occurs over much of Mower County. It crops out at several places and in some areas is covered with a thin layer of soil. At Le Roy the Cedar Valley limestone contains a dense, white limestone stratum interbedded with the ordinary brown dolomitic strata. This bed is quarried and used in the kilns. It occurs near the surface and little stripping is required. Sugar refining demands a lime almost free from magnesia. The white beds in the Cedar Valley limestone at Le Roy are very suitable for this use, for they are among the purest calcium carbonate deposits found in the entire United States.

Government records do not disclose the amount or value of lime produced in Minnesota in recent years, but they show that in 1933 lime was made and sold in the state for building, paper milling, tanning, and other chemical purposes.

Magnesium is not manufactured in the state, but the Oneota dolomite at Merriam Junction and the Shakopee dolomite along the Minnesota River and at various points along the Mississippi River have satisfactory compositions for this purpose, since they have 43 to 48 percent $MgCO_3$ (see page 137).

Portland Cement

Portland cement has never been made from Minnesota limestones or marls. The only Portland cement plant in Minnesota is located at Duluth. It is operated by the Universal Atlas Cement Company, a subsidiary company of the United States Steel Corporation. Raw materials consist of blast-furnace slag from the nearby plant of the American Steel and Wire Company, and of limestone from Michigan. About 250 men are employed. The plant has an annual capacity of 2,250,000 barrels of cement.

Portland cement is the product obtained by calcining (driving off volatile constituents such as carbon dioxide and water) finely ground raw materials to a temperature of incipient fusion in a rotary kiln and grinding the resulting clinker to a fine powder. When Portland cement is mixed with a suitable quantity of water it hardens in air or under water. The principal raw material used in manufacturing Portland cement is limestone. Silica and alumina are also required; they are added as clay, shale, slate, or blast-furnace slag. Some limestones contain considerable clay and therefore do not need to be mixed with much argillaceous substance before they are calcined. Some gypsum may be added to the clinker before grinding to retard the setting time. Magnesia is an objectionable impurity, for it swells and causes the cement structure in which it is used to disintegrate. Therefore a limestone having more than 5 or 6 percent of magnesia is considered unfit for making Portland cement.

Most Minnesota limestones are dolomitic, and some are nearly pure dolomites. They are not desirable for the manufacture of Portland cement because of their excessive magnesia content. Two limestones in the state, however, have a composition suitable for this use. They are the Cedar Valley limestone at Le Roy in Mower County, and the Prosser limestone in Olmsted and Fillmore counties. Shale may also be obtained in the Prosser limestone area. The Prosser limestone is the bottom portion of the Galena limestone. In Fillmore County it has a maximum thickness of 60 feet and is a high-grade limestone. Raw materials in this area seem to be favorable for the manufacture of Portland cement, but before erecting a plant the region should be studied as to the possible markets, the costs of operation, and the transportation facilities. It should be borne in mind also that a plant in this vicinity would have to compete with five established plants in Iowa.

Limestone is preferred by manufacturers of Portland cement, but in areas where this rock is not available in sufficient quantities of the proper composition, marl has been used. Establishments in New York, Michigan, Ohio, Indiana, and Utah, and in Canada have operated successfully with marl.

The conditions essential to the success of a marl-using Portland cement plant have been summarized by Kirk,[78] as follows:

1. An adequate supply of marl and of clay must be known to be available. It has been estimated that 320 acres of marl 200 feet deep would be needed to supply a 2,000-barrel mill for thirty years. Other marl beds near by would be desirable.
2. The quality . . . must be high. Careful investigation should be made . . . by competent analysts.
3. The plant should be designed by competent engineers and controlled by experienced engineers and chemists.
4. Modern equipment should be used. . . .
5. No fancy salaries should be paid . . . and little money should be spent for promotion.
6. The machinery and methods . . . must be such as to keep the water content of the slurry below 50%.
7. A capital of not less than $3,000,000 is recommended as a minimum figure.
8. The plant must be advantageously located with respect to a market for its products, and with respect to shipping facilities. Freight rates largely determine the location of cement plants.
9. The plant for use of marl should be located in a territory where there are no limestones suitable for use in the making of Portland cement.

With these nine conditions in mind, it might be worth while to investigate more carefully some of the larger marl occurrences near Minneapolis and St. Paul. The large marl bed in Twin Lakes at Robbinsdale and the deposits in southeastern Stearns County, especially the one located in Otter Lake northwest of Annandale, would be worthy of further consideration. Preliminary surveys indicate that these deposits contain considerable tonnages of marl of good grade, and railroads pass over or near them. They are within 50 miles of the Twin Cities, and a plant at one of them would be advantageously situated with respect to the Twin Cities market. Such a plant would have to compete with limestone-using plants located at Duluth, in Iowa and Michigan, and at Manitowoc, Wisconsin.

[78] Kirk, Raymond E., The manufacture of Portland cement from marl: Univ. of Minn., Engineering Experiment Station, Bull. 4, p. 55, 1926.

Rock Wool

"Mineral wool" is a general term used to designate insulating materials composed of silicates in the form of fine, glassy fibers, and "rock wool"[79] is a mineral wool made from rock. In the manufacture of rock wool the usual practice is to melt stone in a cupola furnace. As the molten material issues from a small opening it is blown with a steam jet into fibers, which fall in a downy mass to the floor of a concrete chamber. The raw material used is a clayey limestone or dolomite. Experiments at the University of Illinois[80] indicate that most limestones and dolomites with a carbon dioxide content of 20 to 30 percent can be satisfactorily melted and blown into rock wool. They are classed as "wool rocks." Other limestones and dolomites with a carbon dioxide content ranging between 15 and 20 percent, or between 30 and 38 percent, are classed as "sub-wool rocks." They also may be used, but they require the addition of moderate quantities of such material as shale, sandstone, limestone, or dolomite to yield a mixture of the proper composition.

Rock wool was made in 1941 at Mankato, and a new plant was built at Red Wing. Recent analyses of Minnesota limestones and dolomites indicate that several stratigraphic horizons contain great quantities of "wool rocks" and "sub-wool rocks." The St. Lawrence dolomite, with an average thickness of 30 feet, is good "wool rock" throughout. Thinner layers occur in the Platteville, Galena, and Oneota dolomites. An argillaceous layer near the bottom of the Oneota, plus 10 percent of clay, is being used in the plant at Mankato. Partial analyses of the raw materials and the finished product are given in the table below, and analyses of other possible wool rocks are given on page 110.

Analyses of Raw Materials and of Rock Wool, Mankato, Minnesota

Constituent	*Shaly Dolomite*	*Clay*	*Rock Wool*
SiO_2	21	65	42.5
Al_2O_3	5	11	10.0
Fe_2O_3	2	3	1.5
CaO	21	6	24.5
MgO	15	2	17.0
Other oxides	4	3	4.5
Ignition loss	32	10	

Rock wool is an excellent insulating material, for its heat conductivity is almost as low as that of asbestos. It can be blown into the walls of houses or used to insulate steam pipes and ovens. It retails for about $50 to $70 a ton. Since only about 12 tons of this bulky material can be shipped in a boxcar, transportation costs are high.

[79] The section on rock wool was supplied by Dr. G. A. Thiel.

[80] Lamar, J. E., *et al.*, Rock wool from Illinois Mineral Resources: Ill. Geol. Survey Bull 61, 1934.

PARTIAL ANALYSES OF MINNESOTA LIMESTONES POSSIBLY AVAILABLE FOR ROCK WOOL[1]

Formation	Locality	SiO_2	Fe	Al_2O_3	CaO	MgO	CO_2	Ign. Loss	H_2O
Maquoketa	Clinton Falls	16.98	1.29	3.76	34.22	7.05	33.2	33.7	0.5
Maquoketa	Clinton Falls	51.92	1.72	6.28	16.58	2.97	15.1	15.3	0.2
Galena	Nerstrand	5.44	1.62	1.78	41.36	7.73	20.1	40.7	0.6
Platteville	Mendota	13.18	2.24	4.60	31.40	9.91	34.7	35.5	0.8
Shakopee	Waterford	9.52	1.22	1.20	29.02	17.19	40.8	41.3	0.5
Oneota	Merriam Junction	4.06	1.51	0.94	29.80	18.89	43.4	44.0	0.6
St. Lawrence	Red Wing	34.88	1.53	6.61	16.60	10.73	24.6	24.9	0.3
St. Lawrence	Red Wing	50.52	2.59	8.04	10.64	6.31	14.9	15.2	0.3

[1] For additional analyses see Bulletin 23, Minnesota Geological Survey.

BROKEN AND CRUSHED ROCK OTHER THAN LIMESTONE

The major portion of the crushed rock sold annually in Minnesota is from limestone ledges in the southeastern quarter of the state.[81] The sections on limestones and marls may be referred to for information concerning this product. In 1939 other crushed and broken stone produced in Minnesota included granite, basalt or traprock, and minor amounts of sandstone and quartzite. The granite sold or used by producers as crushed rock in Minnesota in 1939 amounted to 42,130 short tons, valued at $53,446.[82] There were general increases in 1940 and 1941. The origin, character, distribution, and other uses of these rocks have been discussed in the chapters on general geology and building stone.

Granite. — Waste from the block-granite industry in Minnesota, particularly in the St. Cloud district, is a source of crushed rock for concrete aggregate, road metal, and railroad ballast. Rubble for rough masonry and retaining walls is another by-product. Gabbro is an igneous rock with a texture like that of granite, but it has a different mineral composition. It has been quarried for construction work in Lake and St. Louis counties. The Duluth Crushed Stone Company quarried gabbro at Duluth for road stone, railroad ballast, concrete aggregate, rubble for retaining walls, and riprap (large fragments for piers, breakwaters, etc.).

Basalt. — Basalt is a fine-grained, dense, dark-colored rock which solidified from lava flows. Ancient basalts occur at Taylors Falls and along the north coast of Lake Superior, and elsewhere in northeastern Minnesota. They are sometimes called "traprock" and are used for concrete aggregate, road stone, ballast for railroad grades, rubble, and riprap. Basalt is quarried for such purposes to some extent in St. Louis County. Roofing granules for surfacing composition shingles are produced near Ely, Minnesota, from a green basalt known as the "Ely Greenstone." Some of the fine material from the crushing operation may be used as a filler in asphalt and other products.

Sandstone. — Waste from the sandstone quarries in the bluffs bordering the Kettle River near Sandstone, Minnesota, is crushed for use in concrete aggregate. Some of the screenings are sold to foundries in Minneapolis, St. Paul, and Duluth, to be used in molding sand mixtures.

Quartzite. — Quartzite is a hard, well-cemented sandstone. The Sioux quartzite at Pipestone, Jasper, New Ulm, and Luverne in southwestern Minnesota is used as crushed rock. Some of the material is a by-product of the production of building stone, "flint" pebbles, and "flint" tube-mill linings. Some screenings are marketed as refractory sand for foundry

[81] The section on crushed rock other than limestone was compiled chiefly by Dr. G. A. Thiel.

[82] Bowles, O., and Jensen, M. S., Stone, Minerals Yearbook 1940, p. 1181, 1941.

work, and some are sold as ganister for the manufacture of silica brick or as furnace lining or furnace sand. At Pipestone, more or less definitely-sized chips are made for roofing granules. At Babbitt in St. Louis County, the Mesabi Iron Company produced crushed rock from quartzite-like, low-grade, iron-formation (taconite), and a small plant near Hibbing has crushed the Pokegama quartzite.

PEAT

GENERAL STATEMENT

The occurrence of peat in Minnesota has been described in a bulletin by Soper.[83] Peat has been used for fuel in other countries. In the United States it is used chiefly for the improvement of heavy soils.

Peat is partly decomposed and disintegrated vegetable matter which has suffered chemical and physical changes but still contains most of the carbon of the original vegetable matter. Much of it contains such plant remains as leaves, roots, stems, and seeds in a state of good preservation.

Muck is an impure peat or peaty soil. Such inorganic mineral matter as clay, silt, and sand may be equivalent to or in excess of the amount of combustible organic matter. All gradations between peat and muck soil exist in Minnesota.

COMPOSITION

Considered geologically, peat is the youngest intermediate product in the series from vegetable matter to coal. By pressure resulting from deep burial beneath other rock formations, and by deformation, peat in the course of geologic time may be metamorphosed into lignite or brown coal, bituminous coal, anthracite, and graphite.

In the bog, peat contains from 80 to 90 percent water. Calculated on a dry basis it has about 62 per cent carbon and from 4 to 25 percent ash (mineral matter). If the ash content exceeds 25 percent the material is classed as "muck" and is considered undesirable for fuel.

Humification, or decomposition of vegetable matter under water, goes on slowly but continuously in peat bogs, and the lowest layers, the oldest deposits in the bog, generally possess the highest carbon content.

ORIGIN

Peat deposits are beds of vegetable remains which have accumulated over a long period of time. In Minnesota they have been built up since the close of the glacial epoch, estimated by geologists to have been 10,000 to 30,000 years ago. One condition essential for the formation of peat is a profuse growth of plants, the decay of which, normally caused by oxidation and bacterial action, has been arrested. Since decay is retarded by immersion in water to the exclusion of air, it is evident that topography and climate are influencing factors. Peat occurs most abundantly in basins filled with water and on flat, or gently sloping, undrained land surfaces.

From a study of the various layers of plant remains in the peat bogs of Minnesota, and from a knowledge of the topography of the bottoms of the bogs, it is possible to divide the peat deposits of the state into two

[83] Soper, E. K., The peat deposits of Minnesota: Minn. Geol. Survey Bull. 16, pp. 1–261, 1919.

The more recent data in this section were supplied chiefly by Dr. G. A. Thiel.

types: (1) filled-in deposits formed by the filling of lakes or ponds with plant remains, and (2) built-up deposits which developed on flat marshy surfaces and which do not represent filled lakes. There are also combinations of these two types.

In the chapter on topography it was pointed out that the present topography of Minnesota is largely the result of glaciation. The melting ice sheets deposited rock and soil debris, obliterating to a large extent the preglacial drainage systems. Depressions of glacial origin include basins between morainic hills, slight depressions in gently undulating drift surfaces, kettle holes, basins formed by the damming of old stream channels by morainic debris, and glacial lake beds. It was glaciation that produced the topographic environment favorable to peat accumulation in Minnesota. Except for such small bogs as those along the Atlantic coast and the tule marshes of California, glaciation was responsible also for nearly all the peat in North America. Some depressions that do not owe their origin to glaciation are the valleys of streams, depressions formed by postglacial erosion, and some basins formed by the building of beaver dams across streams.

Conditions favorable for peat formation may be summarized as follows:

1. Profuse growth of moisture-loving plants.
2. A topographic environment with basins and poorly drained flat areas where water covers the plant remains.
3. A humid atmosphere to prevent rapid evaporation.
4. Impervious soil or subsoil to prevent rapid drainage of the surface.
5. Temperature warm enough for plant growth and cool enough to prevent too rapid evaporation.

DISTRIBUTION IN MINNESOTA

So much of Minnesota has peat that it is easier to list the areas that do not have it than those that do. Three areas in Minnesota do not contain peat deposits: one is the driftless area in the southeastern corner of the state; another is along the western border, principally in the silt and clay-covered treeless area near the Red River; and the third is in the extreme southwestern corner of the state (fig. 23).

The peat deposits of the state may be divided into the following groups: (1) deposits in northern Minnesota, (2) deposits in central Minnesota, and (3) deposits in southern Minnesota.

Northern Minnesota.—Peat deposits north of an east-west line through Minneapolis are of three general types:

1. Deposits in "muskeg" swamps and open bogs. They are largely made up of successive layers of sphagnum, or peat moss, and these deposits are the largest, the deepest, and of the best quality in the state. Many of the swamps are very large; a single bog may cover more than 50 square miles. The peat in built-up deposits averages seven to nine feet thick

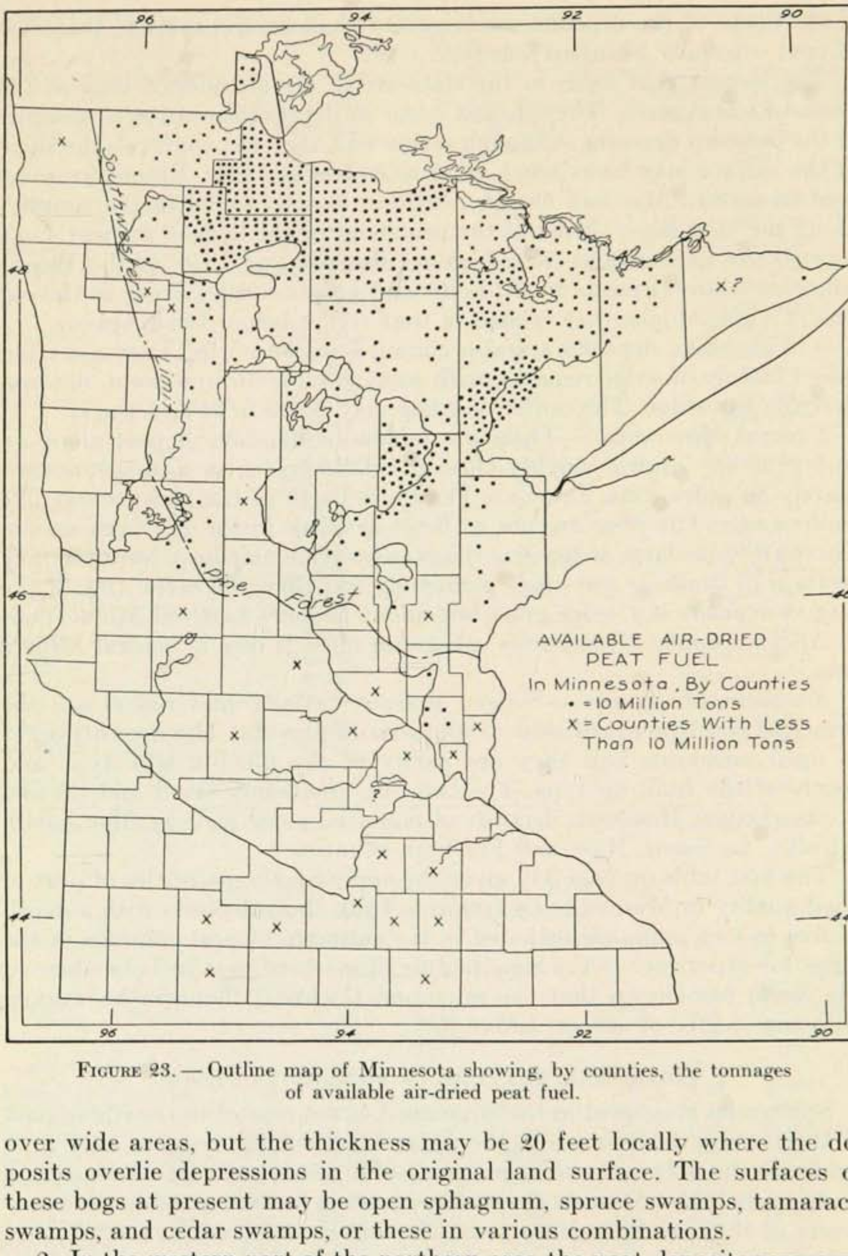

FIGURE 23. — Outline map of Minnesota showing, by counties, the tonnages of available air-dried peat fuel.

over wide areas, but the thickness may be 20 feet locally where the deposits overlie depressions in the original land surface. The surfaces of these bogs at present may be open sphagnum, spruce swamps, tamarack swamps, and cedar swamps, or these in various combinations.

2. In the western part of the northern area the peat deposits represent the accumulation of sedge-grass, cattails, and rushes. Although they are built-up deposits like the sphagnum bogs, very little sphagnum occurs in

them. Some of the deposits are large but shallow; the average thickness of peat is usually less than four feet.

The largest peat areas in the state are in the abandoned beds of the glacial Lake Agassiz. They do not occur in depressions but are examples of the built-up deposits. Although rather flat, they are not level; the slope of the surface may be as much as 10 to 20 feet per mile. Except for some peat in eastern Marshall County, little or none is found in the counties along the Red River. Most of the peat bogs in the beds of ancient Lake Agassiz are in Beltrami, Koochiching, Roseau, and Lake of the Woods counties. Many deposits in St. Louis and Lake counties occur in the old bed of a glacial lake that existed in that region before Lake Agassiz.

3. Filled-lake deposits are also common in the north. They are composed mainly of sedge remains, with some pondweeds and pond lilies underlying the sedge. The center of a bog may be 20 to 25 feet thick.

Central Minnesota.—There are numerous deposits of peat along an east-west line drawn roughly through Minneapolis, in a zone approximately 30 miles wide. Some are like those north of the zone, others like those south. The bogs are not as large as those in the northern region. There are some large sedge-grass bogs (wire-grass marshes), but tamarack swamps or muskegs are small, commonly less than 100 acres. One of the largest deposits is a sedge-grass bog about 12 miles north of Minneapolis in Anoka County. The fibrous sphagnum moss is rare in central Minnesota.

Southern Minnesota.—Sedges, grasses, cattails, and rushes are the principal constituents of peat in southern Minnesota. The deposits occur in open meadows, and they are partly of the filled-in lake type and partly of the built-up type. The bogs are commonly small and the deposits shallow. However, deposits of potential value exist in Blue Earth, Nicollet, Le Sueur, Rice, and Freeborn counties.

The first table on page 117 gives the approximate quantities of peat of good quality in Minnesota by counties. Only those deposits with a depth of five feet or more are included in the estimate of peat reserves in the state, for experience in the manufacture of machine peat fuel elsewhere in the world has shown that the minimum thickness that can be worked with any degree of success is five feet.

COLOR AND TEXTURE OF MINNESOTA PEATS

Sphagnum moss peat in the large muskeg swamps of the northern part of the state is dark brown in the upper layers of the bog but may be a lighter shade of brown and even greenish in the deeper parts. Sedge-grass peat is yellowish brown on the surface, grading to dark green in the lower layers of the bog. Sphagnum peats are fibrous or mossy in texture, and sedge peats in the south are also fibrous except in the lower portions of the deposits. In the bottom layers of many bogs there is some black, structureless peat commonly containing silt, sand, and clay. Well-decomposed peat has about the consistency of soft soap.

ESTIMATED QUANTITY OF PEAT FUEL OF GOOD QUALITY IN MINNESOTA, BY COUNTIES [1]

County	Area of Peat Deposits (acres)	Average Thickness of Peat (feet)	Quantity of Air-Dried Machine Peat Fuel Available (tons)
Aitkin	397,300	6	476,760,000
Anoka	30,000	7	42,000,000
Becker	12,800	5	12,800,000
Beltrami	1,299,200	7	1,818,880,000
Carlton	35,000	10	70,000,000
Cass	75,000	5	75,000,000
Clearwater	128,000	5	128,000,000
Crow Wing	61,300	6	73,560,000
Douglas	5,000	6	6,000,000
Hubbard	10,000	6	12,000,000
Isanti	10,000	5	10,000,000
Itasca	250,000	6	300,000,000
Koochiching	1,000,000	7	1,400,000,000
Lake	150,000	6	180,000,000
Marshall	50,000	5	50,000,000
Mille Lacs	25,000	5	25,000,000
Morrison	10,000	5	10,000,000
Ottertail	75,000	5	75,000,000
Pennington	10,000	5	10,000,000
Pine	75,000	5	75,000,000
Ramsey	1,500	5	1,500,000
Roseau	250,000	5	250,000,000
St. Louis	1,192,000	7	1,668,800,000
Todd	10,000	5	10,000,000
Wadena	5,000	5	5,000,000
All others	50,000	5	50,000,000
Total	5,217,100		6,835,300,000

[1] Soper, E. K., The peat deposits of Minnesota: Minn. Geol. Survey Bull. 16, 1919.

ANALYSES OF PEAT SAMPLES FROM MINNESOTA
(Analyzed by U. S. Bureau of Mines)

County	Analysis Number	Moisture as Received	Calculated to 100%: Volatile Matter	Fixed Carbon	Ash	Sulphur	Nitrogen	Thermal Value-B.T.U. per Pound (moisture free)
Aitkin	15	10.40	68.53	21.15	10.32	.28	2.21	9,090
Anoka	18	9.40	62.86	20.53	16.61	.30	2.96	8,062
Beltrami	28	8.95	71.99	12.63	15.38	1.24	2.49	10,906
Beltrami	30	7.80	59.82	13.93	26.25	.84	1.98	7,072
Hennepin	95	10.10	72.02	15.97	12.01	.46	3.43	8,210
Itasca	111	9.95	67.41	21.04	11.55	.29	2.64	8,732
Koochiching	119	11.35	68.58	20.14	11.28	.24	1.35	7,753
Koochiching	128	9.65	74.54	21.31	4.15	.23	2.49	9,211
Pine	156	9.45	70.62	19.05	10.33	.25	2.30	8,738
Roseau	174	11.25	69.01	19.33	11.66	.79	2.45	8,247
St. Louis	217	8.55	69.91	24.43	5.77	.23	1.49	9,196
St. Louis	224	6.45	50.08	19.40	30.53	.16	1.61	7,458

CHEMICAL COMPOSITION

Two hundred and forty-six samples of peat from bogs throughout Minnesota were analyzed by the U. S. Bureau of Mines. The samples were allowed to dry in air and were shipped in canvas bags. All proximate analyses were reduced to a moisture-free basis. The lower table on page 117 gives a few typical analyses of Minnesota peat. For additional analyses the reader is referred to Bulletin No. 16 of the Minnesota Geological Survey. The constituents are given in percentages and the heating value is given in B.T.U. (British thermal units) per pound of peat. One B.T.U. is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit.

For comparison the following heating values of coke, coal, and peat from other states are tabulated below:

Fuel	*Locality*	*Heating Value B.T.U. per pound*
Mixed coke		12,366
Anthracite	St. Nicholas, Pennsylvania	12,523
Bituminous	Average of six districts	13,174
Lignite	Wilton, N. D.	7,069
Peat (water free)	Michigan (range of 18 samples)	7,500–10,000
Peat (water free)	Indiana (range of 29 samples)	7,500–10,000
Peat (water free)	Wisconsin (average)	8,070

USES

At present no peat is being produced for fuel purposes in the United States except as it may be dug and dried by individuals for domestic use. Probably the largest present market for peat in this country is in agriculture, where it is used as a fertilizer filler and soil conditioner. Peat is used for soil improvement on lawns, golf courses, gardens, nurseries, and greenhouses; as litter for stock and poultry; as packing material for plants, shrubs, eggs, fruit, and fragile objects; and for insulation.

Other possible uses of peat are for paper stock, woven fabrics, artificial wood, nitrates, tanning materials, surgical dressings, ammonium sulphate, dye-stuffs, tars, producer gas, and coke. Peat coke is too soft to compete with coal coke in smelting iron ores.

Some dried peat briquettes treated with chemicals to produce colored flame have been imported for use in grates and open fireplaces. If the demand proves fairly constant an industry might be developed for the production and sale of such briquettes. Attractive preparation and packaging are probably essential for sales at department stores.

Much of the peat in Minnesota is suitable for fuel. The percentage of combustible matter and the amount of ash compare favorably with those of peats in other parts of the world, but at present no peat is in a position to compete with other fuels in this country.

Minnesota peat has an unusually high nitrogen content. Peat in bogs throughout the state averages about 2.24 percent nitrogen, making it an excellent filler for artificial fertilizers. It improves the fertilizer both physically and chemically.

A vast quantity of peat moss of good quality is available for packing purposes, stable and poultry litter, and other uses.

AGRICULTURAL USE OF PEAT LAND

With proper drainage and the use of fertilizers, particularly lime for a sweetener, peat lands produce satisfactory crops of vegetables (except asparagus), small grains, and forage plants. Peat soils are subject to summer frost, however, but if the peat soil is covered with a few inches of sand, clay, or loam, damage by early frosts may be prevented.

Peat bogs north of Red Lake are being investigated by the Minnesota Division of Drainage and Waters and the United States Department of Agriculture to determine how open drainage ditches are influencing ground-water storage and run-off. A knowledge of these factors will be of great aid in planning the future development of these areas.

PREPARATION OF PEAT FOR FUEL

Removal of Water.—Raw peat contains 80 to 90 percent water by weight and the principal difficulty encountered in the manufacture of peat fuel is the removal of this large amount of moisture. At present the only method for water removal which may be commercially successful is one utilizing the energies of sun and wind. Air-drying under average weather conditions dries the peat to a moisture content of about 25 percent. The drying season in Minnesota would be approximately three to four months. Frost action crumbles peat, making it a poor fuel; therefore peat fuel should not be stored on the bog over winter.

Unsuccessful attempts have been made to dry peat with hydraulic presses, by filtration, by centrifugal force, and by electric current. The costs of these methods are prohibitive, and the results are far from satisfactory. After hydraulic pressing peat still contained about 70 percent water; filtration and the use of centrifugal force gave no better results; and the electro-endosmose process reduced the water content only to 65 percent. Drying by artificial heat is too costly.

Excavation and Manufacture.—If the peat is to be sold and not used at the bog, the location of the deposit is important. Bogs close to a large market are the most desirable. The deposit should be such that it can be easily drained by ditching; it should be an open, flat bog, or one that can be readily cleared of trees and bushes; and it should be large enough for long-time operation. Five feet is the minimum thickness which can be worked successfully. Apart from the fact that peat is usually poorer in shallow bogs, a thin deposit would entail additional expense in more frequent shifting of equipment.

Peat may be dug by hand, but in modern practice hand labor should be replaced by machinery as far as possible for successful operation.

Draglines, dipper dredges, a combination screw digger and elevator, and bucket dredges have been employed.

Maceration of the peat is essential. It is done in special machines, usually equipped with rotating knives, which cut and mix the peat into a pulpy mass and extrude it through a die. Maceration makes the product harder, denser, less friable, and more nearly uniform. The bricks are allowed to dry on one side and then are turned by hand. Air-drying usually requires three weeks or longer, according to the weather. However, the best fuel is produced from bricks allowed to dry for several months.

Power from Peat. — No plants in the country use peat for generating power. In 1908 the Wiesmoor Plant was erected in the middle of a large bog in Germany. Air-dried peat bricks were fired for steam-raising purposes, and electrical energy was generated by steam turbogenerators. Power was transmitted to surrounding cities. Fuel consumption amounted to about six pounds of peat per kilowatt hour. In the United States, a land of abundant coal and high-priced labor, it is unlikely that the success enjoyed by this plant can be duplicated.

PRODUCER GAS FROM PEAT

Gas producers convert a solid fuel into a gaseous fuel. The gas may be piped to consumers or utilized in internal combustion engines to generate power. The design of the producer varies with different types of fuel and different uses of gas. Gas producers burning peat and recovering by-products, mainly ammonium sulphate, have been operated in Europe.

Some years ago an experimental gas producer was operated at the Mines Experiment Station, University of Minnesota. Peats from Minnesota and Canada were used in the work. Down-drafts were not successful, for the gas was of poor quality and clinker formation hindered continuous operation. Up-draft tests were more satisfactory; the gas was more uniform and of higher heating value, and there was no formation of clinker.

More recently the use of peat has been studied by the Division of Chemical Engineering under the direction of Charles A. Mann, under a grant from the State Legislature. The division tried complete gasification in a powdered-fuel producer, using air enriched with oxygen. The process seemed to work out if the peat was well dried; and thus the attention of the workers was turned to processes of drying. Dr. Northrup of Owatonna investigated the drying process under a patent obtained by Mr. Winter, and found that if 1,800 pounds of peat (90 percent water) are macerated with 54 pounds of a mixture of inorganic salts, starch, and molasses, and then formed into briquettes and air-dried for 10 days, the water content is reduced to 9.6 percent.

DISTILLATION OF PEAT

The Joint Peat Committee of Ontario made some distillation tests with air-dried peat costing $3.60 a ton and obtained the following data:

Products per Ton of Peat

Gas (quantity not given, probably used in plant)	
Tar oils, 140 lbs. at 1 cent per lb.	$1.40
Alcohol, 1 gal.	.50
Ammonium sulphate	.30
Charcoal, 750 lbs. at $16.00 per ton	6.00
	$8.20

Deducting for cost of peat, labor, operating, and overhead expenses, the estimated profit was $1.20 per ton of air-dried peat.

PRODUCTION OF PEAT IN THE UNITED STATES

About 80 percent of the peat produced in the United States in 1935 was reported as peat humus, mainly for soil improvement, and about 20 percent as peat moss for litter and packing purposes. New York and New Jersey produced the most peat in 1935. Other producing states were Maine, Massachusetts, New Hampshire, Pennsylvania, Ohio, Michigan, Minnesota, Indiana, Illinois, Iowa, Florida, California, and Washington. No separate data were obtained for Minnesota. Data for the country as a whole are given in the following table.

Quantity and Value of Peat Produced in the United States, 1917–38,[1] in Addition to Local Production for Local Needs

Year	Short Tons	Value	Year	Short Tons	Value
1917	97,363	$ 709,900	1925	72,436	$376,834
1918	107,261	1,047,243	1926	61,936	364,413
1919	69,197	705,532	1934[2]	40,544	214,185
1920	73,204	921,732	1935	37,060	199,377
1921	30,406	260,110	1936	46,126	266,883
1922	60,680	397,729	1937	51,223	305,156
1923	61,355	376,834	1938	45,933	286,127
1924	55,469	395,470	1942	71,500	516,887

[1] Statistics from Minerals Yearbook, 1939 (U.S. Bureau of Mines).
[2] Data not available for 1927–33 (no canvass for those years).

Peat moss was imported by the United States in 1939 to the value of $1,204,883. It is likely that local sources could now fill the demand.

SPECIFICATIONS

The following excerpts from the federal specifications used in purchasing the peat requirements of the Federal Government may be of interest to producers and consumers: [84]

Moss (sphagnum or moss peat) . . . shall contain approximately 30 percent moisture by weight when oven dried; . . . moisture content in excess of 30 percent may be accepted, but settlement will be made on weights corrected to 30 percent moisture basis; . . .

Reed muck or sedge muck (peat humus); dark brown to black; granulated . . . ; free of lumps; low in ash content (8 to 15 percent); . . . water content not to exceed 60 percent

[84] Treasury Department, Procurement Division, Branch of Supply: Specifications and Proposals for Supplies, Washington, D.C., 1935.

by weight when oven dried; moisture content in excess of 60 percent may be accepted, but settlement will be made on basis of weights corrected to 60 percent . . .

Reed peat or sedge peat; brown, raw, shredded or granulated; low ash content (5 to 10 percent); . . . water absorbing capacity ranging from 350 to 800 percent; water content not to exceed 50 percent by weight when oven dried; if satisfactory in other respects, moisture content in excess of 50 percent may be accepted, but settlement will be made on basis of weights corrected to 50 percent moisture content . . .

PEAT RESERVES

The peat reserves of the United States have been estimated to amount to 13,827,000,000 tons of air-dried peat. Minnesota has approximately 6,835,300,000 tons, or almost half of these reserves.

SUMMARY

With the ample supply of more efficient fuels produced and delivered at a reasonable price, peat is unable to compete in the fuel market of the United States. At some future date, when other fuel supplies are less plentiful and the technology of preparing peat for fuel is more advanced, peat may have a place in the fuel production of the nation. Emergency demands for nitrogen compounds might result in some developments, but it is likely that for many years Minnesota peat will be used mainly in fertilizers or as a soil conditioner.

MISCELLANEOUS NON-METALLIC MINERALS

WATER RESOURCES

General Statement.—The sources of water supply in Minnesota[85] are varied and may be classed as surface waters from lakes and streams and subsurface waters from springs and wells. The waters derived from each of these sources differ widely in character and quality because of local variations in geological conditions. In the northern half of the state the water supplies are derived chiefly from the glacial drift or from surface streams and lakes. In the southwestern part of Minnesota, Cretaceous rocks contain sandstone formations that furnish abundant water supplies, and in the southeastern counties thick, porous, sedimentary strata are saturated with water under sufficient hydrostatic pressure to supply millions of gallons of water daily to hundreds of artesian wells. For data on the individual counties the reader is referred to the bulletins of the Minnesota Geological Survey and Water Supply Paper 256 of the United States Geological Survey.[86]

Several other reports of the United States Geological Survey and the Minnesota State Drainage Commission give details of surface water observations.

Commercial Spring Waters.—There are many springs in Minnesota issuing from bedrock and from glacial drift, particularly along the Mississippi, Minnesota, and St. Croix rivers and their tributaries. However, water is bottled and sold from only three springs, described in the following paragraphs.

1. The Glenwood-Inglewood Springs, located in the valley of Bassett's Creek in Glenwood Park, Minneapolis, have been in use since 1883. The water, at about 46° F., rises to 16 feet above the creek level. The largest spring yields about 10,000 gallons an hour. Pipes convey the water to the plant, where it is filtered and bottled. The bottled water is distributed directly to customers in Minneapolis and the nearby area. The table on page 124 shows an analysis of this water made recently by the University of Minnesota.

2. The Highland Springs, located near the intersection of Randolph Street and Lexington Avenue in St. Paul, have been in use for more than forty years. The water is bottled and distributed to customers in St. Paul and the surrounding area. Two springs, with water at about 45° F., issue at an elevation of 208 feet above the level of the Mississippi River. The

[85] Data supplied chiefly by Dr. G. A. Thiel.

[86] Allison, Ira S., The geology and water resources of northwestern Minnesota: Minn. Geol Survey Bull. 22, pp. 1–245, 1932.

Schwartz, G. M., The geology of the Minneapolis-St. Paul metropolitan area: Minn. Geol. Survey Bull. 27, pp. 1–267, 1936.

Hall, C. W., Meinzer, O. E., and Fuller, M. L., Geology and underground waters of southern Minnesota: U. S. Geol. Survey Water Supply Paper 256, pp. 1–406, 1911. A revision of this paper is well advanced and the data will probably be issued as a bulletin of the Minnesota Geological Survey.

ANALYSIS OF WATER OF GLENWOOD-INGLEWOOD SPRINGS

		Parts per Million
Residue:		
Dried at 105° C.		340
Dried at 180° C.		332
After ignition		310
Silicon dioxide		18.8
Calcium		78.4
Magnesium		29.6
Sodium		3.9
Potassium		0.8
Sulphate		29.7
Chloride		2.8
Nitrate		7
Bicarbonate		347.7
Iron	less than	0.2
Alumina	less than	0.1
Manganese		0.2

smaller spring, with a flow of 800 gallons an hour, is used for washing and rinsing bottles; the water of the larger one, with a flow of 1,000 gallons an hour, is bottled for delivery to homes and offices. The analysis of the water given below was made by the American Bottlers of Carbonated Beverages Laboratory, Washington, D.C.

ANALYSIS OF WATER OF HIGHLAND SPRINGS

	Grains per Gallon
Total hardness	16.7
Permanent hardness	6.07
Temporary hardness	10.6
Total solids 110° C.	37.8
Ignited solids	18.7
Bicarbonate	28.6
Silica	0.114
Iron oxides and alumina	0.108
Calcium	6.2
Magnesium	1.92
Chlorides	1.33
Sulphates	1.26

3. Water from the Rock Springs, located at Shakopee, Minnesota, is used mostly for making carbonated beverages.

No statistics are available concerning the amount of Minnesota spring water sold annually, but it is probably about 1,500,000 gallons. Artesian water from deep wells in the Minneapolis-St. Paul area is used mostly for drinking water and in the manufacture of soft drinks. Chippewa Spring Water from Wisconsin is also sold extensively in Minnesota.

SOILS

The soils of Minnesota are among the state's most valuable resources. "Minnesota ranks eighteenth among the states in population . . . eleventh in land area, but second in the number of acres of excellent and good agricultural land"[57] Several counties have more than half a million acres

[57] Committee on Agricultural Resources, Minnesota Resources Commission: pamphlet issued in 1940.

of good land. Minnesota soils are the subject of special studies made by the Minnesota State Bureau of Soils, the University of Minnesota Agricultural Experiment Station, and the United States Department of Agriculture.[88] Maps have been made of the soils of many counties. The geological sources of soil materials — the subsoils or surface formations of the state — have been mapped by Leverett and Sardeson.[89] They are closely related to the glacial deposits (fig. 5), of which there are many varieties.

FELDSPAR

Definition. — Feldspar[90] is the name given to the most abundant mineral group of the earth's crust. It is composed essentially of aluminum silicates combined with more or less potassium, sodium, and calcium. According to their chemical compositions feldspar minerals may be classified into two subgroups: (1) potash feldspars, microcline and orthoclase ($KAlSi_3O_8$), and (2) plagioclase feldspars, popularly known as "soda-lime feldspars," and ranging in composition from $NaAlSi_3O_8$ (albite) to $CaAl_2Si_2O_8$ (anorthite). The feldspars of commerce are almost never pure. Potash feldspar commonly contains intimately associated soda feldspar, and material sold as "soda feldspar" invariably contains some lime and often a little potash.

Origin. — Feldspars occur in rocks associated with other minerals. Potash and soda feldspars are found mainly in granite, an igneous rock that solidifies from a molten mass deep in the earth. Soda-lime feldspars are constituents of darker colored igneous rocks, such as the gabbro that crops out in the vicinity of Duluth. In most granitoid rocks the grains of feldspar are too small to be economically separated from other minerals occurring with them. Feldspar stained with iron or containing dark-colored iron-bearing minerals cannot be marketed. A few feldspar rocks are so nearly free from other minerals that they can be marketed without being sorted.

Coarse rocks, the pegmatite dikes or veins, essentially of the same mineral composition as granite, are associated with many granite batholiths (vast intruded masses many miles across and extending to great and un-

[88] Free copies of certain county maps and reports may be obtained from your representative in Congress or from the Office of Information, U. S. Department of Agriculture, Washington, D.C. After these supplies are exhausted copies may be purchased from the Superintendent of Documents, Government Printing Office, Washington, D.C. Some of the early reports are now out of print but may be consulted in libraries.

For a few counties the Division of Soils, University Farm, St. Paul, has a limited supply of reports. Requests for individual county reports will be filled as long as the supply lasts.

[89] Leverett, F. E., Surface formations and agricultural conditions of northwestern Minnesota: Minn. Geol. Survey Bull. 12, 1915.

Leverett, F. E., and Sardeson, F. W., Surface formations and agricultural conditions of northeastern Minnesota: Minn. Geol. Survey Bull. 13, 1917.

Leverett, F. E., and Sardeson, F. W., Surface formations and agricultural conditions of southern Minnesota: Minn. Geol. Survey Bull. 14, 1918.

[90] The data on feldspar were supplied chiefly by Dr. F. F. Grout.

known depths). Pegmatites are intruded after the granite has more or less crystallized, and they commonly extend out beyond the borders of the batholiths into the wall rocks. They are more coarsely crystalline than granite, and the chief mineral constituents are feldspar and quartz. These dikes or veins are the chief source of the feldspar of commerce. Quartz, mica, and some ores and gems may be by-products. Pegmatites may form as much as 1 or 2 percent of the granite areas, but the very coarse masses in which feldspar can be most easily separated from other minerals constitute only a small part of the total pegmatites.

Anorthosite in Minnesota.—Anorthosite is a coarse-grained feldspar rock of the gabbro clan. Such rocks crop out at many places along the north shore of Lake Superior in Lake and Cook counties. They appear as prominent, white-weathering hills visible from the highway at many places. The rock is composed almost entirely of soda-lime feldspar, and the masses lie scattered in the large intrusive diabases in the region.[91]

There are significant concentrations of anorthosite masses near Split Rock, at Beaver Bay and a few miles north, northeast of Lax Lake, at Nicado Lake, east of Finland along the north side of the road to Little Marais, and at Carlton Peak. There are thousands of minor masses scattered even more widely. Individual masses range from single crystals to blocks more than a quarter of a mile across. Most of them are boulderlike but in various shapes, commonly rounded. Possibly they are derived from the anorthosite facies of enormous size in the Duluth gabbro, several miles north; but none of the anorthosite in gabbro seems to be as accessible as that near Lake Superior.

Chemical analyses showing the availability of these feldspars are given on page 127. Some have less than 0.50 percent of iron oxides, but few samples, even after attempts at purification, have less than 0.30 percent. Commercial tests are being made to determine whether the best masses can be used as mined, or, if not, whether they can be cheaply purified to produce a commercial grade usable in glass.

Pegmatite Feldspar in Minnesota.—Granites with local pegmatites crop out at places from the Minnesota Valley to the Canadian boundary. The only feldspar mine in the state is located in the Northwest Angle, where the most northerly portion of the United States projects into Lake of the Woods, north of the 49th parallel. Other pegmatites within a mile or two may be worth prospecting. Granite and pegmatite areas between the Mesabi range and the Canadian boundary may also be of interest.

Feldspar in the Northwest Angle.—The Feldspar Products Company, Inc., owns a feldspar mine in Sec. 6, T. 167 N., R. 33 W., Lake of the Woods County, but its office and mill are located in Warroad, Roseau County. (See figures 24 and 25.)

A large granite outcrop is exposed on the south shore of Lake of the

[91] Grout, Frank F., and Schwartz, George M., The geology of the anorthosites of the Minnesota coast of Lake Superior: Minn. Geol. Survey Bull. 28, 1939.

ANALYSES OF ANORTHOSITES FROM THE MINNESOTA COAST OF LAKE SUPERIOR

	1	2	3	4	5	6
SiO_2	49.78	47.97	51.54	50.68	51.45	49.14
Al_2O_3	29.37	32.45	28.87	30.67	28.47	32.72
Fe_2O_3	0.34	0.62	1.06	0.21	0.80	
FeO	0.60		0.22	0.29	1.00	
MgO	1.07	0.16	0.39	0.42	1.07	
CaO	11.86	15.57	12.70	13.79	12.08	15.34
Na_2O	4.39	3.00	3.72	3.40	3.90	2.82
K_2O	0.46	0.53	0.27	0.09	0.33	0.03
H_2O	1.76	0.38	0.82	0.50	0.63	0.21
H_2O-			0.08	0.03	0.18	
TiO_2	none		0.12	0.07	0.15	
P_2O_5	traces		0.09	0.16	0.04	
CO_2			0.03	0.03		
MnO	0.08		0.01	0.01	0.02	
	99.80	100.68	99.92	100.35	100.12	100.26
Specific gravity	2.676		2.680	2.691	2.699	2.719

1. Carlton Peak, Tofte, Cook County. *American Geologist*, 26:281 (1900), A. N. Winchell, analyst. Thin sections recently made show plagioclase (99 percent), accessory and secondary iron oxides, and secondary zeolite.
2. Sec. 27, T. 56 N., R. 8 W., three miles northwest of Beaver Bay. *Econ. Geol.*, 22:26 (1927), R. J. Leonard and R. B. Ellestad, analysts. The rock is 99 percent plagioclase with traces of augite and magnetite and secondary chlorite and zeolite.
3. Brown anorthosite on Highway No. 61, Sec. 1, T. 56 N., R. 7 W., R. B. Ellestad, analyst. The rock is 97 percent plagioclase and 2 percent reddish iron oxides, with traces of magnetite, augite, and secondary chlorite and sericite.
4. Split Rock quarry rock, Sec. 5, T. 54 N., R. 8 W., R. B. Ellestad, analyst. The rock has 95 percent plagioclase, 2 percent primary augite, and secondary zeolite and chlorite.
5. Black anorthosite, Beaver Bay, Sec. 12, T. 55 N., R. 8 W., T. Kameda, analyst. The rock has 98 percent plagioclase, with traces of primary pyroxene and magnetite and secondary serpentine and zeolite.
6. Bytownite, Crystal Bay quarry, Lake Superior, University of Toronto Studies, Geological Series, No. 35 (1933), p. 37, V. Ben Meen, analyst.

Woods near Warroad, Minnesota, but in the Northwest Angle such granite areas are smaller. In this area numerous low exposures of Ely greenstone are invaded by granite; and pegmatites, which are probably related to the granite, also intrude the greenstone. The pegmatite zone near the mine trends northeast along a low ridge, probably 200 yards wide and more than one-fourth of a mile long. The pegmatite does not crop out continuously along this zone but occurs in irregular lenses or oval areas ranging in length from one to 200 yards. One of the largest lenses was mined for feldspar.

The feldspar is in masses up to three feet long. Much of it is pink potash feldspar with an irregular intergrowth of lighter colored soda feldspar, forming a mixture known as "perthite." Mica may be a by-product but is not in large sheets in the feldspar mine.

Mining was done in an open cut. A pneumatic drill was used, and the drill holes were loaded with dynamite and fired. The broken rock was hand sorted, and pieces of impure feldspar and other minerals were re-

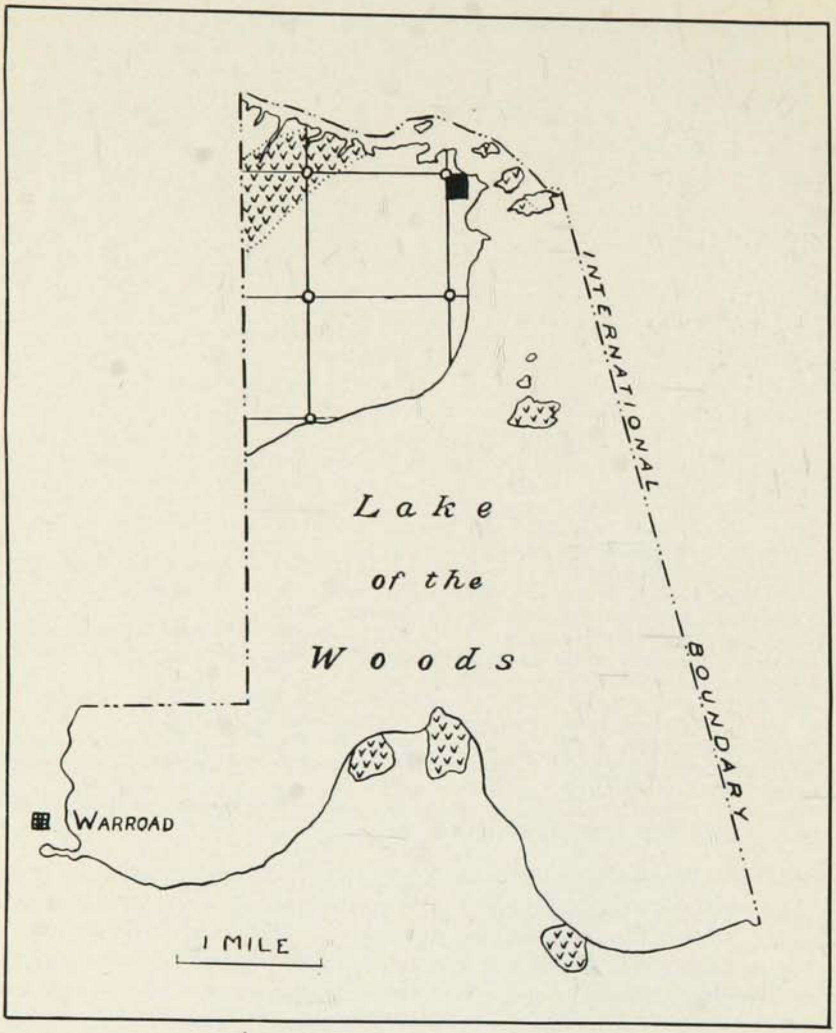

FIGURE 24. — Sketch of Northwest Angle, Lake of the Woods, showing in black the area of Sec. 6, T. 167 N., R. 33 W., including the feldspar deposit. The check marks show areas of granite outcrops.

jected. The feldspar was loaded on a barge and delivered to the mill at Warroad. The hand-sorted feldspar contains relatively few dark grains or spots, but close attention is needed to keep the iron content low.

Crushing and grinding were done at Warroad in a mill with an annual capacity of 10,000 tons. The feldspar was reduced to about 200 mesh by fine grinding in a Hardinge conical mill. Silica lining and silica pebbles were employed instead of steel to avoid contamination of the product

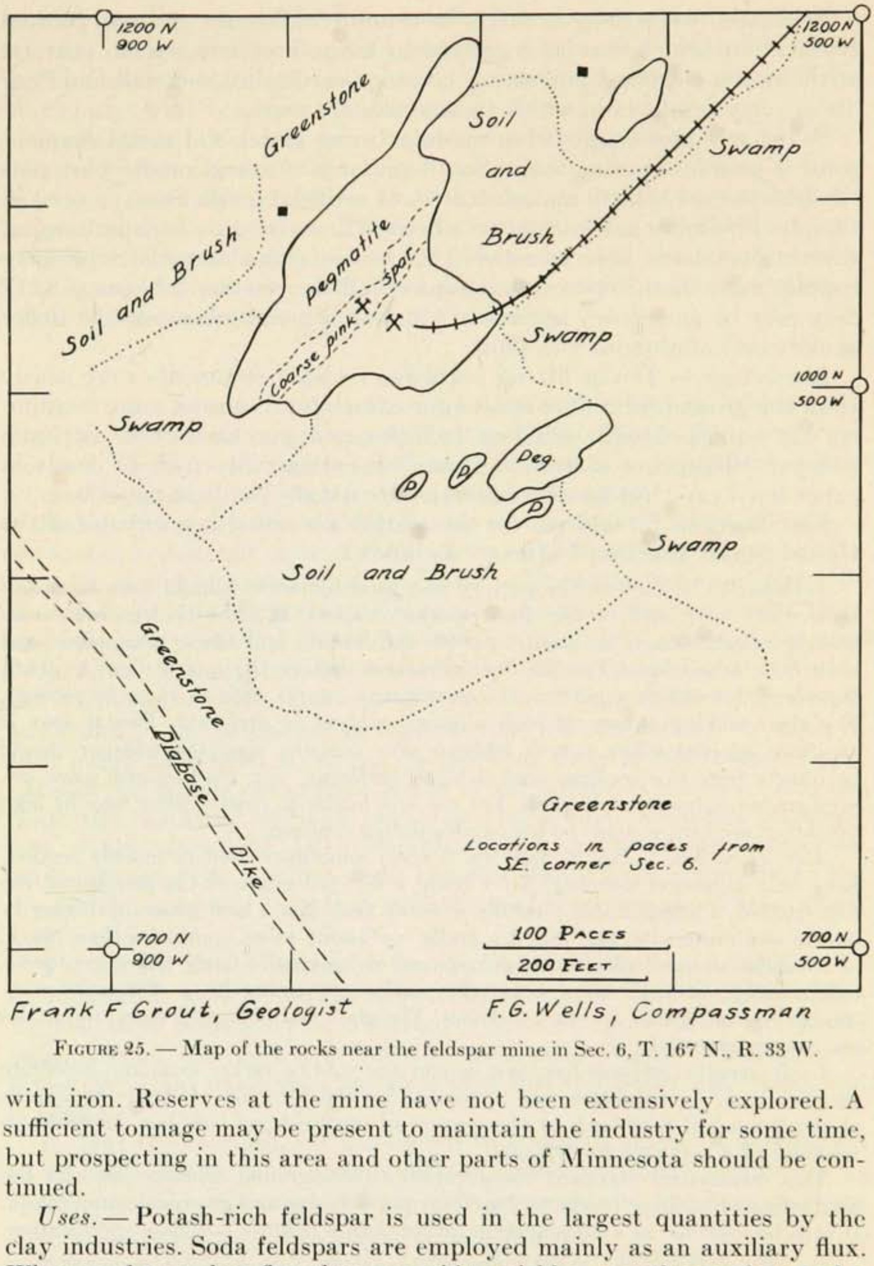

FIGURE 25. — Map of the rocks near the feldspar mine in Sec. 6, T. 167 N., R. 33 W.

with iron. Reserves at the mine have not been extensively explored. A sufficient tonnage may be present to maintain the industry for some time, but prospecting in this area and other parts of Minnesota should be continued.

Uses. — Potash-rich feldspar is used in the largest quantities by the clay industries. Soda feldspars are employed mainly as an auxiliary flux. When used as a glass flux they are said to yield a smoother surface and a higher gloss than the potash variety does. Lime feldspars are of interest to glass makers who desire a little alumina in their mix.

Feldspars, when used as fluxes in ceramic industries, cause a gradual vitrification, which can be regulated in kilns. Porcelain, china, pottery, earthenware, electrical porcelains, lavatory porcelains, and wall and floor tile are clay products in which these fluxes are used.

Feldspar is also employed in manufacturing glazes and metal enamels. Some is used in scouring soaps. Small amounts of exceptionally pure potash feldspar are sold to manufacturers of artificial teeth. Some is used as a binder for emery and corundum wheels. The soda-calcic feldspar masses, anorthosites, have been considered for use in abrasive work. Since they contain more than 30 percent alumina and little iron (see table on p. 127), they may be emergency sources of aluminum metal whenever the richer bauxite ores of alumina run short.

Marketing.—Ten or fifteen years ago feldspar shipments were nearly all in the ground form (200 mesh approximately), but now some consumers are equipped with grinding facilities and purchase crude or lump feldspar. Shipments of ground "spar" in carload lots may be made in paper-lined cars, but smaller deliveries are usually made in paper bags.

Specifications for feldspar for the market are noted in a circular of the United States Bureau of Mines,[92] as follows:

> Feldspar to be used in the pottery and glass industries should burn to a uniform white color and be free from specks or spots. It must be free from iron-bearing minerals such as biotite, garnet, hornblende and black tourmaline, and have little or no mica. For the finer grades of pottery the quartz limit is about 5 percent, for ordinary pottery the quartz may run as high as 15 to 20 percent. For glass making a spar of high alumina content is preferred. Dental spar is carefully selected white potash feldspar. For scouring soap the feldspar should be quartz free. For roofing, cement-block surfacing, and chicken grit more impure grades of spar may be used. For use as a binder in emery, silica may be high but other impurities must be low, and grinding uniform.
>
> The terms No. 1, No. 2, and No. 3 spar, sometimes used in market reports, have only a general meaning, No. 1 being a selected grade of the product of the district, No. 2 a grade less carefully selected than No. 1 and generally higher in quartz and muscovite, and No. 3 a grade containing more impurities than No. 2.
>
> Manufacturers of clay wares demand an exceptionally finely pulverized product, usually not more than 1 percent residue remaining on a 200-mesh sieve, though coarser grades are used at times. The glass and enameled metal industries use coarser material.
>
> Until recently, feldspar has been bought and sold on rather loose and indefinite specifications. A committee was appointed by the Division of Trade Standards of the Bureau of Standards at the request of the Feldspar Grinders' Institute to recommend a standard for feldspar.
>
> This commercial standard classification covers ground feldspar used in the production of ceramic products, based on particle size and chemical composition. It is to be regarded as a classification rather than a definite purchase specification.

Commercial Standard (C.S. 23-30) has as its essential features (1) fine-

[92] Bowles, O., and Lee, C. V., Feldspar: U. S. Bureau of Mines, Information Circular 6381, 1930.

ness of grinding, determined by standard screen tests, and (2) chemical features determined by standard methods. Chemically controlled blending has become standard practice. A complete chemical analysis is the best guide to the behavior of a feldspar on firing.

Production. — No data are available concerning production and shipment of feldspar in this state. In government records Minnesota is listed as one of the smaller producers. In 1935, twenty-nine plants were engaged in grinding feldspars in the United States, producing 189,289 short tons of ground feldspar, valued at $2,460,073, f.o.b. mill. The average value of the ground products was $13 per short ton, and the average value of crude feldspar was $5.30 a long ton, f.o.b. mine.

MICA

Mica [93] is essential in electrical insulation and is best in light-colored varieties, muscovite or phlogopite. In the United States there are some workable deposits of muscovite, all of which occur in pegmatites, coarse rocks of approximately the same composition as granites.

Many of the pegmatites of Minnesota have muscovite "books" up to a few inches across, but most of the books seen are defective. The specifications for electrical work require the mica to be nearly free from pinholes, mineral inclusions of conducting minerals, and crumpling by strain. Only sheets of such perfection and of fair size command high prices. Some may be found in the numerous dikes near Rainy Lake and Lake of the Woods, and possibly elsewhere. The wide distribution of pegmatites in Minnesota was noted in the discussion of feldspar, but few large sheets of mica of clear grade have been noted. At the feldspar mine in Northwest Angle, Lake of the Woods, scrap mica might be sorted out as a by-product, because the industrial demand for scrap and ground mica has increased very greatly since 1930. Other deposits near by may include commercial books of muscovite. On the south shore of Rainy Lake pegmatites yield three-inch books, but they have pinholes and crumpled structures, which reduce their value.

The United States Bureau of Standards has methods of testing micas for high-grade work,[94] and the American Society for Testing Materials, in its Tentative Standards for 1934, gives tests for sheet mica and plates built up from splittings. The prices of small sizes increase when demand is heavy.[95] The small sizes are used also for wall paper and paint and in rubber.

In 1942 the Government attempted to stimulate domestic production of strategic mica,[96] and designated the Colonial Mica Corporation as agent to lease equipment, supervise development, and purchase strategic

[93] The paragraphs on mica were supplied by Dr. F. F. Grout.

[94] Horton, F. W., Mica: U. S. Bureau of Mines, Information Circular 6822, 1935.

[95] Mining and Metallurgy, p. 102, 1940.

[96] Houck, L. G., Marketing Strategic Mica: U. S. Bureau of Mines, Information Circular 7219, pp. 1–24, 1942.

mica. Strategic mica must be clear and reasonably flat, and must yield sheets at least 1 by 1 inch in size. Specifications vary with use.

PYRITE AND PYRRHOTITE

Pyrite and pyrrhotite, compounds of sulphur and iron, are common sources of sulphur and sulphuric acid. They occur in several places in Minnesota [97] and might be mined if a local industry needed acid for leaching or other chemical treatment. Near the Cuyuna range, where sulphur compounds might be used for leaching if emergency reserves of manganese were needed, there are known sulphide belts south and southeast of Long Lake (12 miles southeast of Aitkin). Other occurrences are known in the Vermilion and Gunflint districts. Pyrite is widely distributed in small amounts in a great variety of rocks in all parts of the state, but few large bodies are known.

POTASH-BEARING MATERIALS FOR SOIL IMPROVEMENT

Glauconite. — Glauconite [98] is essentially a hydrous silicate of iron and potassium. Variable amounts of alumina, magnesia, and lime are usually present in the mineral, and a small quantity or trace of phosphate may be found. The potash content may amount to 7 or 8 percent in some samples. The glauconite is green and normally occurs in small granules about the size of fine sand grains. It is abundant in marine sediments near the shore in the vicinity of the "mud line." It is the chief constituent of the so-called greensand, which occurs in sedimentary formations of nearly all geologic periods.

Attempts have been made in New Jersey to extract potash from glauconite, but they were not commercially successful. Greensand has been used as a fertilizer filler with some success. Although the potash in this material is only slightly soluble in water, small amounts of it are available for plant use. There is also an expanding demand for greensand for water softening.

In Minnesota the Franconia sandstone and the St. Lawrence formation, both of Cambrian age, contain glauconite. They are exposed at places along the St. Croix and Mississippi rivers from Chisago County south to the Iowa line, and the St. Lawrence formation crops out at St. Lawrence and Judson on the Minnesota River. Although they do not contain glauconite throughout their vertical or horizontal extent, there are locally thick, glauconite-rich layers. In the driftless area weathering has leached the dolomites, leaving localized concentrates of glauconite.

Decorah Shale. — Decorah shale, the distribution of which is shown on the map (fig. 19) accompanying the chapter on clays and shales, contains about 7 percent potash. It has been ground and used experimentally on small plots of land, and the soil thus treated has shown an increase in

[97] Thiel, G. A., Iron sulphides in magnetic belts near the Cuyuna range: Econ. Geol., vol. 19, pp. 466–472, 1924.

[98] Data on potash-bearing materials were supplied by Dr. G. A. Thiel and Dr. F. F. Grout.

productivity. This rock contains the potash-bearing minerals feldspar and sericite in a fine state of division, and even though they are only very slightly water-soluble some of the potash seems to be available for plant use. Calcareous material in some beds of this shale also serves as a soil sweetener.

Further experiments designed to test the merits of Minnesota greensands and the Decorah shale when used on different types of soil and with various plants would be illuminating.

COAL

Coal occurs in seams up to six inches thick in the Cretaceous beds in the western half of Minnesota; for example, at Springfield in Brown County. It is of subbituminous rank and might be mined if it occurred in thicker beds.

A thin seam at Two Rivers, south of Little Falls, has long been known. Thicker beds have been reported in places drilled in search for water. Some of these are fragments (boulders) in the glacial drift, but in a few counties near the northwestern corner of the state such coal occurs in Cretaceous beds that are reasonably persistent.

OIL AND GAS

Considerable drilling for oil and gas has been done in Minnesota, beginning as early as 1887. Several old wells drilled for water found natural gas in glacial drift. Some yielded gas enough for the owner's use for a few years. There has also been an occasional leak from some storage tank of gasoline into the neighboring soils and surface deposits, which created much unjustified hope of commercial accumulations. More regular rock formations below the drift have not yielded these products.

GRAPHITE

Graphite is a common mineral in the slates of northern Minnesota, but in most places is so impure that it has no value. Some better graphite has been encountered in slates on the Cuyuna range and in similar slates near Carlton. Two graphite occurrences have been test pitted on Pigeon Point, one in the "red rock" granite and one as pellets in a gray quartzite. No commercial deposits have been found. No such rocks elsewhere in the world supply valuable amounts of graphite, and the prospects are not encouraging.

PIGMENTS

Small amounts of the iron ores of the Minnesota iron ranges have been used as pigments. Red ocher also has been produced in a few places for use as a pigment. A paint mine was opened in the weathered rock in the gorge of Redwood River below Redwood Falls. The "paint-rock" of the Mesabi range is a lean aluminous iron ore of little or no value as a pigment. A shortage of pigments might result in some development of pigment industries in the state.[99] Both the red and brown deposits related to iron ores and the green residual glauconite related to weathered dolomite in the southeastern counties deserve attention. Even the graphite noted in the preceding paragraph may be of interest.

The iron oxide pigments which might be produced in Minnesota range through yellows, browns, and reds, to blacks. Yellow ocher is goethite (limonite) mixed with clay. It should have 17 to 60 percent Fe_2O_3. Raw siennas have iron silicate in addition to the material of the ocher, and have 40 to 75 percent Fe_2O_3. Burnt siennas are prepared by heating siennas to drive off water. The color can be controlled by the amount of dehydration yielding browns and reddish browns.

Richer goethite ores, more than 65 percent Fe_2O_3, are calcined to metallic browns or mineral browns. With increasing manganese, around 8 to 15 percent, they grade into umbers — burnt umbers after they are calcined.

Natural red mineral pigments are largely hematite. They should have more than 60 percent Fe_2O_3. If a Minnesota product can be found with deep red color in oil, more than 80 percent Fe_2O_3, and a low content of calcium carbonate, it may replace imports from Spain or the Persian Gulf, from which supplies have been obtained in the past.

Black pigments may be made from magnetite if it is purer than 90 percent Fe_3O_4, but they would meet with competition from graphite and synthetic pigments.

Pure graphite is not as suitable for pigment as that with some clay impurity. Some rocks with as little as 25 percent graphitic carbon may be ground directly into pigment. When mixed with oil they spread more satisfactorily than the purer graphite.

Terre verte is a green, powdered glauconite. The pigment is durable, but its color is dull and it has poor opacity. Foreign sources of this material are reported to be almost exhausted.

Specifications for pigments are different for different purposes. Commonly there is a minimum for the percentage of coloring mineral or constituent and a maximum of 5 percent of calcium compounds. A claylike texture is preferred. The economic factors include the tonnage, cost of mining, and distance from such consuming centers as Chicago. Progressive pigment manufacturers examine all domestic iron oxide pigments sent them in the hope that both they and the owner will make a profit.

In 1942 the natural pigments produced and the iron oxide pigments manufactured in the United States amounted to 97,327 short tons, valued at $7,764,232. Camouflage paint required greatly increased amounts of pigment.

TRIPOLI

Tripoli was once developed at Stillwater, but the deposit has not sup-

[99] Harness, C. L., Marketing Natural Mineral Pigments: U.S. Bureau of Mines, Information Circulars 7198 and 7217, 1942.

plied any large industry.[100] It was apparently a silt deposited in a glacial lake and is at least partly interlaminated with clay.

CORUNDUM

Corundum has been reported at various places in Minnesota, but has been identified only in a few sedimentary sand grains. Quarries were once opened in anorthosite with the mistaken idea that the feldspar was corundum.

ALUM

Alum has been observed in thin crusts on overhanging cliffs of Rove slate in Cook County, and probably occurs on protected outcrops of other pyrite-bearing shales. It is seldom pure and no useful deposits have been reported.

GARNET

Garnet is a widespread mineral in the altered rocks in the northern half of the state. There has been no development of the mineral for sandpaper or other uses.

PHOSPHATE ROCK

No commercial phosphate is known in Minnesota, but certain dark horizons in the gray Platteville limestone carry black pebbles and disseminated grains richer in phosphate than the rest of the formation.

SALT

No beds of rock salt have been reported from Minnesota, but some springs and wells produce salt water. Salt was made from a brine from a well in Kittson County as early as 1884. Many salt springs and wells have been reported from other places in the state, but no large industry has developed.

[100] Minn. Geol. and Nat. Hist. Survey, Final Report, vol. 2, pp. 394–397, 1888.

MISCELLANEOUS DEPOSITS OF METALS

ALUMINUM

Bauxite, the common ore of aluminum, occurs in impure form at several places in Minnesota. It resulted from prolonged weathering of the pre-Cambrian complex. Any exposures of an old weathered surface may well be observed with care and perhaps sampled for assay. On the Mesabi range the rocks near the base of the Cretaceous are highly ferruginous, but southwest from the middle of the state many aluminous rocks were deeply weathered to residual concretionary crusts that greatly resemble the concretionary bauxites. Some prove to be kaolinite in spite of their structure, but others have considerably more alumina than silica. Some, even far from the iron ranges, are highly ferruginous.

Samples have been tested (1) from the mouth of Two Rivers near Little Falls,[101] and (2) from a group of concretionary exposures along the Minnesota River Valley near Morton.

ANALYSES OF BAUXITIC CLAYS

	I	Ia	II	III	IV
Silica, SiO_2	19.81	22.42	36.8	28.6	42.1
Alumina, Al_2O_3	52.43	35.48	26.1	37.6	38.3
Iron oxides, Fe_2O_3	1.32	21.38	19.6	12.1	3.2
Soda, Na_2O	.44				
Calcium Carbonate, $CaCO_3$	1.64				
Water, H_2O	23.23				
Titania, TiO_2			1.3	1.0	1.0
Ignition, H_2O, etc.		18.45	14.0	19.4	14.8
Total	98.87	....	97.8	98.7	99.4

I. Pre-Cretaceous crust, probably bauxitic, Two Rivers. J. A. Dodge, analyst.
Ia. Same location. About 22 percent bauxite. Oliver Bowles, analyst.
II. Concretionary ferruginous crust over residual clay, in road cut east of Morton; X-ray study by Dr. Gruner shows some gibbsite; Sec. 4, T. 112 N., R. 34 W.
III. Lighter colored concretionary rock below II.
IV. Light concretionary rock in road cut southwest of Morton, close to the northern line of Sec. 3, T. 112 N., R. 35 W.
Analyses II, III, and IV by the Aluminum Company of America.

Many analyses of clays and feldspar rocks show large amounts (about 30 to 40 percent) of alumina, the oxide of aluminum. (Note that only 53 percent of the alumina is aluminum.) When these analyses come to the attention of owners of the deposits or others interested they stimulate a great many inquiries as to possible extraction and production. Many researches have been made on such silicate materials, and it is known that metallic aluminum can be made from them, but the processes are too expensive to be commercially practical in normal times. The recent great demand for aluminum and the shortage of good bauxite inside the United

[101] Upham, Warren, The geology of Morrison County: Minn. Geol. and Nat. Hist. Survey, Final Report, vol. 2, p. 602, 1888.

States has again stimulated researches of this character. The kaolin of the Minnesota Valley (page 92) and the anorthosite along the north shore of Lake Superior (page 126) are easily accessible deposits of such silicates with little associated iron mineral.

MAGNESIUM METAL FROM DOLOMITE[102]

The urgent demand for light metal for airplanes has stimulated the search for magnesium. Some magnesium may be obtained from dolomites with very low silica and iron content. At places in Minnesota the lower 20 feet of the Oneota dolomite has only about 2 percent of impurity, and locally parts of the Shakopee dolomite have equally little impurity. The lower part of the Cedar Valley limestone, however, is generally more suitable and more accessible, particularly at Spring Valley, where it is at least 17 feet thick and has little overburden. The United States Bureau of Mines[103] reported in 1942 that dolomite rock for making magnesium should contain more than 40 percent magnesium carbonate and not less than 97 or 98 percent total carbonates. In the following table are analyses of samples from various exposures which would seem to be excellent as a source of magnesium. The sesquioxides (R_2O_3) include the iron and aluminum oxides, and these with silica make up the impurities or non-carbonates. The magnesium carbonate amounts to 2.09 times the percentage of MgO tabulated.

ANALYSES OF MINNESOTA DOLOMITES (1942)

Sample	R_2O_3	SiO_2	MgO	Location	Formation	Thickness (feet)
7K	0.86	1.74	20.68	Zumbro Falls	Shakopee	10
8B-E	1.35	1.54	19.77	Lake City	Oneota	60
19A and B..	0.61	0.84	20.90	Etna	Cedar Valley	20
20C	1.06	1.24	19.58	Etna (Vanderbosch)	Cedar Valley	10
21A and B..	1.05	1.01	20.66	Spring Valley (Larson)	Cedar Valley	20
22A	1.14	1.44	21.07	Hamilton	Cedar Valley	10

GOLD

In 1865 a gold rush to Vermilion Lake was started by the discovery of gold and silver there. Shafts were sunk and stamp mills were built, and land that subsequently became valuable for iron ore was taken for gold claims. By 1867 it appeared that the gold deposit was too lean, and the country, together with its valuable iron deposits, was abandoned.[104]

One gold mine on an island in Rainy Lake, the Little American mine, operated in 1894 and 1895, is the source of the only gold production in Minnesota. The production of the mine in 1894 was valued at $4,635.33.

Many prospects have furnished specimens and many gravel deposits

[102] The section on magnesium was supplied chiefly by Dr. C. R. Stauffer.

[103] In a personal communication.

[104] Grout, Frank F., Petrographic study of gold prospects of Minnesota: Econ. Geol., vol. 32, p. 61, Jan.–Feb., 1937.

have yielded visible gold on panning, but explorations since 1895 have revealed no other gold ore of value. The total production since 1894 is valued at less than the amount produced at the Little American mine in 1894. These small amounts were reported before 1900. Drilling in 1936 near the Little American mine failed to reveal any extension of that ore body.

A general study has been made of the character of the material since the adoption of modern methods of ore classification. There is no a priori reason to believe that the region is unfavorable geologically for gold deposits, but the long record of unsuccessful exploration should be emphasized and investors should be warned against overoptimism.

COPPER AND NICKEL

Copper has been prospected for at several places in Minnesota in the Keweenawan rocks correlated with the productive rocks of Michigan. Test pits have been opened at Taylors Falls, Hinckley, Pine City, and at several points between Duluth and Grand Marais. The deepest were at Chengwatana, the site of an old Indian village near Pine City.[105] Drilling was done also in traprocks on Knife River, northeast of Duluth. Metallic copper is found at all of these openings, but not enough to encourage further work. Different kinds of copper prospects occur northeast of these Keweenawan flows. At Susie Island, near Pigeon Point, a vein carries copper sulphides. The veins are variable, however, parts of them being less than 12 inches thick, and although they have been explored by a considerable shaft and incline, no shipments are recorded.[106]

Copper is associated with nickel in small amounts in sulphide diabase, intrusive into the Rove slate area, at several places in T. 64 N., R. 5 E. It is rumored that a Canadian company will explore the area by drilling in 1943. Traces of nickel have also been reported in some assays of titaniferous magnetites described on pages 29–30.

COBALT

For many years a mineral vein that cuts the Rove slate and a diabase sill on the south side of Loon Lake in Cook County has been known. It has been variously prospected for silver, gold, copper, and other metals, with no great success. In 1940 a specimen, given to the Minnesota Geological Survey with the statement that it came from the prospect in Sec. 35, T. 65 N., R. 3 W., was found to contain arsenides of cobalt.

SILVER

Silver has been mined in Ontario near the Minnesota boundary, and the same rock formations occur near Pigeon Point, Minnesota. Several

[105] Schwartz, G. M., A guidebook to Minnesota trunk highway No. 1, Minn. Geol. Survey Bull. 20, pp. 52–54, 1925.

[106] Grout, Frank F., and Schwartz, G. M., The geology of the Rove formation, northeastern Minnesota: Minn. Geol. Survey Bull. 24, pp. 60–69, 1933.

prospects have been opened on veins, but no commercial production is recorded. The veins carry barite and small amounts of galena (lead sulphide) and sphalerite (zinc sulphide), which commonly occur with silver.

LEAD AND ZINC

Lead and zinc are known in Minnesota in the veins near Pigeon Point just mentioned and in the Platteville limestone from the Twin Cities to the southeast. This limestone in Wisconsin, Illinois, and Iowa contains valuable lead and zinc ores, but no deposit of commercial importance has been found in Minnesota. Traces of galena and sphalerite are widespread.

VANADIUM

See the note on page 30 about vanadium in titaniferous magnetites.

APPENDIXES AND LISTS OF PUBLICATIONS

MINERALS OF INTEREST TO COLLECTORS

Besides the minerals of commercial importance, Minnesota has many common rock minerals and rare species of interest to collectors.[107] Two lists of minerals found in the state have been published in the reports of the Geological and Natural History Survey of Minnesota.[108] Clubs have been organized in several cities, encouraging amateurs to collect and polish minerals and gems. Probably the minerals best known to collectors are the agates and thomsonites.

1. *Agates* are collected at Agate Bay near Two Harbors and elsewhere along the north shore of Lake Superior. Many are collected from the red drift (fig. 5) from the Twin Cities northward to the iron ranges. Some jasper materials from the iron formations are almost as highly prized as the agates. Bright red jaspers are found near Section 30 Mine east of Ely.

2. *Thomsonites* have been collected chiefly from a small boulder beach about six miles west and southwest of Grand Marais. Here the green rings (mesolite?) concentric with the pink thomsonites make the stones especially attractive. More ordinary pink thomsonites are available at many points along the shore.

3. *Staurolite* in mica schist is exposed at low water in the Mississippi River below Little Falls.

4. *Kyanite* occurs in large blue blades in mica schist on the shores of Saginaw Bay, Rainy Lake, NE 1/4 of NW 1/4 of Sec. 12, T. 70 N., R. 21 W. If there were large amounts available for concentration it might find a market for use as a refractory and in glass and ceramics.

5. *Laumontite (with copper)* occurs on the dumps of the old shafts a few miles down the Snake River from Pine City.

6. *Analcite (with copper)* is found at the same location as laumontite.

7. *Prehnite (with copper)* occurs on the dump of an old mine four miles east of Hinckley.

8. *Plagioclase (bytownite)* is exposed in large volumes in anorthosite along the highway near the north shore of Lake Superior in Lake County.

9. *Xonotlite (with afwillite)* is found in veins at Silver Creek cliff on the same highway.

10. *Perthite* is mined at the feldspar mine in the Northwest Angle, Lake of the Woods County. It is found also near Anderson Bay on Rainy Lake in large pieces in the beach gravels.

11. *Muscovite* occurs with perthite in the Northwest Angle and in several pegmatite dikes on Rainy Lake.

12. *Specular hematite* is abundant at the Soudan mine and its vicin-

[107] Data for this section were supplied chiefly by Dr. F. F. Grout.

[108] Berkey, C. P., Notes on Minnesota minerals: 23d Annual Report, pp. 194ff., 1894. Winchell, N. H., Mineralogy and petrology of Minnesota: Final Reports, Minn. Geol. and Nat. Hist. Survey, vol. 5, pp. 937ff., 1898–1900.

ity in St. Louis County. Red hematite is widely distributed on all three iron ranges.

13. *Magnetite*. Remarkable octahedrons of magnetite occur in the soft ore of the Kinney and Brunt mines on the Mesabi range. Fine grains are disseminated in many rocks.

14. *Limonite (after pyrite)* forms cubes in slates on Ely Island, Lake Vermilion, St. Louis County. Limonite ores are abundant on the Mesabi and Cuyuna iron ranges.

15. *Augite* is collected as coarse cleavage pieces from pegmatite at the railway Y, Allen Junction, St. Louis County, and between Hovland and Grand Portage on the Lake Superior shore.

16. *Chalcocite with zoned calcite* is scattered along the beach on the east shore of Susie Island in Lake Superior, about five miles east of Grand Portage, Cook County.

17. *Pectolite* fills cavities at Hat Point on the shore of Lake Superior, east of Grand Portage.

18. *Barite (heavy spar)* has been known from early days in a vein cutting almost vertically into the bluff on the north side of Pigeon Point.

19. *Purple fluorite* is collected on Gold Island in Saganaga Lake. It is scattered in small grains in the granite, but larger grains occur associated with white quartz and red orthoclase in the pegmatites that have been blasted out where prospected for gold.

20. *Pipestone (catlinite)* in Minnesota is an odd shale, only 18 inches thick, in the Sioux quartzite near the southwest corner of the state. The Indians used it for pipes in prehistoric times. The bed is now accessible only with some difficulty. It is sericitic, with replacements by pyrophyllite and diaspore.[109]

21. *Pearls*. Fresh-water pearls are found in clams in a few rivers of Minnesota. The search is rather a diversion for campers than the basis of a profitable industry.

22. *Quartz*. Handsome groups of quartz crystals are sometimes encountered in vugs in the Soudan mine on the Vermilion range.

23. *Epidote*. Crystals of epidote are reported in cavities in a granite prospected for gold near Buyck.

A List of the Minerals of Minnesota [110]

* Microscopic or rare; not specimens for collectors.

*Acmite-augite, a pyroxene
*Actinolite, an amphibole
*Adularia, a feldspar
*Aegirine = acmite
*Afwillite
Agate
Albite, a feldspar
*Allanite, an epidote
Almandite, a garnet
*Alum
*Amesite, a chlorite
Amethyst (purple quartz)
Amphibole group: actinolite, anthophyllite, asbestos, cummingtonite, glaucophane,

[109] Berg, E. L., Notes on catlinite and the Sioux quartzite: Amer. Mineralogist, vol. 23, pp. 258–268, 1938.

[110] List supplied by Dr. F. F. Grout.

gruenerite, hornblende (green and brown), pargasite, riebeckite, tremolite, uralite
Analcime, a zeolite
*Anatase
*Andalusite
Andesine, a feldspar
Ankerite
Anorthoclase
Anthophyllite, an amphibole
*Antigorite, a serpentine
*Apatite
*Aragonite
*Arsenopyrite
Asbestos, an amphibole or serpentine
Augite and titan-augite, a pyroxene

*Babingtonite, a pyroxene
Barite
*Bastite, a serpentine
Biotite, a mica
Bobierrite
Bornite
*Bowlingite
Braunite
Bronzite, a pyroxene
*Brookite
Bytownite, a feldspar

Cairngorm = smoky quartz
Calcite
Carnelian
Catlinite, see pyrophyllite
*Ceylonite
Chalcedony: varieties are agate, carnelian, chert, flint, jasper, sardonyx
Chalcocite
Chalcopyrite
Chert
Chlorite group: amesite, delessite, penninite, strigovite
*Chondrodite
*Chrysotile, see asbestos and serpentine
Clay mineral group: kaolinite, montmorillonite, pyrophyllite, nontronite ?
*Clinoenstatite, a pyroxene
Cobaltite
*Collophanite
*Columbite
Copper
*Cordierite
*Corundum
*Covellite
*Cristobalite
*Cummingtonite, an amphibole
*Cuprite
Cyanite, see kyanite

Datolite
Delessite, a chlorite
Diallage, a pyroxene
*Diaspore
Diopside, a pyroxene
Dolomite

Enstatite, a pyroxene
Epidote group: allanite, clinozoisite?, epidote, zoisite

Fayalite, an olivine
Feldspar group: adularia, albite, andesine, anorthoclase, bytownite, labradorite, microcline, orthoclase, perthite, plagioclase series, valencianite
Flint
Fluorite
*Fuchsite, a mica

*Galena
Garnet group: almandite, andradite, spessartite
Gibbsite (bauxite)
Glauconite
Goethite (limonite)
*Gold
Graphite
Greenalite
*Gruenerite, an amphibole
Gypsum

*Halite
Hematite
Heulandite, a zeolite
*Hisingerite
Hornblende, green and brown — an amphibole
Hortonolite, an olivine
Hypersthene, a pyroxene

Ice
*Iddingsite
Ilmenite
*Iolite = cordierite
*Iron alloy (meteorite)

*Jarosite
Jasper

Kaolinite, a clay mineral
Kyanite

Labradorite, a feldspar
Laumontite, a zeolite
*Leucoxene
Limonite, see goethite
Lintonite, a zeolite

Magnetite
Malachite
*Malacon
Manganite
Manganosiderite
*Marcasite
*Martite (hematite)
*Maskelynite (meteorite)

Mesotype, a zeolite
Mica group: biotite, fuchsite, muscovite, phlogopite, sericite
Microcline, a feldspar
*Molybdenite
*Monazite
Montmorillonite, a clay mineral (potash-montmorillonite)
Muscovite

*Nickel-iron (meteorite)
*Nontronite?, a clay mineral

*Octahedrite = anatase
Oligoclase, a feldspar
Olivine group: fayalite, hortonolite, olivine
*Orthite = allanite, an epidote
Orthoclase, a feldspar

*Paraffin
*Pargasite, an amphibole
*Pectolite
Penninite, a chlorite
*Pentlandite
Perthite, a feldspar
*Phlogopite, a mica
Plagioclase, a feldspar
Prehnite
Psilomelane
Pyrite
Pyrolusite
Pyrophyllite, a clay mineral
Pyroxene group: acmite = aegirine, augite, babingtonite, bronzite, clinoenstatite, diallage, diopside, enstatite, hypersthene
Pyrrhotite

Quartz: varieties are amethyst, cairngorm, milky quartz, rock crystal, smoky quartz

Rhodochrosite
*Rhodonite
*Riebeckite
Rock crystal = quartz
*Rutile

Sanidine (soda sanidine)
Sardonyx
Selenite = gypsum
Sericite, a mica
Serpentine group: antigorite, bastite, asbestos = chrysotile
Siderite
*Sillimanite
Specularite = hematite
*Spessartite, a garnet
*Sphalerite
*Sphene
*Spherosiderite
*Spinel
Staurolite
Stilbite, a zeolite
Stilpnomelane
Strigovite, a chlorite

*Talc
*Tantalite
Thomsonite, a zeolite
*Titanite = sphene
*Topaz
*Tourmaline
*Tremolite, an amphibole
*Tridymite (meteorite)
*Troilite (meteorite)

Uralite, an amphibole

*Valencianite, a feldspar
*Vermiculite
*Violarite
*Vivianite

*Xenotime
Xonotlite

Zeolite group: analcime, heulandite, laumontite (lintonite), mesotype, stilbite, thomsonite
*Zircon
*Zoisite, an epidote

A List of the Publications of the GEOLOGICAL SURVEY OF MINNESOTA 1872–1942

W. H. Emmons, Professor of Geology, University of Minnesota, Director

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