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PRELIMINARY REPORT ON THE GEOLOGY OF EAST CENTRAL MINNESOTA INCLUDING THE CUYUNA IRON-ORE DISTRICT

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PRELIMINARY REPORT ON THE GEOLOGY OF EAST CENTRAL MINNESOTA INCLUDING THE CUYUNA IRON-ORE DISTRICT

By E. C. Harder and A. W. Johnston

INTRODUCTION

The geologic work in the Cuyuna iron-ore district is being done jointly by the Minnesota Geological Survey and the United States Geological Survey. Since only a few outcrops of bed rock occur in the district or in the region adjacent to it, the study has been based largely on the results of exploration and mining work. Many drill cores and records of diamond drilling from various parts of the district have been examined, and in addition the occurrence and structure of the rocks as shown in the underground and open pit workings of various mines have been studied in detail, and detailed geologic and topographic maps have been made of several of the open pit mines.

In order to gain a more comprehensive idea of the major structure of the rocks of east central Minnesota, and particularly to note if possible the relation of the rocks of the Cuyuna district to such major structure, a careful study of the rock outcrops of the region lying west, south, and east of the Cuyuna district was made. This included the detailed mapping of most of the rock exposures lying nearest to the Cuyuna district in Cass, Todd, Morrison, Mille Lacs, Kanabec, Pine, Carlton, and Aitkin counties, and a more general study of the outlying exposures in these counties and also in Stearns, Benton, and Sherburne counties. North of the Cuyuna district, in the region lying between it and the Mesabi district, no rock outcrops are known and the relation between the rock formations of these two districts will have to be determined by underground exploration.

As the development work in the Cuyuna district is constantly in progress, it has been considered advisable to publish the present preliminary report giving the general results of the investigations up to the present and to delay the publication of a more complete report pending the accumulation and study of further data.

The present report is incomplete in many ways. The descriptions of the rock outcrops are very general. Thin sections for microscopic examination of many of the rocks have not yet been made, and the exact mineral composition of these remains to be determined. In the descriptions, therefore, only the general characters and geologic relations of the rocks are discussed, the details of texture and mineral composition being only briefly mentioned.

The structure and stratigraphy of the rocks of the Cuyuna district also remain to be determined. Information is as yet too incomplete to attempt arranging the various beds into a stratigraphic succession. It is a question even whether it will be possible to work out such a succession for many years to come because of the general similarity of the rocks and the complex deformation which they have suffered. As regards the structure of the rocks more data are available and it is hoped that some progress may be made in this respect before the publication of the final report.

The origin of the iron ore is only briefly mentioned, a more complete discussion being reserved for the final report.

Accompanying the present report is a map showing the trend and location of the different belts of iron-bearing formation in the Cuyuna district. This is the first map which has been published giving in detail the surface distribution of the iron-bearing formation in the Cuyuna district, and it should be realized that the information on it is as yet far from complete. Doubtless this map will have to be revised, and the only reason for publishing it at the present time is the hope that it may assist in the exploration work which in this district is being conducted under many difficulties.

ACKNOWLEDGMENT

In the preparation of this report on the Cuyuna district the writers have had to depend very largely on the generosity of the exploration and mining companies in furnishing information and in allowing access to their records and files. Almost without exception the information has been willingly furnished and permission to examine drill cores, maps, and reports has been cheerfully given. In many instances companies and individuals have gone to considerable expense in furnishing blue prints and other materials to aid in the preparation of the report. For this coöperation the writers wish to express their sincere thanks.

The writers are indebted to L. G. Ravicz, W. B. Lang, and E. A. Sweetman for assistance in the field.

TERMINOLOGY

The pre-Cambrian rocks of the Lake Superior region include a number of rather uncommon lithological types. These have received distinctive names which are in fairly general use throughout the region. Below are given brief explanations of some of the less well-known rock terms used in this paper as well as of more general rock terms whose usage in this paper has been restricted to certain definite types of rock.

Iron-bearing formation is a term intended to include all the various ferruginous rocks which make up the iron-bearing beds, original as well as altered.

Cherty iron carbonate or cherty siderite is a light to dark-colored, dense, fine-grained rock, usually banded and consisting of interlayered and intermixed chert and siderite. When much argillaceous material occurs in it, the term slaty or argillaceous iron carbonate is used. The iron in most of the iron-bearing formations of the Lake Superior region was probably originally deposited as carbonate.

Greenalite rock is a dark green, granular, ferrous silicate rock occurring in the Mesabi district. Greenalite is believed to be the original rock from which the ferruginous chert and ore of the Mesabi district are derived.

The term ferrous rock includes both ferrous carbonate and ferrous silicate rocks as well as mixtures of the two.

Hematitic and limonitic cherts are variegated rocks, consisting of white, gray, or pink chert intermixed with more or less hematite or limonite. Commonly the chert and iron oxide occur interlaminated, forming a banded rock. Often, however, they are irregularly intermixed. Hematitic and limonitic cherts form the principal surface rocks of the iron-bearing formation. Ferruginous chert is a general term including both hematitic and limonitic cherts. Taconite is a granular ferruginous chert which occurs in the Mesabi district and is believed to be derived from the oxidation of greenalite rock.

Hematitic and limonitic slates are thinly laminated dark red to brown argillaceous rocks heavily impregnated with hematite or limonite. They show distinct banding and lamination and are of sedimentary origin. Ferruginous slate is a general term used to include both hematitic and limonitic slates. Paint rock is a term applied to soft altered phases of ferruginous slate. The term slate is perhaps a misnomer as applied to these rocks, since they only locally show slaty cleavage. They are rather indurated and metamorphosed shales for which the term argillite might be more properly used. The term slate, however, is in such general use for these rocks in the Lake Superior district that for the present it seems best to retain it.

Jaspilite, or banded jasper, is a hard, dense, recrystallized, ferruginous chert. Hematite and jasper generally occur interbanded, the former frequently being in the specular form.

Magnetitic slate, or, more properly, magnetitic argillite, is a dark, distinctly laminated rock containing amphibole, magnetite, quartz, and other constituents usually somewhat segregated in parallel bands. It is a metamorphosed phase of the original iron-bearing formation.

Amphibole-magnetite rock is similar to the magnetitic slate (or magnetitic argillite) but shows coarser banding and crystallization and usually contains more quartz.

Hematitic schist is a dark red, soft, homogeneous, schistose rock which is formed by alteration and impregnation with hematite from the green or gray chloritic schist which is commonly associated with the bands of iron-bearing formation. It is distinguished from ferruginous slate (or ferruginous argillite) in showing no distinct lamination and it is probably of igneous origin. The term paint rock is applied to hematitic schist as well as to ferruginous slate.

The term gneiss in this paper is applied to banded, metamorphosed, crystalline rocks which have approximately the composition of some deep-seated igneous rock. Usually they are siliceous in character. The distinct banding or lamination is a requisite.

Gneissoid granite is a granite which has suffered a certain amount of deformation or recrystallization so that the ferro-magnesian minerals have a somewhat parallel arrangement, giving the rock a foliated appearance. It does not show banding.

Greenstone is a general term applied to dark green, massive, igneous rocks which have suffered alteration so that the original character is not obvious in the hand specimen.

Green schist is a name given to dark green chloritic and amphibolitic rocks with schistose or slaty texture. Some are schistose greenstones, while others may be metamorphosed sediments. The more obviously laminated slaty green rocks of sedimentary origin are usually called green slates.

Phyllite is finely crystalline quartz-mica schist.

Slate is an indurated argillaceous rock showing slaty cleavage. It is usually very finely crystalline.

The term argillite is used in this paper to denote indurated argillaceous rocks which have no slaty cleavage, in contradistinction to the term slate. This usage, however, is not strictly adhered to because of the general use into which the term slate has come for all indurated, argillaceous rocks in the Lake Superior region.

GENERAL GEOLOGY OF MINNESOTA

The basal rocks of Minnesota consist of a complex of granite, gneiss, and greenstone of Archean age with some metamorphosed sediments. Lying on these and folded into them are Huronian quartzite, conglomerate, slate, schist, and iron-bearing formation, with locally crystalline limestone. These older rocks throughout much of the eastern part of the state are unconformably overlain by rocks of Keweenawan age, consisting in the north of flows and intrusive sheets of igneous rocks, both silicic and subsilicic, and in the south of red clastic sediments associated with detrital igneous rocks. The Keweenawan rocks also have suffered considerable deformation locally, but not to such a degree as the Huronian rocks. Keweenawan and Huronian silicic and subsilicic igneous rocks intrude older rocks as dikes, bosses, and sheets.

The pre-Cambrian rocks form the bed rock underneath the glacial drift throughout the northeastern part of the state and for a considerable distance west of the Mississippi River. In the southwestern part of the state also, several large patches of pre-Cambrian rocks are known to lie directly underneath the glacial drift. In the southeastern part of the state, however, the pre-Cambrian rocks are overlain by more or less flat-lying sediments of Paleozoic age, while throughout most of the western part of the state flat-lying, slightly consolidated, Cretaceous sediments occur overlying the pre-Cambrian rocks. The glacial drift forms a mantle covering the different bed rocks practically throughout the state.

The accompanying sections show the general relations between the rock strata in the southern and northeastern parts of the state.

General Section of Rocks in Southern Minnesota and Western Wisconsin[1]

	Approximate Maximum Thickness
Quaternary	
Recent................Alluvium	....
Pleistocene............Glacial till	575 feet
Cretaceous	
Benton shale (soft blue shale and unconsolidated sandstone) Dakota sandstone (white sandstone, shale, and red clay)	500 feet
Devonian (limestone and sandstone)	100 feet
Ordovician	
Maquoketa shale (shale, dolomite, and argillaceous sandstone)	100 feet
Galena limestone Decorah shale Platteville limestone (limestone and shale)	350 feet
St. Peter sandstone (white or yellow sandstone, with some shale)	200 feet

[1] 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. 31-49. 1911.

Hall, C. W., The gneisses, gabbro-schists, and associated rocks of southwestern Minnesota: *U. S. Geol. Survey Bull.* 157. 1899.

Weidman, S., and Schultz, A. R., The underground and surface water supplies of Wisconsin: *Wis. Geol. and Nat. Hist. Survey Bull.* 35, pp. 25-43. 1915.

Winchell, N. H., Upham, W., and Harrington, M. W., (Geology of the southern counties of Minnesota), *Geol. and Nat. Hist. Survey of Minnesota, Geol. of Minnesota,* vols. I and II. 1884, 1888.

Prairie du Chien group ("Lower Magnesian")	
Shakopee dolomite (yellow, buff, pink, or red dolomite, with sandstone lenses)	75 feet
Oneota dolomite (buff to reddish dolomite)	200 feet
Cambrian	
Upper Cambrian	
Jordan sandstone (coarse-grained white sandstone)	50 feet
St. Lawrence formation (dolomite, shale, and sandstone)	60 feet
Franconia sandstone (fine-grained white or yellow sandstone, with fossils and some greensand)	160 feet
Dresbach sandstone (heavily bedded coarse sandstone)	100 feet
Eau Claire shale (interbedded shale and shaly sandstone)	250 feet
Mt. Simon sandstone (coarse sandstone)	250 feet
Algonkian(?)	
Keweenawan(?)	
Red clastic series (red sandstone and shale, with volcanic clastic rocks)	2,250 feet
Algonkian	
Huronian	
Sioux quartzite (red quartzite and pipestone)	Unknown
Crystalline schist (hornblende and biotite schists)	Unknown
Archean	
Granite, gneiss, and schist	Unknown

General Section of Rocks in Northeastern Minnesota and Adjacent Parts of Wisconsin[2]

	Average Maximum Thickness
Quaternary	
Recent................Alluvium	....
Pleistocene...........Glacial till	400 feet
Cretaceous	
Ferruginous conglomerate	Small
Algonkian	
Keweenawan	
Upper Keweenawan	
Bayfield group (In older reports mistaken for Cambrian, Lake Superior sandstone)	
Chequamegon sandstone (red and white quartz sandstone)	1,000 feet
Devils Island sandstone (pink and white sandstone)	300 feet
Orienta sandstone (red and white sandstone)	3,000 feet

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[2] Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior region: *U. S. Geol. Survey Mon.* 52, pp. 118-224, 370-380. 1911.

Thwaites, F. T., Sandstones of the Wisconsin coast of Lake Superior: *Wis. Geol. and Nat. Hist. Survey, Bull.* 25. 1912.

Winchell, N. H., Upham, W., Todd, J. E., and Grant, U. S. (Geology of the central and northern counties of Minnesota), *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, 2 and 4. 1888 and 1899.

Oronto group	
Amnicon formation (red and green shale and arkose)	5,000 feet
Eileen sandstone (red and white feldspathic sandstone)	2,000 feet
Freda sandstone (red arkose sandstone)	12,000 feet
Nonesuch shale (black shale)	300 feet
"Outer" conglomerate	1,200 feet
Middle Keweenawan	
Diabase sills and laccoliths	Varying
Diabase amygdaloid, melaphyr, quartz porphyrite, and felsite extrusives, with interlayered conglomerate in upper part	4,000–20,000 feet
Red rock, intrusive into Duluth gabbro and older rocks	....
Duluth gabbro, laccolith at base of middle Keweenawan	9,500–25,000 feet+
Lower Keweenawan	
Puckwunge conglomerate	100–400 feet
Huronian	
Upper Huronian (Animikie group)	
Virginia ("St. Louis") and Rove slates (argillaceous, siliceous, and carbonaceous slate, with lenses of quartzite, grit, graywacke, limestone, and iron-bearing formation)	Unknown
Biwabik and Gunflint formations (iron bearing)	620 feet
Pokegama quartzite	200 feet
Lower-middle Huronian	
Giants Range and other granites	....
Knife Lake slate Unknown (Slate and graywacke of Mesabi Range)	3,000–5,000 feet
Agawa formation (iron bearing) 0–50 feet (Slate and graywacke of Mesabi Range)	
Ogishke conglomerate 0-2000 feet (Slate and graywacke of Mesabi Range)	
Archean	
Laurentian	
Granite and gneiss	
Keewatin	
Soudan formation (iron bearing) (Greenstone, green schist, slate, and graywacke of Lake of the Woods region)	
Ely greenstone (Greenstone, green schist, slate, and graywacke of Lake of the Woods region)	

As shown by these sections, the rocks of Minnesota consist of a great series of pre-Cambrian plutonic, volcanic, metamorphic, and sedimentary rocks overlain in places by a comparatively thin veneer of Paleozoic and Mesozoic rocks and more generally by a thin but wide-spread blanket of glacial deposits.

The complex of pre-Cambrian metamorphic rocks and associated intrusives is comparatively near the surface in the southwestern, central, and northeastern parts of the state, and surface outcrops are abundant in many places. In the northwestern part also these rocks are at no great depth, although outcrops are less common. In the southeastern part, however, a marked depression in their surface occurs in the form of a northeast-southwest basin, the bottom of which is several thousand feet below the general elevation of the pre-Cambrian rock surface in other parts of the state.[3] It is in this basin that the Keweenawan red clastic rocks occur, as well as the overlying Paleozoic sediments.

A basin probably existed over part of this area before the Paleozoic sediments were deposited, but some sinking has taken place since that time. The original depression is believed to have been caused by deformational forces resulting in a tilting to the southeast. The relief of the pre-Cambrian surface before deposition of the Paleozoic sediments was very marked and the present approximately level pre-Cambrian rock surface in the northern and western parts of the state is due to subsequent peneplanation.[4] Only locally in the southwestern part and beneath the sedimentary rocks in the southeastern part is the old uneven bed rock surface preserved.

In southern Minnesota the principal pre-Cambrian rocks are granite, gneiss, Sioux quartzite, crystalline schists, and probably the red clastic series. Granite and gneiss are abundantly exposed along Minnesota River and at several localities in the region to the south. Elsewhere they are generally overlain by a thin layer of Cretaceous sediments. Hall[5] states that wherever the crystalline rocks have been encountered underneath the Cretaceous strata in drilling they have been found to be profoundly decomposed. Directly underneath the Cretaceous strata there is usually a layer of white clay varying in thickness up to 50 feet, which grades downward into decomposed granite or gneiss of yellow, red, or gray color. The Cretaceous itself consists principally of blue and red shale with some fine white quartz sandstone, products of decomposition of the underlying crystalline rocks. This decomposition indicates a long period of erosion previous to the deposition of the Cretaceous beds which probably extended through the Paleozoic and most of the Mesozoic era. That the residual material accumulated to such depths would indicate that the land surface during at least the latter part of the erosion period was low and comparatively level, though at the beginning of the Paleozoic there was probably considerable relief, as has already been stated.

The Sioux quartzite is exposed at a number of places in southwestern Minnesota and probably forms the bed rock in most of the southwestern corner of the state. It consists largely of red quartzite, but locally thin layers of red slate (pipestone) occur in it. While the quartzite is hard and indurated and has suffered some folding, ripple marks and cross-bedding are still visible in it.[6] Its relation to the granite, gneiss, and

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[3] Hall, C. W., Meinzer, O. E., and Fuller, M. L., *op. cit.* pp. 32-33.
[4] *Ibid.*, p. 33.
[5] *Ibid.*, p. 49.
[6] *Ibid.*, p. 32.

crystalline schists on the one hand and to the red clastic series on the other hand is not known. The Sioux quartzite may lie unconformably above the crystalline rocks, or the crystalline rocks may be in part intrusive into it. Its relation to the red clastic series also is not determined. Although apparently much more indurated and of somewhat different composition, it is not impossible that it may be of the same age as the red clastic rocks. Winchell and Upham[7] believed that the Sioux quartzite, the red clastic series, and the supposed upper Keweenawan sediments south of Lake Superior (the latter formerly believed to be the same as the upper Cambrian Lake Superior sandstone of Michigan), are all of lower Cambrian age. Hall[8] on the other hand states that the red clastic rocks are the southward continuation of the Keweenawan of the Lake Superior region but that the Sioux quartzite is not related to them. In general it has been held by geologists that the Sioux quartzite is probably of Huronian age.

Hornblende and biotite schist which are believed to be the southwestward continuation of the Huronian schist and slate which occur in east central Minnesota, have been encountered in well-drilling in the western part of the state north of Minnesota River.

The red clastic series of southern Minnesota is only known from deep drilling. Outcrops of it are wanting, the beds being everywhere covered either by drift or by a considerable thickness of Paleozoic sediments ranging in age from Upper Cambrian to Devonian. The red clastic beds consist principally of red sandstone and shale, but conglomerate beds also occur in it and volcanic clastic material is found locally. The finer sediments are found mainly in the upper part. The series apparently lies conformably beneath the known Upper Cambrian and unconformably above the pre-Cambrian crystalline rocks. Their age has not been determined, but because of their lithological similarity to the sandstone occurring on the south shore of Lake Superior in Wisconsin, which has recently been referred to the upper Keweenawan,[9] it is supposed that they are equivalent. The continuation of one into the other, however, has not been proven because of the scarcity of exposures in east central Minnesota and because of the general similarity between the red clastic rocks and the rocks forming the lower portion of the Upper Cambrian.

In northern Minnesota outcrops of pre-Cambrian rocks are abundant in many places, and a much more complex series of them has been found

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[7] Winchell, N. H., and Upham, W., *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.* vol. 1, pp. 422, 424, and 537. 1882.

[8] Hall, C. W., Meinzer, O. E., and Fuller, M. L., *op. cit.*, p. 48.

[9] Thwaites, F. T., *op. cit.*

to exist than occurs in the southern part of the state. There are Archean metamorphic and igneous rocks, Huronian intrusive rocks, and metamorphosed sediments, and Keweenawan intrusive and extrusive rocks and sediments. These rocks have been studied in considerable detail in several districts, particularly in the Mesabi and Vermilion iron-ore districts and along the north shore of Lake Superior.[10] They have been shown to be of great complexity both in structure and distribution. The Archean rocks are most abundant along the northern boundary of the state and to the southward Huronian and Keweenawan rocks appear with increasing prominence.

The Archean rocks are principally Laurentian granite and gneiss and Keewatin greenstone. The greenstone is either massive or schistose and locally contains metamorphosed sediments, such as iron-bearing formation in the Vermilion district and slate and graywacke in the Lake of the Woods region. In some localities the greenstone has suffered so little deformation that original structures are still clearly visible, while elsewhere it has been metamorphosed to such an extent as to be transformed into green chloritic schist. Large and small masses of Laurentian granite and gneiss occur intruded into the greenstone in the form of batholiths, bosses, and dikes. Much of the granite has been rendered gneissoid by later deformation and recrystallization so that now great areas in northern Minnesota are underlain by coarse gneiss and all gradations from granite to gneiss occur. In composition the Laurentian intrusives vary from granite to syenite and texturally both granitic and porphyritic types occur. Special phases of the intrusives are felsitic rocks, such as rhyolitic and trachytic porphyries.

Metamorphosed sedimentary rocks of lower-middle Huronian age are not very extensively distributed in northern Minnesota. In the Vermilion district this series is represented by the Ogishke conglomerate, iron-bearing Agawa formation, and Knife Lake slate. The conglomerate occurs at the base, and is overlain locally by Agawa iron-bearing formation, and above this is the Knife Lake slate.

The Ogishke conglomerate varies extremely in thickness in different parts of the district. It has been thoroughly indurated and locally pronounced metamorphism has resulted in the development of schistose phases while intense folding has brought about complex relations between it and the underlying Archean. The materials composing the conglom-

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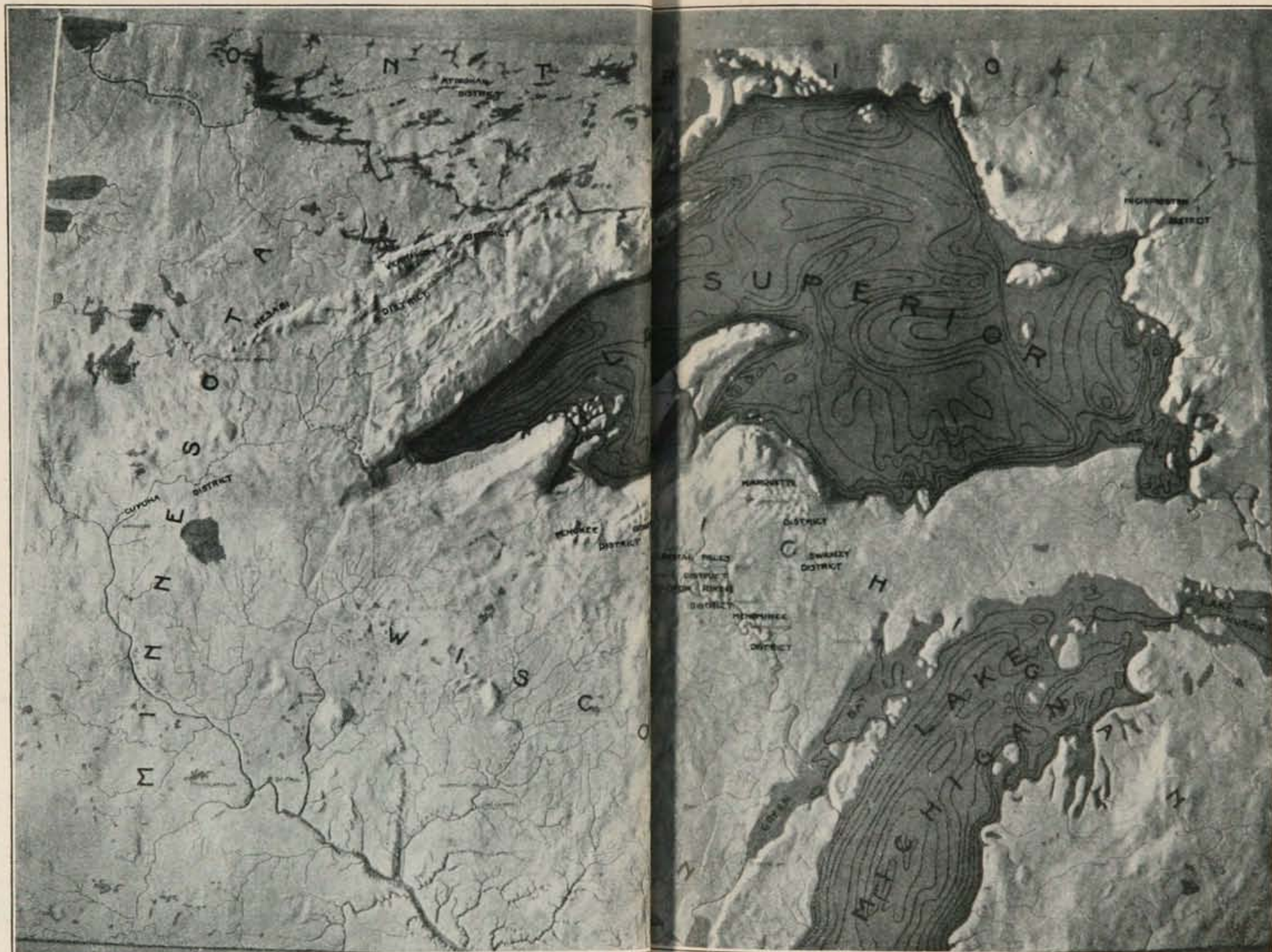
[10] Van Hise, C. R., and Leith, C. K., *op. cit.*, pp. 118-210.
Leith, C. K., The Mesabi iron-bearing district of Minnesota. *U. S. Geol. Survey, Mon.* 43. 1903.
Clements, J. M., The Vermilion iron-bearing district of Minnesota. *U. S. Geol. Survey, Mon.* 45. 1903.



RELIEF MAP OF THE LAKE SUPERIOR DISTRICT SHOWING THE IRON-ORE DISTRICTS, AFTER VAN HISE AND LEITH
SCALE, [illegible] MILES

erate have been derived from the underlying Keewatin and Laurentian rocks, pebbles of greenstone, granite, porphyry and jasper being found in it.

The Knife Lake slate covers considerable areas and is of great thickness. It includes many different phases such as argillaceous slate, biotitic, amphibolitic, quartzitic, and sericitic schists, graywacke, and conglomerate. Its metamorphism has been intense, and complex folding has resulted in the development of secondary structures, such as cleavage and schistosity, throughout the formation.

The iron-bearing Agawa formation occurs as thin lenses or layers below the Knife Lake slate and above the Ogishke conglomerate. It consists of ferruginous chert, jasper, and other iron-bearing rocks interbedded with layers of slate.

In the Mesabi district the lower-middle Huronian is represented by a thick series of slate, graywacke, and conglomerate. These rocks occur in local areas, being complexly infolded into the underlying Keewatin greenstone. Metamorphism has resulted in the development of cleavage and fissility, and in the formation of secondary minerals, such as sericite, biotite, and chlorite. The conglomeratic phases particularly show the effects of metamorphism in the elongation of pebbles and the recrystallization and alteration of minerals.

In general the lower-middle Huronian metamorphosed sediments have a complex distribution, occurring in local irregular areas with intricate structural relation with the underlying Archean. In some localities they appear to have suffered practically as much metamorphism as the Keewatin greenstone itself.

The lower-middle Huronian sediments are intruded by the Giants Range granite, principally a pink to gray hornblende granite, low in quartz, which occupies a large area north of the Mesabi district. Silicic intrusives of lower-middle Huronian age are abundant in many parts of the Lake Superior region. They are difficult to distinguish from the Laurentian intrusives, however, and it is only in the more recent detailed geologic work in which the relations between the intrusives and the associated metamorphosed sediments have been carefully studied that the separation has been possible.

On the eroded surface of the Archean and lower-middle Huronian rocks lie the much less deformed upper Huronian or Animikie beds. The Animikie group in northern and central Minnesota consists in general of a thick slate formation at the base of which are comparatively thin layers of iron-bearing formation and quartzite. The principal area of Animikie rocks in Minnesota begins at the international boundary near Gunflint Lake and runs southwestward as a narrow, discontinuous strip to the

Mesabi district where it widens and spreads out over most of east central Minnesota as far southward as Mille Lacs Lake. In the Mesabi district the Animikie rocks lie on the south slope of the Giants Range and have a gentle dip to the southeast. The Pokegama quartzite occurs at the base of the group. It is a thin but fairly continuous bed consisting of vitreous quartzite, which locally gives place to micaceous quartzitic argillite and elsewhere is conglomeratic.

The iron-bearing Biwabik formation which lies above the quartzite is somewhat thicker than the latter and is continuous throughout the length of the Mesabi district. It contains various common phases of the iron-bearing formation such as ferruginous chert of the form known as taconite, ferruginous slate, iron ore, greenalite rock, and quartz-amphibole-magnetite rock. The principal part of the iron-bearing formation consists of taconite. The ferruginous slate occurs in this as layers and lenses some of which are quite continuous and may be traced from mine to mine.[11] Quartz-amphibole-magnetite rock is found at the eastern end of the Mesabi district and has resulted from the metamorphism of the original iron-bearing formation by the Keweenawan gabbro intrusion. Iron ore occurs as local concentrations in the taconite, while remnants of greenalite rock are found in places where the iron-bearing formation has been protected from oxidation.

The Virginia slate, which overlies the Biwabik formation, consists of argillaceous and carbonaceous slate with local layers of siliceous slate and graywacke. It forms the main upper portion of the Animikie group throughout east central Minnesota, having a great but unknown thickness. In the Mesabi district this rock is usually soft and but slightly metamorphosed, although mica occurs in it locally. It shows no secondary cleavage, being really an argillite or indurated shale. South of the Mesabi district, however, along St. Louis River near Cloquet and Carlton, the slate, which in the past has been called "St. Louis slate," but which Van Hise and Leith referred to as the Virginia slate, has suffered metamorphism and deformation to a marked degree, as have also the slate and garnetiferous and staurolitic schist exposed along Mississippi River near Little Falls.

The schists, slates, and related rocks of the Cuyuna district and the adjacent region are also correlated with the Virginia slate by Van Hise and Leith and are believed to be of upper Huronian or Animikie age. They are principally sericitic, biotitic, and chloritic schist, slate, and phyllite with locally lenses of black, carbonaceous slate and some quartzite and

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[11] Wolff, J. F., Recent geologic developments on the Mesabi iron range, Minnesota. *Bull. Amer. Inst. Min. Engrs.*, Oct., 1916, pp. 1763-1787.

quartzitic schist. A prominent member of the series is the Deerwood iron-bearing member, which occurs as layers and lenses interbedded with the schist. The rocks of the Cuyuna district have been complexly folded into a series of close anticlines and synclines striking northeast-southwest. The beds usually have very steep dips either to the southeast or northwest, while the pitch of the folds is usually very low so that frequently the crests of the anticlines are horizontal for long distances. The rocks of the Cuyuna district will be described in more detail later.

Overlying the older rocks in northeastern and eastern Minnesota, and intruded into them, are rocks of Keweenawan age. The oldest of these are sedimentary beds supposed to be of lower Keweenawan age, which occur unconformably overlying the Animikie rocks at several places in northeastern Minnesota. Among them is the Puckwunge conglomerate found along St. Louis River west of Duluth.

The principal Keweenawan rocks of northern and eastern Minnesota are intrusive and extrusive igneous rocks of middle Keweenawan age. They form a large area extending along the north shore of Lake Superior from Duluth northeasterly into Canada, and a smaller area along the upper St. Croix River south of Lake Superior. The extrusive rocks occurring along the north shore of Lake Superior are mainly diabase amygdaloids, but important layers of felsite and quartz porphyrite occur locally. The principal intrusive rock is the Duluth gabbro which forms an extensive laccolith at or near the base of the lavas. Smaller sills and sheets of diabase, such as the Beaver Bay laccolith, are found intrusive in the volcanic rocks at several horizons. The rocks in the area along St. Croix River are mainly extrusive rocks of amygdaloid type, associated with crystalline phases, such as diabase, and with beds of tuff and volcanic breccia.[12] Thin layers of conglomerate occur locally.

Sediments of upper Keweenawan age are abundant along the south shore of Lake Superior extending from Superior eastward into northern Michigan. They consist mainly of red and white sandstone and arkose with increasing shale in the lower part and a thick conglomerate at the base. The upper portion of the series, recently classed as the Bayfield group of the upper Keweenawan,[13] has generally been called Lake Superior sandstone and included in the Cambrian,[14] while the lower portion, known as the Oronto group, has always been classed as upper Keweenawan. Certain of the formations in the Bayfield group, extend southwestward into Minnesota, but their extent and distribution are not

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[12] Grout, F. F., Contribution to the petrography of the Keweenawan: *Jour. Geology*, vol. 18, pp. 633-657. 1910.

[13] Thwaites, F. T., *op. cit.*

[14] Van Hise, C. R., and Leith, C. K., *op. cit.*, pp. 378-379, 415, 616.

known, due to lack of exposures. At some point east or southeast of Mille Lacs Lake they give place to the lower members of the fossiliferous Upper Cambrian series extending northward from southeastern Minnesota and western Wisconsin. This boundary has not yet been located. It seems probable that the red clastic series, which underlies the Upper Cambrian rocks in southeastern Minnesota, emerges from beneath the latter on going northward and comes to the bed rock surface in east central Minnesota. In this case it might be directly continuous with the Bayfield group extending southwestward from Lake Superior.

The Paleozoic rocks of southeastern Minnesota range from Upper Cambrian to Devonian in age.[15] They consist in general of interlayered, comparatively thin beds of sandstone, limestone, and shale. The upper beds, such as the Devonian, are found only in the southeastern part of the state while successively older formations come to the bed-rock surface on going northward. Thus the Platteville limestone and St. Peter sandstone constitute the principal surface rocks in the region adjacent to St. Paul and Minneapolis, while the Oneota and Shakopee dolomites and the upper members of the Upper Cambrian form outcrops along St. Croix River below Taylor's Falls. Above Taylor's Falls various Upper Cambrian strata occur along St. Croix River continuing northward until they give place to Keweenawan trap rock.

The Paleozoic beds are very uniform in character. For this reason and because of the abundance of fossils in them, even thin beds can be recognized over great areas. The lower portion of the Paleozoic section represents a fairly continuous period of deposition, although minor unconformities may occur.[16] A marked break, however, is found in the upper part, for the Devonian strata rest unconformably on the eroded surface of the Ordovician, indicating an erosion period covering the Silurian and part of the Devonian. The uniformity in the lithology and general character of the Paleozoic beds over large areas presents a strong contrast to the pre-Cambrian rocks of the State, which as a rule are most irregular in their lithology and stratigraphy.

The mantle of Cretaceous rocks, although thin, is fairly continuous throughout the western part of Minnesota, while isolated areas of various sizes occur also in the eastern part. In the southern and western parts of the State these rocks consist typically of thick beds of plastic gray-blue shale associated with thin beds of white sandstone.[17] The latter occur mainly in the upper and lower parts of the series. Locally beds of red clay are found.

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[15] Hall, C. W., Meinzer, O. E., and Fuller, M. L., *op. cit.*, pp. 31-48.

[16] *Ibid.*, p. 33.

[17] *Ibid.*, p. 42.

In the east central and northern parts of the State isolated patches of Cretaceous sediments are found in many places. In the Mesabi and Cuyuna districts they consist mainly of ferruginous conglomerate associated with argillaceous material. Elsewhere, however, as along Mississippi and Sauk rivers in the central part, beds of slightly consolidated calcareous clay and sand are found.

ROCKS OF EAST CENTRAL MINNESOTA

PREVIOUS GEOLOGIC WORK

The first geological investigations of any considerable importance made in east central Minnesota were those of R. D. Irving and E. T. Sweet in connection with similar work in northern Wisconsin.[18] The work was done between 1873 and 1879 and consisted in an examination of Keweenawan and Huronian rocks adjacent to the Wisconsin boundary. In a report[19] published in 1880, Irving stated his belief that the slates occurring along St. Louis River were to be correlated with the iron-bearing rocks of the Penokee region, and that they probably occupied the northern limb of a syncline of which the rocks of the Penokee district formed the southern limb. At this time no subdivision had as yet been made of the Huronian rocks and the schists, slates, and other metamorphosed sediments of northern and central Minnesota and neighboring regions were all grouped together as Huronian to distinguish them from the overlying Keweenawan and from the granite and gneiss, these three being the only subdivisions of the pre-Cambrian recognized at that time.

The investigations of the United States Geological Survey began in this region about 1880 under the direction of R. D. Irving assisted by C. R. Van Hise and W. N. Merriam. Brief reconnaissance surveys were made in the early 80's in central and northern Minnesota and the first general geologic map of the Lake Superior region to be published by the United States Geological Survey appeared in 1883.[20] On this map the Huronian metamorphosed sedimentary rocks of northern and eastern Minnesota, including those of the Vermilion district as well as

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[18] Irving, R. D., The geological structure of northern Wisconsin: *Geol. of Wis.*, vol. III, Survey of 1873-79, p. 18. 1880.

Sweet, E. T., Geology of the western Lake Superior district: *Geol. of Wis.*, vol. III, Survey of 1873-79, p. 334 et seq., 1880.

[19] Irving, R. D., *op. cit.*

[20] Irving, R. D., The copper-bearing rocks of Lake Superior: *U. S. Geol. Survey Third Ann. Rept.*, 1881-1882, p. 162 and Pl. III. 1883.

Irving, R. D., The copper-bearing rocks of Lake Superior: *U. S. Geol. Survey Mon.* 5, p. 384 and Pl. I. 1883.

those occurring along the Giants Range or Mesabi Range, are all grouped with the Animikie rocks of the north shore of Lake Superior, and the slates and schists occurring along St. Louis and Kettle rivers are connected directly with the Animikie rocks on the north shore. The Animikie rocks at this time apparently were regarded as a somewhat less metamorphosed phase of the other Huronian rocks without recognition of difference in age. Apparently it was not then recognized that the less metamorphosed rocks of the Mesabi district are younger than the highly metamorphosed slates and associated rocks of the Vermilion district.

In a later report accompanied by a general map,[21] Irving correlates the "St. Louis" slate with the slates and schists occurring along Mississippi River in the vicinity of Little Falls, and on the basis of this correlation an area of Huronian metamorphosed rocks is shown in east central Minnesota extending from Duluth southwestward to Mississippi River, including the present Cuyuna district and the northern part of Mille Lacs Lake. It is shown as being bounded on the south and west by areas of granite the age of which is not given, and on the north by a drift-covered area in which the bed rock is unknown. The area of Huronian rocks of east central Minnesota is not directly connected with the Animikie area extending from the Giants Range northeastward along the north shore of Lake Superior as was done in the previous report, but the statement is made that they are probably equivalent to them.

In 1888 Irving published a map of northeastern Minnesota[22] in which the Animikie rocks occurring along the Giants Range are mapped as extending southward into east central Minnesota without a break. On this map the metamorphosed sediments of the Vermilion district and of the international boundary are separated from the Animikie rocks of the north shore of Lake Superior and of the Giants Range because of their greater metamorphism, but it is believed nevertheless that they are equivalent in age, the difference in lithology being due to difference in the intensity of metamorphism. The granite and gneiss of northern and central Minnesota, which had hitherto been left unclassified, are placed in the Laurentian, and with them are grouped certain green schists and mica schists which were believed to be older than Huronian. The following classification of the pre-Cambrian rocks is used. It is of interest because it is the forerunner of the classification used at present by the United States Geological Survey for Lake Superior rocks.

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[21] Irving, R. D., Preliminary paper on an investigation of the Archean formations of the northwestern states: *U. S. Geol. Survey Fifth Ann. Rept.*, 1883-1884, pp. 196-197. 1885.

[22] Irving, R. D., Classification of early Cambrian and pre-Cambrian formations: *U. S. Geol. Survey Seventh Ann. Rept.*, 1885-1886, pp. 417-423. 1888.

Cambrian
  Potsdam sandstone
Keweenawan
  Volcanic flows and sediments
  Basal intrusive gabbro
Huronian
  Animikie series
  Vermilion Lake iron-bearing series
Laurentian
  Green schists
  Mica schists
  Granite

In 1892, C. R. Van Hise published a report on the pre-Cambrian rocks of North America, which contains a section on the geology of the Lake Superior region.[23] A general table shows the correlation of rocks in different parts of the region, the following subdivisions being used:

Algonkian
  Keweenawan
  Upper Huronian
  Lower Huronian
Archean
  Mareniscan
  Laurentian

This is a further stage in the development of the classification of Lake Superior pre-Cambrian rocks. As regards the application to the rocks of northern and central Minnesota, it is similar to those previously used except that the term Archean is substituted for Laurentian, the latter term being restricted to intrusive granite and gneiss, while a new term, Mareniscan, is used to cover the older metamorphic rocks, such as green schists and mica schists. The younger metamorphosed sediments (Huronian) which are grouped together with the Keweenawan under the general subdivision Algonkian, are definitely separated into two series, the earlier (lower Huronian) including the metamorphosed sediments of the Vermilion region, which had formerly been but indefinitely separated from the Animikie, and the later (upper Huronian) including the Animikie rocks and "St. Louis" slate. A map accompanying this discussion shows the general geology of the Lake Superior region and is very similar to the maps previously published. On it the "St. Louis" slate is shown as extending across east central Minnesota, including the present

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[23] Van Hise, C. R., Correlation papers: Archean and Algonkian: *U. S. Geol. Survey Bull.* 86, pp. 51-208. 1892.

Cuyuna district and Little Falls region, being bounded on the west and south by granite classified as Archean.

While this work was being done by the United States Geological Survey, N. H. Winchell, Warren Upham, and others of the Geological and Natural History Survey of Minnesota, were also engaged in extensive geological investigations in central and northern Minnesota. The work of the Minnesota survey began in 1872, but during the early years it was confined largely to the southern part of the state. Later, however, extensive investigations were made on the crystalline and metamorphic rocks of central and northern Minnesota. The work consisted chiefly in the mapping of rock outcrops[24] in this region, but attempts were also made by Winchell to correlate the various rock formations with similar rocks in the neighboring states, in Canada, and in New England.[25]

This resulted in the adoption of a somewhat different nomenclature from that used by geologists of the United States Geological Survey. The table on the following page shows the classification of Lake Superior rocks used by the Geological and Natural History Survey of Minnesota, as compared with that used later in reports of the United States Geological Survey.[26]

This classification was partly the outcome of work by Winchell in northern and eastern Minnesota, and partly of work by A. C. Lawson in the Lake of the Woods and Rainy Lake regions for the Geological and Natural History Survey of Canada.[27] Not only does the nomenclature itself differ from that used by the United States Geological Survey, but the position assigned to many of the rock formations in the stratigraphic series is radically different. Perhaps the most fundamental difference

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[24] Winchell, N. H., Upham, Warren, and others, *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vols. 2, 4, and 6. 1882-1901.

Upham, Warren, Notes of rock outcrops in central Minnesota: *Geol. and Nat. Hist. Survey of Minn. Eleventh Ann. Rept.*, pp. 86-136 and Pl. I. 1882.

[25] Winchell, N. H., The crystalline rocks of the northwest: *Geol. and Nat. Hist. Survey of Minn. Thirteenth Ann. Rept.*, pp. 124-140. 1884.

............, The crystalline rocks of Minnesota: *Geol. and Nat. Hist. Survey of Minn. Seventeenth Ann. Rept.*, pp. 5-74. 1888.

............, The crystalline rocks: *Geol. and Nat. Hist. Survey of Minn. Twentieth Ann. Rept.*, pp. 1-28. 1891.

[26] Winchell, N. H., Note on the age of the rocks of the Mesabi and Vermilion iron districts: *Geol. and Nat. Hist. Survey of Minn., Eleventh Ann. Rept.*, pp. 168-170. 1882.

............, Pre-Silurian rocks of Minnesota: *Geol. and Nat. Hist. Survey of Minn., Twenty-first Ann. Rept.*, Table opp. p. 4. 1892.

Winchell, N. H., Upham, Warren, and others, *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 6, Geological map—frontispiece. 1900-1901.

[27] Lawson, A. C., Report on the geology of the Lake of the Woods region, with special reference to the Keewatin (Huronian?) belt of Archean rocks: *Geol. and Nat. Hist. Survey of Canada, Ann. Rept. for 1885*, vol. 1 (new series) pp. 5-151. CC.

............, Report on the geology of the Rainy Lake region: *Geol. and Nat. Hist. Survey of Canada, Ann. Rept. for 1887-1888*, vol. 3 (new series) pp. 1-196 F.

............, Lake Superior stratigraphy: *Am. Geol.*, vol. 7, pp. 320-327. 1891.

in the two classifications is that the entire "Taconic series" is classed as Paleozoic by Winchell, being regarded as analogous to the so-called Taconic rocks of New England. The rest of the crystalline and metamorphic rocks are classed as Archean, no Algonkian being recognized. There is no distinction made by Winchell and Lawson between the rocks of the lower Huronian and those of the Keewatin, all being grouped together under the term Keewatin, while the Vermilion series included the Coutchiching rocks of Lawson, as well as various other crystalline schists of northern and central Minnesota. In this group, which Winchell at first designated as Montalban, were placed the garnetiferous and staurolitic schist found along Mississippi River near Little Falls, as well as certain gneisses occurring in Morrison County east of Little Falls. The Animikie of Winchell included the original Animikie rocks on the north shore of Lake Superior, the iron-bearing series of the Mesabi district, and the slates occurring along St. Louis River, but did not include the slates and schists of the Kettle River region, these being classed by Winchell as Keewatin on account of their greater metamorphism.

Minnesota Geological and Natural History Survey	*United States Geological Survey*
Paleozoic	*Paleozoic*
Upper Cambrian	Upper Cambrian
Taconic	*Algonkian*
Keweenawan (Nipigon)	Keweenawan
Upper	Upper
Brown sandstone	
Lower	Middle
Traps and amygdaloidal rocks	
Gabbro and anorthosite	Lower
Animikie	Huronian
Metamorphosed sediments, including Mesabi series, Sioux quartzite, and others	Upper
	Middle
Archean	Lower
Ontarian	
Keewatin	*Archean*
Sericitic and green schists, slate, graywacke, and other metamorphosed rocks of Vermilion district	Laurentian
	Kewatin
Vermilion (Montalban, Coutchiching)	
Holocrystalline hornblende and mica schists	
Laurentian	
Gneiss	

The slate, graywacke, and schist of St. Louis and Kettle rivers, and of the Little Falls region, which were all believed by geologists of the United States Geological Survey to be of approximately the same age, were not so regarded by Winchell, who grouped them under three different subdivisions, the more highly metamorphosed rocks being placed in the Archean and the less highly metamorphosed ones in the Taconic.

In 1894, J. E. Spurr published an article on the so-called "Thomson" or "St. Louis" slate[28] in which he brings forth various arguments why these slates should be classed as "Keewatin (lower Huronian)" rather than as Animikie (upper Huronian) as had been done hitherto. He bases his arguments chiefly on the lithological similarity of the "St. Louis" slate with what he calls "Keewatin (lower Huronian)" rocks of the Mesabi district, and on the fact that secondary structures, such as cleavage, seem to indicate that they suffered deformation by the same dynamic forces. In his paper the slates and schists of the Kettle River region and of the Little Falls region are also classed as "Keewatin (lower Huronian)" and are believed to be directly continuous with the "St. Louis" slate.

The first general report of the United States Geological Survey on the iron ores of the Lake Superior region was published in 1901.[29] It contains a short discussion of the general stratigraphy of the Lake Superior region, and more detailed descriptions of the geology of the Vermilion and Mesabi districts. The classification of the rocks is similar to that in present use, with the exception that the middle Huronian had not yet been recognized. The general terms Archean and Algonkian are used. The Archean includes the greenstones, various schists, and associated iron-bearing formation as well as the older granites and gneisses. The Algonkian is divided into (1) lower Huronian, which includes various highly metamorphosed sediments of the Vermilion and Mesabi districts, (2) upper Huronian, which includes the iron-bearing rocks of the Mesabi district and of the Gunflint area, and (3) Keweenawan, under which are grouped various later igneous and sedimentary rocks. It is recognized that not all the silicic igneous rocks of the region are Archean in age, but that later intrusive rocks occur such as the lower Huronian granite of the Giants Range. No special reference is made to the slates and schists of eastern and central Minnesota.

Various monographs of the United States Geological Survey describing the iron ores of the Lake Superior region, which were published between 1892 and 1900, contain discussions of the general geology of the

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[28] Spurr, J. E., The stratigraphic position of the Thomson slates: *Amer. Jour. Sci.*, 3d ser., vol. 148, pp. 159-166. 1894.

[29] Van Hise, C. R., The iron-ore deposits of the Lake Superior region: *U. S. Geol. Survey, Twenty-first Ann. Rept.*, pt. 3, pp. 307-434. 1901.

region, but the first ones which dealt directly with the geology of Minnesota were the monographs on the Vermilion and Mesabi iron-ore districts[30] which appeared in 1903.

In the monograph on the Vermilion district, the various intensely metamorphosed Huronian rocks of northern Minnesota are classified under subdivisions of the lower Huronian, while the greenstone, green schist, and associated iron-bearing formation are placed in the Keewatin series of the Archean. Silicic intrusives of two ages are recognized, those north of the Vermilion district being mapped as Laurentian, while those south of the district are mapped as lower Huronian.[31] The crystalline and metamorphic rocks of northern Minnesota were thus definitely correlated with similar rocks in northern Wisconsin and Michigan described in the earlier monographs.

In the monograph on the Mesabi district, the iron-bearing rocks are classed as upper Huronian while certain metamorphosed slates and graywackes included in the Archean by Winchell, Grant, and Spurr[32] of the Minnesota survey, are included in the lower Huronian. The Giants Range granite is classified as lower Huronian, while a supposedly later granite, the Embarrass granite, believed to be intrusive into the upper Huronian, is included in the Keweenawan.

An interesting discussion in the report deals with a possible connection between the upper Huronian rocks of the Mesabi district of Minnesota and those of the Penokee-Gogebic district of Michigan and Wisconsin.[33] It is accompanied by a map showing the hypothetical course of a possible iron-bearing belt extending southwestward from the western end of the Mesabi district for some distance and then turning and running eastward through the present Cuyuna district almost to Duluth, at which point it again turns, and after running southwestward for a considerable distance, makes several more turns and then connects with the western end of the Penokee-Gogebic iron-bearing belt. The existence of such a connecting belt was based on the similarity in lithology and succession of the rocks of the Mesabi district with those of the Penokee-Gogebic district, while its general trend was suggested by the structure of the Lake Superior syclinorium and by a number of scattered rock

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[30] Clements, J. M., The Vermilion iron-bearing district of Minnesota: *U. S. Geol. Survey, Mon.* 45. 1903.

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

[31] Clements, J. M., *op. cit.*, pp. 33 and 275-395.

[32] Grant, U. S., and Winchell, N. H., (Detailed geology of areas in northeastern Minnesota), *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 4, 1896-1898, pp. 346-580. 1899.

Spurr, J. E., The iron-bearing rocks of the Mesabi range in Minnesota: *Geol. and Nat. Hist. Survey of Minn., Bull.* no. 10. 1894.

[33] Leith, C. K., *op. cit.*, pp. 202-204.

outcrops. Its course through the Cuyuna district was determined by certain quartzite exposures near Dam Lake three miles south of the town of Kimberly, which are identical in lithology with the Pokegama quartzite of the Mesabi district. On the shore of Long Lake, southwest of Dam Lake, are outcrops of subsilicic igneous rocks which were presumed to be equivalent to the Archean greenstone of the Mesabi district and to underlie this quartzite. Variations in magnetic attraction had been reported at various times from localities in Crow Wing and Aitkin counties, and these were considered as additional evidence for drawing the supposed iron-bearing belt through the Cuyuna district. Leith at this time, following Spurr,[34] supposed that the slate outcrops at Carlton and Cloquet and at Little Falls were of lower Huronian age, and believed that they were southwest of the iron-bearing belt and within the area of the underlying lower Huronian and Archean. In the latter were included also the granite outcrops occurring at Staples, St. Cloud, and at various places west, south, and southeast of Mille Lacs Lake.

In more recent reports on the geology of the Lake Superior district by Van Hise and Leith,[35] prepared since the discovery of iron-bearing formation and iron ore in the Cuyuna district, the slates and schists of east central Minnesota are all classified as upper Huronian and are correlated with the Virginia slate of the Mesabi district. The slates occurring along St. Louis and Kettle rivers, the schists and associated metamorphosed rocks of the Cuyuna district, and the slates and schists found along Mississippi River near Little Falls are all believed to be more or less equivalent. The iron-bearing formation of the Cuyuna district is called the Deerwood iron-bearing member and is described as occurring in beds and lenses in the lower part of the Virginia slate. The base of the slate, however, is not known anywhere in eastern or central Minnesota, so that the underlying formations, whatever they may be, have not been discovered. The granite, gneiss, and other igneous rocks of central Minnesota which had previously been regarded as lower Huronian or Archean, are in this report classified as Keweenawan on account of their supposed intrusive relation to the upper Huronian slates.

Outside of east central Minnesota but few changes were made in the classification of the rocks. The Giants Range granite, however, and various highly metamorphosed sediments of the Mesabi and Vermilion districts which had hitherto been included in the lower Huronian are reclassified as lower-middle Huronian to correspond with the lower and middle Huronian of northern Michigan.

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[34] Spurr, J. E., The stratigraphic position of the Thomson slates: *Amer. Jour. Sci.*, 3d ser., vol. 148, pp. 159-166. 1894.

[35] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: *U. S. Geol. Survey, Mon.* 52, pp. 211-224. 1911.

................................, Pre-Cambrian rocks of North America: *U. S. Geol. Survey Bull.* 360, pp. 196-252. 1909.

GENERAL DISTRIBUTION AND LITHOLOGY OF THE ROCKS

A heavy mantle of glacial till covers the older rocks throughout east central Minnesota, obscuring their distribution and their relations to each other. Only here and there isolated masses of the underlying rocks project up through it. Such projections are mainly of harder rock, which formed hills and ridges above the general level of the surface on which the glacial material was deposited. Locally also the rivers have cut down through the glacial drift and exposed the underlying rock. Outcrops of bed rock are closely spaced in parts of Stearns, Sherburne, Benton, Morrison, Mille Lacs, Kanabec, Pine, and Carlton[36] counties, but in other counties, among them Crow Wing, Todd, Cass, and Aitkin, rock exposures are either entirely lacking or are relatively rare.

In the east central part of Minnesota, as has been mentioned, the bed rock consists mainly of ancient metamorphosed pre-Cambrian rocks. Paleozoic and Mesozoic rocks do not cover large areas. Probably they never extended over the entire area and where they were deposited they were nearly everywhere removed by erosion before the advent of the glacial epoch. Some Paleozoic rocks, however, occur in the area traversed by the lower courses of St. Croix and Rum rivers, and outliers of Mesozoic sediments are present in many places in the region traversed by Mississippi River.

The boundary between the pre-Cambrian rocks on the west and northwest and the Paleozoic rocks on the east and southeast, trends a little east of north through the south central part of the State, and continuing northward crosses Mississippi River into the southeastern part of Sherburne County. From there the boundary continues in the same general northeast direction to the upper St. Croix River, but its location has not been definitely established. As already stated, the Keweenawan sediments which extend southwestward from the west end of Lake Superior are very similar lithologically to the sediments forming the lower part of the Paleozoic, and have not as yet been separated from them in this region. Fossiliferous Paleozoic sediments have been identified as far north as the southern part of Pine County, while sediments classed as upper Keweenawan[37] are definitely known as far south as the southern part of Carlton County, and probably they extend some distance farther. Numerous outcrops of red, pink, and white sandstone occur in eastern Kanabec and western Pine counties, but since fossils have not been found

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[36] Hall, C. W., Keewatin area of eastern and central Minnesota: *Geol. Soc. America Bull.* vol. 12, pp. 343-376. 1901.

Upham, Warren, Notes on rock outcrops in central Minnesota: *Geol. and Nat. Hist. Survey of Minn., Eleventh Ann. Rept.*, pp. 86-136 and Pl. I. 1882.

[37] Thwaites, F. T., Sandstones of the Wisconsin coast of Lake Superior: *Wis. Geol. and Nat. Hist. Survey Bull.* 25. 1912.

at any of these localities it has not been possible to determine the age of these rocks. There is thus in east central Minnesota an area of sandstone of undetermined age between the northernmost known Paleozoic sediments and the southernmost known sediments of supposed upper Keweenawan age.

The Paleozoic sediments in the southern part and the Keweenawan sediments and igneous rocks in the northern part of east central Minnesota form the eastern margin of an extensive area of pre-Cambrian metamorphosed sediments and igneous rocks. On the west, these older, metamorphosed rocks are covered by nearly flat-lying, partly consolidated Cretaceous sediments. The eastern limit of the main Cretaceous area is west of Mississippi River. The boundary is a very irregular one, patches of Cretaceous rock occurring in many places within the area of older rocks both east and west of Mississippi River.

The following is a tentative section of the rocks of east central Minnesota, essentially that employed by the United States Geological Survey.[38]

Section of Rocks for East Central Minnesota

Quaternary
- Recent
  - Alluvium
- Pleistocene
  - Late Wisconsin till
  - Early Wisconsin till

Cretaceous
- Yellow and gray clay and sand, in part calcareous
- Ferruginous conglomerate

Cambrian
- Upper Cambrian
  - Sandstone and shale

Algonkian
- Keweenawan
  - Intrusives. Granite, syenite, diorite, diabase, and gabbro
  - Pink and red sandstone and arkose
  - Volcanic flows. Amygdaloid, tuff, breccia, and diabase
- Huronian
  - Upper Huronian (Animikie group)
    - Virginia slate (including "St. Louis" slate and slates and schists of Cuyuna Range and Little Falls area)—quartzitic, carbonaceous, micaceous, chloritic, amphibolitic, garnetiferous, and staurolitic schist and slate with lenses of graywacke, quartzite, grit, limestone, and Deerwood iron-bearing member, with which are associated masses of metamorphosed subsilicic igneous rocks

[38] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: *U. S. Geol. Survey Mon.* 52, pp. 595-626 and 211-224. 1911.

Lower-middle Huronian (possibly present)
Granite (equivalent to Giants Range granite)

Archean (possibly present)
Granite and gneiss

No rocks of undoubted Archean age occur in east central Minnesota. There are, however, in Cass, Todd, Morrison, Stearns, Sherburne, Benton, Mille Lacs, Kanabec, Aitkin, and Pine counties, numerous outcrops of granite and gneiss the age of which has not been definitely determined. Some of the granite in the eastern part of this area is intruded into schist believed to be of upper Huronian age and is therefore, post-upper Huronian. Other granites, especially those in the western part of the area, give some indication of being lithologically and areally related to the lower-middle Huronian Giants Range granite of the Mesabi district.

Besides these, however, there are many outcrops of coarse gneissoid granite, banded gneiss, and augen-gneiss which resemble the Archean rocks more closely than any of the later intrusives. Banded gneisses and gneissoid granites are prominently exposed on Hillman Creek and Skunk River in Morrison County, on Rum River in Mille Lacs County, and along the Minneapolis, St. Paul, and Sault Ste. Marie Railway west of Denham and elsewhere in Pine County. Augen-gneiss occurs in a series of outcrops near McGrath and Arthyde in Aitkin County, and near Denham in Pine County.

Outcrops of subsilicic igneous rocks are also found in east central Minnesota, but less abundantly than those of silicic rocks, and most of them represent intrusions into the upper Huronian schists. They are, therefore, probably related to the subsilicic intrusives of Keweenawan age which occur so abundantly north and south of Lake Superior. In a number of places, however, outcrops of subsilicic rock occur of which the relationship is not clear. This is especially true of the diabase and diorite exposures occurring along the shores of Long Lake in Aitkin County and at various localities in Carlton County. Winchell[39] correlated the rocks cropping out at Long Lake with the Keewatin greenstone of the Vermilion district in northern Minnesota, while Van Hise and Leith[40] have classified them as Keweenawan. Recent exploration in the Cuyuna district, however, has shown that similar rocks occur both intrusive into and interbedded with upper Huronian schists in this district. It has been found also that many of these rocks have suffered considerable dynamic metamorphism. Therefore it seems probable that subsilicic rocks of upper Huronian as well as Keweenawan age occur in

[39] Winchell, N. H., The Cuyuna iron range: *Econ. Geology*, vol. 2, pp. 565-571. 1907.
[40] Van Hise, C. R., and Leith, C. K., *op. cit.*, Pl. I.

east central Minnesota, but the existence of Archean subsilicic igneous rocks in this region seems doubtful.

There is thus considerable uncertainty as to whether Archean rocks are found in east central Minnesota. Since, however, the age of most of the silicic igneous rocks in this region has not been determined and since rocks similar to those which exist here are known to occur in the areas of Archean rocks in the southwestern and northern parts of the state, it does not seem improbable that some of the silicic intrusive rocks of east central Minnesota are of Archean age.

No rocks of known lower or middle Huronian age have been found in east central Minnesota. The granite outcrops of Cass and Todd counties, which will be described later, present certain similarities, however, to the Giants Range granite of the Mesabi district and may be continuous with it. This view is supported by the fact that granite has been encountered in drilling at several localities between the western end of the Mesabi district and the Cass and Todd county outcrops. Among the other outcrops of silicic igneous rocks of undetermined age in east central Minnesota many may be of lower-middle Huronian age as well.

The most interesting rock exposures of east central Minnesota as regards structure and correlation are those of metamorphosed sediments which occur in various parts of the region and which have been classed as upper Huronian or Animikie in age. The most important of these are the slate, graywacke, phyllite, and mica schist outcrops occurring along St. Louis and Kettle rivers in Carlton and northern Pine counties, the quartzite outcrops at Dam Lake, south of Kimberly, Aitkin County, and the slate, phyllite, and mica, staurolite and chlorite schist outcrops occurring along Mississippi River and a few of its branches in Morrison County. Drilling and mining operations in the Cuyuna iron-ore district have shown the presence of an extensive area of metamorphic rocks, covered by glacial drift in central Crow Wing and western Aitkin counties. Most of the metamorphosed rocks which have been found in east central Minnesota are of sedimentary origin, but some of them have a structure, distribution, and general character that strongly suggest an igneous origin.

The outcrops in Carlton and Pine counties consist mainly of slate, graywacke, phyllite, and mica and hornblende schists. Slate, graywacke, and phyllite occur in the northern part, at Carlton and Cloquet, while to the south phyllite and coarse mica schist occur near Moose Lake and northeast of Denham, and hornblende schist is found at several localities along Kettle River west of Moose Lake. South of Denham, near the southern edge of the main region of metamorphosed sediments, there occurs a series of interbedded mica and amphibole schist, quartzite, grit, and crystalline limestone which is bounded on the south by an extensive area of gneiss. The strike of the sedimentary structures throughout this region is approximately east and west, while the dips vary on each side of vertical.

The detailed work on the outcrops of Pine and Carlton counties is not yet completed and the general structure has not been definitely determined. The rocks appear to lie in a series of east-west trending folds with horizontal or slightly eastward or westward pitching axial lines. Probably the predominating pitch of the folds is to the east indicating that to the west rocks of lower stratigraphic horizons may be expected to occur. The largest folds found up to the present have a width of several miles and numerous minor folds down to fine crenulations occur on their limbs.

The quartzite outcrops at Dam Lake consist of light gray to pink quartzite. They show no bedding or secondary structures by which their relation to the other rocks of central Minnesota might be determined.

The schist and slate outcrops along Mississippi River grade from finely micaceous slate and phyllite near Little Falls to coarsely crystalline, garnetiferous and staurolitic biotite schist in the southern part of Morrison County. Where it is possible to distinguish the bedding as at the mouth of Little Elk River, and at Little Falls, the strike of the rocks is in general northeast-southwest. The dips vary due to undulatory folding.

Northwest of Little Falls near Randall several areas of outcrops consisting of chloritic schist occur not far from Little Elk River, 8 to 10 miles above its mouth. These rocks have the same strike as the slate beds of Little Falls, and apparently form a belt running parallel to and northwest of the slate belt.

No connection has been demonstrated between the slate and mica schist near Little Falls and that occurring near Carlton and Moose Lake. As they are found approximately along the same general line of strike, however, it is possible that they may be continuous. This view is somewhat strengthened by the fact that, in recent exploration work in the Cuyuna district, the chloritic schist occurring at Randall has been shown to continue northeastward through Crow Wing County and for some distance into Aitkin County. If the slate and mica schist belt follows along parallel to the chloritic schist belt and southeast of it, as might be expected, this would bring it to within a comparatively short distance of the exposures at Moose Lake and Carlton. Drilling in T. 45N., R. 24W., about 10 miles east of the north end of Mille Lacs Lake has shown the presence of mica schist in this intervening area.

The relation of the slate, phyllite, and schist of east central Minnesota to the Virginia slate in the Mesabi district has not been determined.

As regards the metamorphism and deformation which they have suffered, the contrast between them is great. While the Virginia slate has a gentle dip to the south and shows little or no secondary cleavage, being practically an indurated shale, the slate and schist of east central Minnesota have been closely folded and highly metamorphosed so that cleavage is developed throughout, and locally the mineral constituents have been coarsely recrystallized. Van Hise and Leith, however, believe that the Virginia slate continues southward from the Mesabi district into east central Minnesota where it is represented by these metamorphosed phases. But since no rock outcrops are known for at least 40 miles south of the Mesabi district, certain correlation is difficult. It is not impossible that the schist and slate of east central Minnesota are of middle or lower Huronian age. In their general character and in the deformation which they have suffered they resemble the older rocks very closely.

The metamorphosed sediments have been intruded by both silicic and subsilicic igneous rocks in many parts of east central Minnesota. Subsilicic rocks, such as gabbro, diabase and diorite, are especially common in the western portion. Silicic rocks such as biotite granite, occur more abundantly in the eastern portion. The igneous rocks are in the form of dikes, bosses, and irregular masses. Since the metamorphosed sediments are believed to be of upper Huronian age, these intrusives have been designated as Keweenawan. They are believed to be the vents through which were poured out the lavas that at present occupy the valley of the upper St. Croix River and which in former times probably extended westward over a considerable portion of east central Minnesota.

There are a number of localities in east central Minnesota where subsilicic igneous rocks which have suffered considerable dynamic metamorphism occur. These, as has been mentioned, are believed to be older than Keweenawan, being associated with the upper Huronian metamorphosed sediments and probably representing contemporaneous flows or slightly younger intrusive masses. They have been deformed and metamorphosed with the associated sediments.

The Keweenawan rocks occuring along the upper St. Croix River are mainly of the subsilicic extrusive type, including diabase, diabase amygdaloid, tuff, and breccia.[41] Interlayered with these are local beds of conglomerate. A general characteristic of the lava beds is that each bed

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[41] Grout, F. F., Contributions to the petrography of the Keweenawan: *Jour. Geology*, vol. 18, pp. 633-657. 1910.

Hall, C. W., Keweenawan area of eastern Minnesota: *Bull. Geol. Soc. America*, vol. 12, pp. 313-342. 1901.

Berkey, C. P., Geology of the St. Croix dalles: *Amer. Geol.*, vol. 20, pp. 345-383, 1897, and vol. 21, pp. 139-155 and 270-294, 1898.

consists of three texturally distinct phases of rock. The lower few inches usually consist of dense, finely crystalline, finely shattered rock. Above this is the main mass of the flow which is usually medium coarsely crystalline, distinctly ophitic in texture, and is free from amygdules or other cavities. The crystalline phase grades upwards into an amygdaloidal portion which represents the surface of the flow. Locally the upper portions of a flow may be tuffaceous or brecciated, while in other places important layers of volcanic clastic rocks are interbedded between successive flows. The coarseness of crystallization of the main mass of the flow depends largely on the thickness. Some of the more extensive flows, which range up to two hundred feet in thickness, are fairly coarsely crystalline.

The conglomerate layers are usually thin and are very local in their occurrence. At several localities, however, beds as thick as one hundred feet have been reported.[42]

The St. Croix area of Keweenawan lavas is delimited on the west by a fault which extends northeastward toward Lake Superior, forming the boundary between the eastward dipping Keweenawan lavas, on the southeast, and the horizontally bedded, non-fossiliferous sandstone of supposed upper Keweenawan age, already mentioned, on the northwest. Because of this fault it has been impossible to determine the relation which these two formations bear to each other.

In many places in eastern Minnesota outcrops of horizontally bedded sandstone, designated as "Hinckley sandstone," "Potsdam sandstone," and "St. Croix sandstone," have been reported by geologists of the early Geological and Natural History Survey of Minnesota.[43] The outcrops designated as "Hinckley sandstone" or "Potsdam sandstone" are for the most part non-fossiliferous, and, as has been mentioned, many of these probably are to be correlated with the Bayfield group of the upper Keweenawan. In the southern part of the region, however, especially along St. Croix River, there are numerous outcrops of fossiliferous sandstone designated as "St. Croix sandstone," which are probably equivalent

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[42] Hall, C. W., *op. cit.*, pp. 326 and 329.

[43] Upham, Warren, The geology of Mille Lacs and Kanabec counties: *Geol. and Nat. Hist. Survey of Minn.*, vol. 2 (Geology) 1882-1885, pp. 612-628. 1888.

Upham, Warren, The geology of Chisago, Isanti, and Anoka counties: *Geol. and Nat. Hist. Survey of Minn.*, vol. 2 (Geology) 1882-1885, pp. 399-425. 1888.

Upham, Warren, The geology of Pine County: *Geol. and Nat. Hist. Survey of Minn.*, vol. 2 (Geology) 1882-1885, pp. 629-645. 1888.

Winchell, N. H., The geology of Carlton County: *Geol. and Nat. Hist. Survey of Minn.*, vol. 4 (Geology) 1896-1898, pp. 1-24. 1899.

Upham, Warren, The geology of Aitkin County: *Geol. and Nat. Hist. Survey of Minn.*, vol. 4 (Geology) 1896-1898, pp. 25-54. 1899.

Winchell, N. H., The geology of the southern portion of St. Louis County: *Geol. and Nat. Hist. Survey of Minn.*, vol. 4 (Geology) 1896-1898, pp. 212-221. 1899.

to certain of the lower formations of the Upper Cambrian. Fossiliferous sandstones are found along St. Croix River as far north as Rush Creek, a short distance below the mouth of Snake River. Similar flat-lying sediments in which, however, fossils have not been found, occur for some distance north of this point, continuing beyond the mouth of Kettle River.

There is thus along St. Croix River an area of flat-lying sandstone which toward the south contains fossils of Upper Cambrian age. This area is bounded on the west by steeply eastward dipping Keweenawan flows with interlayered conglomerate. Beyond the volcanic rocks, separated from them by a fault, is another belt of flat-lying sandstone, which, however, is non-fossiliferous. It has generally been supposed that these two sandstones are of approximately the same age, and hence they have usually been mapped as one formation. More recent study, however, indicates that eventually a separation may be made between them, throwing the non-fossiliferous sandstone into the Keweenawan.

Slightly consolidated Cretaceous sediments are known to occur at a number of localities in east central Minnesota. Exposures are found at a few places south of Little Falls along Mississippi River and west of it, while in the Cuyuna district these rocks have been encountered in drilling and mining operations. The exposures along Mississippi River consist principally of sandy and calcareous clay. Some portions are slightly consolidated, while other portions are quite soft. Locally beds occur containing little ferruginous concretions. The Cretaceous rock encountered in exploration work in the Cuyuna district is principally ferruginous conglomerate and shale.

DESCRIPTIONS OF ROCK OUTCROPS

OUTCROPS OF SILICIC IGNEOUS ROCKS

SOUTHERN CASS, TODD, AND WESTERN STEARNS COUNTIES

The westernmost outcrops of silicic igneous rocks in central Minnesota are those occurring in the southwestern corner of Cass County, northeast of Staples, those occurring near Long Prairie River south of Staples in Todd County, and those occurring in the vicinity of Sauk Center and Melrose, and in Ashley township, in the western part of Stearns County.

The exposures northeast of Staples are scattered over a prominent ridge north of Crow Wing River, and occupy an area about half a mile long. The principal rock of these exposures is a pink to greenish, light-colored, medium-grained hornblende granite. In some phases of it, quartz and feldspar are almost equally abundant, but in other phases quartz is exceedingly rare and the rock grades into syenite. In this respect it resembles the Giants Range granite of the Mesabi district. The principal ferromagnesian mineral is green hornblende, but biotite is present in some phases. The granite is intruded by dikes of dark green rock of intermediate composition. The dikes are fine-grained along the contacts but are medium-grained in the center. They vary in thickness up to thirty or forty feet. Both the granite and the green dikes are strongly epidotized.

The group of outcrops in Todd County is located in the west township of Ward about 1 mile west of Long Prairie River, and about 5 miles northeast of Browerville.[44] There are several exposures. The rock is described by Upham as a medium-grained gray syenite consisting mainly of quartz, feldspar, and dark hornblende. It is somewhat similar to the rock found northeast of Staples and resembles it also in being epidotized.

In the northwestern part of Stearns County three groups of outcrops occur near the towns of Sauk Center and Melrose, and in the township of Ashley. The outcrops in Ashley township consist of numerous exposures south of Ashley Creek.[45] The rock resembles syenite but has been strongly epidotized so that no hornblende or mica remains, and it consists mainly of feldspar and epidote. The Sauk Center outcrops are found a short distance southeast of the depot. Several varieties of rock occur, the principal one being a feldspathic reddish gneiss, laminated in a northeast-southwest direction. Associated with the gneiss are reddish syenite and masses of pink quartz-feldspar pegmatite. Several exposures of a hard, dark, granular hornblende feldspar rock occur, probably syenite. The outcrops at Melrose are within the village, south of Sauk River. They consist of hard, coarse, red syenite. In the western part of the village a well is said to have been sunk in a dark, coarsely crystalline hornblende rock.[46]

In the eastern part of Cass County, southeast of Leech Lake, drilling has shown the occurrence of granite in three localities along a line running southwestward from the western end of the Mesabi district. This rock has been mapped by Van Hise and Leith[47] as Giants Range granite and is supposed to be continuous with that in the Mesabi district. On the other hand, the granite outcrops at Staples, as well as numerous other outcrops to the south and southeast, have been mapped by them as Keweenawan on the supposition that they are intrusive into the upper Huronian schist and slate. However, this intrusive relation has been definitely established for only a few of the outcrops of silicic igneous rocks in

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[44] Upham, Warren, The geology of Wadena and Todd counties: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 2, 1882-1885, pp. 568-569.

[45] Upham, Warren, The geology of Stearns County: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 2, 1882-1885, pp. 452-454.

[46] Upham, Warren, *op. cit.*

[47] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: *U. S. Geol. Survey Mon.* 52, Plate I.

central Minnesota, and since lithologically the Cass County and Todd County outcrops resemble the Giants Range granite it is not impossible that they may be of the same age, viz., lower-middle Huronian.

MORRISON COUNTY

In Morrison County outcrops of silicic igneous rocks are abundant, especially in the central and eastern part, east of Mississippi River. The principal exposures occur in an area approximately 18 miles long, east and west, and 12 miles wide north and south, but small isolated outcrops are found outside of this area.

Several small exposures of medium to coarse-grained syenite are found on the east bank of Mississippi River in Little Falls, about a quarter of a mile below the dam and approximately opposite the lower part of the island which occurs in the river at this place. The rock consists of hornblende and feldspar, the former locally altered in part to epidote and the latter to zoisite, epidote, muscovite, and quartz. Some quartz and biotite occur in the rock also. Locally chlorite is found as an alteration product of biotite and hornblende. Apatite and titanite are accessory minerals. The occurrence of this igneous rock within a short distance of the slate and phyllite outcrops at the dam and on the island would seem to indicate that it is intrusive into the sedimentary rocks. No actual contacts, however, have been found.

An important group of granite and gneiss outcrops is that occurring in the eastern part of Morrison County on Platte River, Skunk River, and Hillman Creek. In general these are of gray and pink biotite and hornblende granites, locally somewhat gneissoid in texture. A few outcrops of banded gneiss are found.

The northernmost of these outcrops is a group of exposures occurring on both sides of the east-west township road between section 34, T. 42N., R. 31W., and section 3, T. 41N., R. 31W. Two types of granite occur in these exposures, a medium fine-grained grayish brown or brown decomposed biotite granite, considerably epidotized, and a grayish pink or pink hornblende granite. The former has a fairly uniform grain, but the latter varies in texture from fine-grained to very coarse-grained, almost pegmatitic, and also shows porphyritic phases. The hornblende granite appears to be intrusive in the biotite granite.

In the northwest corner of section 1, T. 41N., R. 31W., and the southwest corner of section 36, T. 42N., R. 31W., about 1½ miles east of the outcrops just described, and one mile north of Freedhem, there are a number of exposures of fine-grained, dark gray, biotite granite mixed with a pinkish, medium to coarse-grained granite which usually contains both biotite and hornblende. From the relations it appears that the pink granite is intrusive as dikes and irregular masses into the dark gray granite which is by far the more abundant. The pink granite contains much pink feldspar while the dark gray granite is rich in quartz and biotite. The rocks crop out in a swamp both north and south of the township road.

Near the center of section 6, T. 41N., R. 30W., about 1½ miles south of east from the outcrops just described, are a few scattered outcrops consisting principally of fine to medium-grained, dark gray biotite granite, rich in quartz, which is intruded by dikes of coarse-grained, pink biotite granite. In general the rocks resemble those occurring one mile north of Freedhem but apparently little or no hornblende is present in the pink granite.

A group of exposures of considerable extent occurs north and south of the section line between sections 7 and 18, T. 41N., R. 30W., some distance east of the quarter post. It is located about 1½ miles south of the outcrops in section 6. Two kinds of rock are present, (1) a dark gray, fine to medium-grained biotite granite, and (2) a medium to coarse-grained pink biotite granite. There is a sharp line of division between these two types marked approximately by a diagonal road which cuts across the two sections in a northeast-southwest direction. To the southeast of the road the outcrops are of pink granite, while to the northwest they are of dark gray granite. The pink granite is found also as small irregular intrusions in the gray granite. A small quarry occurs in the area of the gray granite. The dark gray granite consists of fresh, glassy, colorless feldspar and quartz with abundant biotite and some hornblende. Locally hornblende predominates over biotite. The hornblende in places is slightly altered to epidote and the biotite to chlorite. The pink granite consists mainly of pink feldspar and biotite, but quartz is present in small amounts.

In sections 23 and 24, T. 41N., R. 31W., about 1½ miles north of the locality known as Gravelville, and about 2 miles southwest of the outcrops just described, a large number of granite exposures occur in an area of about one square mile. The principal exposures form a prominent ridge surrounded on three sides by low marshy areas. Some smaller exposures occur within the marshy areas. Several types of granite are present, the principal one being a dark gray, medium-grained granite with abundant hornblende and considerable biotite. Next to this in abundance is a coarse pink biotite granite which seems to be intrusive into the hornblende granite, but which since intrusion has suffered deformation. Besides these types a fine-grained black granite occurs which contains both hornblende and biotite, the former epidotized, while a fourth type consists of fine-grained pink biotite granite, in places porphyritic. These various types are irregularly intermixed and grade into each other. The medium-grained, dark gray hornblende granite is much more abundant than the other phases. At one point a small quarry occurs in it and here the rock is quite fresh, showing only a slight alteration of the ferromagnesian minerals to epidote and chlorite. The pink granites appear to be intrusive into it, although the occurrence is very irregular. The coarse and fine-grained varieties of pink granite have a similar mineral composition and are probably phases of the same rock. They contain little or no hornblende. The fine-grained black granite is not very abundant. It occurs mainly in the form of irregular included masses in the hornblende granite.

A considerable number of outcrops of silicic igneous rocks occur on Skunk River and Hillman Creek, east of Little Falls. The area through which the outcrops are scattered is about 15 miles long in a northeast-southwest direction, and about 6 miles wide. The town of Pierz is in the southwestern part of the area. Most of the outcrops occur on the streams or within a short distance from them. As a rule the rocks do not rise far above the surface of the soil and in a few localities they have been exposed only by quarrying.

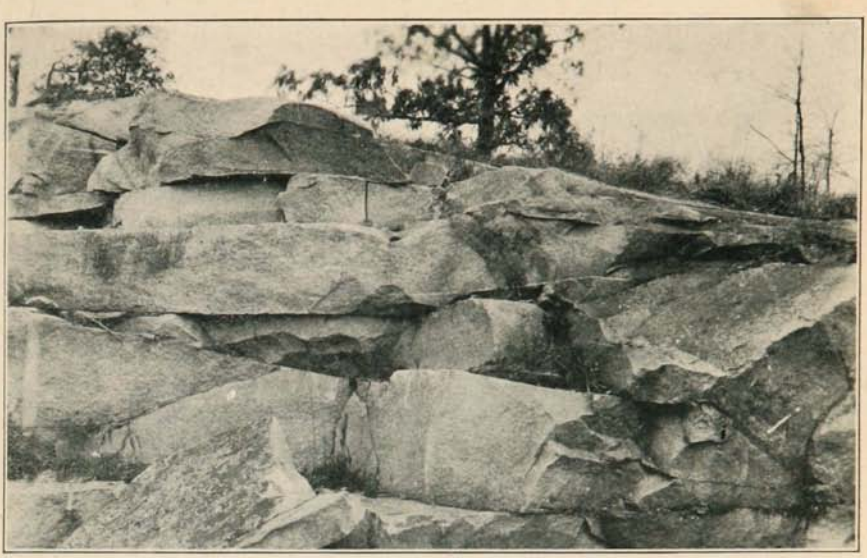
The westernmost of these outcrops is at Meyer's quarry south of Fish Lake and about a mile west of the station of New Pierz. A very uniform, fine-grained, light gray, biotite granite occurs here and some of it has been quarried. There are no outcrops other than those in the quarry.

Several other granite outcrops are found not far from the village of Pierz, one occurring on Skunk River near the station of New Pierz, another one near the junction of Hillman Creek with Skunk River east of Pierz, and a third one along the Minneapolis, St. Paul, and Sault Ste. Marie railroad, about 2½ miles east-northeast of the station of New Pierz.

The first of these is an outcrop of medium-coarse, light gray, biotite granite, about 50 feet long and 60 feet wide. It is situated about a fifth of a mile southeast of the railroad station on the east bank of Skunk River.

The second outcrop is located on the south side of Skunk River about a fourth of a mile above the mouth of Hillman Creek. Several exposures of gray, banded biotite gneiss are found here. Most of the rock is fine-grained and dark, but layers of coarse-grained, light-colored rock occur interbanded with the fine-grained rock. Disseminated crystals of garnet similar to those occurring in the gneiss at Granite City, farther up Skunk River, are abundant. At one point a dike of medium-coarse grained pink syenite cuts the gneiss.

The third one of the outcrops near Pierz occurs in a railroad cut near the west side of section 10, T. 40N., R. 30W. The rock is mainly light



A. GRANITE OUTCROP AT MEYERS QUARRY NEAR PIERZ, MORRISON COUNTY,
SHOWING HORIZONTAL JOINTING
PHOTO BY CARL ZAPPFE

B. INCLUSIONS OF DARK GRAY GRANITE IN PINK GRANITE AT GRAVELVILLE,
MORRISON COUNTY

to dark gray, medium coarse-grained biotite granite. Locally it shows a marked gneissoid texture due to the parallel arrangement of biotite flakes and their segregation along certain bands. Small dikes of light-colored aplite cut the granite.

Besides these another outcrop of granite is mentioned by Upham[48] as occurring in the southwestern part of section 22, T. 40N., R. 30W. The rock is said to have been quarried. No indications of this outcrop, however, were found by one of the writers (Johnston) who visited the locality.

About 8 miles up Skunk River, northeast of Pierz, is a locality known as Granite City where a saw mill and village existed previous to the Indian outbreak of 1862. Outcrops of coarse-grained gray granite and of gray and white banded gneiss occur at this place on both sides of the river. The granite contains quartz, biotite, and white feldspar in approximately equal amounts. Locally the feldspar predominates, however, and occurs in somewhat larger grains, so that it gives the rock a porphyritic appearance. In places the biotite shows a tendency to parallel arrangement, thus giving gradations into gneiss. Dikes of medium fine-grained aplite are found in several places in the granite.

The gneiss occurs as bands bounded by granite. It consists of interlayered fine and coarse-grained material. The coarse-grained layers consist mainly of quartz and feldspar and are usually white or light-colored, while the fine-grained layers contain abundant biotite and are dark gray. At many places the fine-grained layers show fine lamination due to the parallel arrangement of biotite. Locally also they contain fine, light-colored laminae of fine-grained feldspar, or quartz and feldspar. The dark and light-colored layers in the gneiss vary in thickness up to perhaps an inch or more, the dark fine-grained layers being thicker and making up more of the rock. Red garnet is abundant locally in the gneiss, usually occurring in the fine-grained layers as scattered crystals. Hornblende does not occur ordinarily as a constituent either in the granite or gneiss, but locally it is found in the latter in large crystals scattered through certain layers similarly to the garnet.

In the NE¼ of the SW¼ of section 11, T. 41N., R. 29W., about 3 miles northeast of the Granite City locality just described, a small outcrop of granite occurs in the road. The rock consists of fine to coarse-grained gray biotite granite similar to that at Granite City, and contains a few small lenses of pegmatitic material. No gneiss occurs in this outcrop.

In the SW¼ of section 12, T. 41N., R. 29W., at a locality known as Rucker, several small outcrops of rock are found along the west side

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[48] Upham, Warren, The geology of Crow Wing and Morrison counties: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 2, 1882-1885, pp. 580-611.

of Skunk River. Most of the exposures consist of a dark lavender or greenish gray hornblende rock. It has a porphyritic texture, containing phenocrysts of hornblende and gray calcic feldspar, the former predominating. The hornblende has a granular appearance rather than the usual fibrous texture. The rock is probably a syenite or diorite.

At this locality one exposure occurring southwest of the bridge over Skunk River consists of coarse-grained, dark gray, biotite granite, cut by dikes of medium to coarse-grained pink granite. The gray granite is fresh in appearance due to the presence of abundant fresh, colorless or white feldspar. Biotite is abundant in it and some hornblende occurs. The pink granite consists mainly of pink feldspar, but it contains abundant quartz and everywhere a little biotite. The feldspar shows very irregular crystallization, masses of fine-grained and coarse-grained material being closely associated.

A small knoll consisting of gray and pink granite occurs on the north side of Little Skunk River near the east side of section 6, T. 41N., R. 28W., about 2 miles above Rucker. The gray granite is a coarse-grained biotite granite, similar in appearance to that at Granite City. It contains frequent scattered crystals of hornblende, some of them more than half an inch long. The pink granite varies in texture and composition. Some phases of it are coarse-grained and almost free from ferromagnesian minerals, while other phases are medium-grained and contain abundant scattered biotite. Frequently the coarse and medium-grained types are closely associated. A few small dikes of fine-grained, light-colored granite are intruded into the gray granite.

Several other rock outcrops occur on Little Skunk River and on the upper portion of Skunk River, both in section 6, T. 41N., R. 28W., and in section 1, T. 41N., R. 29W. One of the larger ones of these is found near the center of section 1 and consists of granite. Another one is mapped by Upham[49] as occurring along the northern boundary of section 6. The latter, however, could not be found and has probably been confused with the outcrop at Rucker as is indicated by the description.

An interesting group of exposures of various kinds of granite is found along Hillman Creek and Little Hillman Creek in an area about 3 miles long east and west, and about 1 mile wide. The westernmost of these outcrops occur about 4½ miles east of Pierz in the eastern part of section 7 and western part of section 8, T. 40N., R. 29W. They form an elevation along the north side of Hillman Creek and consist of coarse gray biotite granite which is intruded by medium-grained pink biotite granite. The gray granite locally is porphyritic and contains conspicuous

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[49] Upham, Warren, The geology of Crow Wing and Morrison counties: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 2, 1882-1885, Pl. 53 and p. 592.

crystals of white feldspar, but for the most part it is even-grained. The pink granite shows pegmatitic facies locally, while elsewhere it is intruded as narrow dikes and is fine-grained.

In the northeastern part of section 8, fine-grained pink and dark gray granites are intruded into coarse pinkish gray granite. The Minneapolis, St. Paul, and Sault Ste. Marie railroad cuts through two of the outcrops and two small quarries occur in them, one to the north and one to the south of the railroad. The fine-grained pink granite consists mainly of pink feldspar and quartz, but biotite and hornblende occur scattered through it. The fine-grained, dark gray granite contains abundant ferromagnesian minerals, both biotite and hornblende. It is not extensive areally. The coarse-grained gray granite covers a larger area than the other two types. It is fresh and consists of slightly pinkish feldspar and quartz with much biotite. The latter is partly altered to chlorite. The pink granite intrudes it as dikes and as larger intrusive masses. Pink pegmatitic phases occur also. The quarries are both in the pink granite.

Farther up Hillman Creek, in section 35, T. 41N., R. 29W., about a mile above the locality just described, are the remains of an old logging dam. At this place a large number of outcrops occur on both sides of the creek and extend for some distance to the north. The Minneapolis, St. Paul, and Sault Ste. Marie railroad has cut through one of the larger outcrops. Most of the exposures south of the creek consist of coarse-grained gray granite with some gneissic phases, while those to the north are mainly fine-grained pink granite. The pink granite contains only a small amount of ferromagnesian minerals, being composed principally of pink feldspar and quartz. It is intruded into the coarse gray granite as dikes and large masses. In the railroad cut a nearly horizontal sill of pink granite varying up to two feet in thickness, and bounded above and below by coarse gray granite, occurs in both walls of the cut almost along the entire length. North of Hillman Creek, the intrusive masses of pink granite are much larger, though the texture is uniformly fine-grained. The coarse gray granite is a biotite granite similar to that already described as occurring to the southwest. Portions of it apparently have suffered considerable deformation and recrystallization with the result that masses of coarse banded gneiss have developed. These, however, are of restricted occurrence. Not all the dikes are of pink granite. There are also dikes of fine-grained gray biotite granite which cut the coarse-grained granite. One of these is exposed in the railroad cut.

On Little Hillman Creek in section 9, T. 40N., R. 29W., about a mile east of the outcrops in sections 7 and 8, there is another group of exposures of gray and pink granite. The principal rock is a coarse-grained biotite granite, in general having a gray appearance, but in places containing pink feldspar in abundance. This rock is intruded by dikes of fine-grained light gray and dark gray granite and fine-grained white to pink aplite. The light gray granite contains but a small amount of ferromagnesian minerals, while the dark granite contains abundant biotite and some hornblende. The aplite dikes are in places made up almost entirely of quartz and pink feldspar. Locally, however, scattered ferromagnesian minerals are present. The gray coarse granite has suffered deformation and in places shows gneissic structure.

A few small outcrops consisting mainly of very coarse-grained pink biotite granite are found near the west side of section 18, T. 39N., R. 30W., about three miles southwest of Buckman. They occur in a barnyard a short distance from the north-south township road. The rock is considerably weathered and friable. It contains inclusions of a fine-grained dark gray rock. One of the outcrops consists of fresh pink granite with texture varying from fine-grained to coarse-grained in different parts.

STEARNS, BENTON, SHERBURNE, AND WESTERN MILLE LACS COUNTIES

The region surrounding Saint Cloud and Sauk Rapids contains a large number of rock outcrops, principally granite and subordinately diorite and gabbro. They are situated mainly in the eastern part of Stearns County and in the western parts of Benton and Sherburne counties, and extend approximately from Watab on the north to Linden township on the south, and to Rockville on the southwest. The area in which outcrops occur is about 16 miles long north and south, and about 12 miles wide. Outside of this area, however, there are a few scattered outcrops, such as the exposures of granite and of Cretaceous sediments along Sauk River near Coldspring and Torah (Richmond), Stearns County, and the granite exposures on the upper Elk River about 8 miles northwest of Foley, Benton County.

Most of the outcrops occur in groups, but isolated, scattered outcrops are also abundant. The most northerly of the groups of outcrops is that south of Watab on the east side of Mississippi River. Three rocky knolls are found here between the tracks of the Northern Pacific Railway and the river. The knolls consist principally of a dark, fine-grained hornblende rock, probably a diorite. Locally between the knolls fine to medium-grained pink granite which appears to be intrusive in the diorite crops out. In the knoll farthest east near the railroad a quarry occurs in the pink granite, in which several phases are shown.

From Watab southward to Sauk Rapids exposures of diorite and pink and gray granite occur at frequent intervals. Most of them are found from 1 to 3 miles east of Mississippi River, but west of the river there are also scattered outcrops. About 1½ miles north of Sauk Rapids and 2 miles east of the river, are situated a number of quarries. Several different types of granite are taken from these, including medium coarse-grained pink hornblende granite and light to dark gray biotite and hornblende granite.

At Sauk Rapids a number of outcrops are found. On the east side of Mississippi River are exposures of dark gray hornblende granite, while on the west side below the bridge is an exposure of coarsely porphyritic rhyolite porphyry containing both feldspar and quartz phenocrysts in a gray, finely crystalline matrix.

The largest group of outcrops in the Saint Cloud region is situated about 2 miles southwest of Saint Cloud and occupies an area about 4 miles long north and south and about 3½ miles wide.[50] Pink and red granite and syenite exposures are abundant, being scattered at short intervals over the entire area, some of them being several acres in extent. The rock is described by Upham as principally syenite with predominating hornblende but also containing abundant mica.

Near Rockville, about 6 miles southwest of this group of outcrops, a number of massive[51] exposures of coarse-grained gray, biotite granite occur. Several of these exposures are forty or fifty rods in extent and rise forty or fifty feet above the surrounding level. They are found along Mill Creek south of the village and along Sauk River north of the village.

In Saint Augusta township about 4 miles east-southeast of Rockville,[52] an exposure of pink biotite granite is reported to occur near the center of section 19, T. 123N., R. 28W., while an outcrop of gray granite is reported in the northwestern corner of Linden township about 2½ miles south of Saint Augusta.[53]

The outcrops at Coldspring and Torah (Richmond) in Wakefield township are described as consisting mainly of coarse reddish syenite. The Coldspring outcrops occupy an area a quarter of a mile square. Several exposures of very hard, dark diorite are reported as occuring 2 miles east of Torah (Richmond). These are the southernmost outcrops of igneous rock in east central Minnesota.

In the northwestern part of Sherburne County several outcrops occur in Haven township[54] southeast of East Saint Cloud. A number of quarries are found near the State Reformatory about 2 miles from East Saint Cloud in a rock said to be fine-grained gray to red syenite. Ex-

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[50] Upham, Warren, The geology of Stearns County: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 2, 1882-1885, pp. 455-458.
Bowles, O., and Grout, F. F., Unpublished map.

[51] Upham, Warren, *op. cit.*, p. 454.

[52] Upham, W., *op. cit.*, p. 455.

[53] Bowles, O., and Grout, F. F., *op. cit.*

[54] Upham, Warren, The geology of Benton and Sherburne counties: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 2, 1882-1885, pp. 426-444.

posures occur over a considerable area. About 2 miles south of the Reformatory in the west central part of the township is an outcrop of coarse whitish gray syenite[55] covering 4 or 5 acres and rising as a bare rounded knoll above the surrounding prairie.

The outcrops northeast of Foley near the center of Benton County are reported by Upham to be only a few rods in extent and to consist of reddish syenite.

A group of granite outcrops of considerable extent is found northeast of the Saint Cloud region along the upper courses of the West Branch of Rum River and Saint Francis River in northeastern Benton and western Mille Lacs counties.[56] The outcrops on the West Branch of Rum River both in Benton and Mille Lacs counties are said to consist of remarkably uniform, coarse-grained, reddish syenite. They occur along the river through an extent of about 2 or 3 miles. Many different exposures are found, most of them small ledges occurring along the banks or in the channel of the stream. The westernmost group of exposures is a short distance above the mouth of Stony Brook in Benton County, while the easternmost exposures occur about 3 miles west of Milaca.

The outcrop near the headwaters of Saint Francis River is about four miles west of the westernmost outcrop on the West Branch of Rum River in the northern part of section 20, T. 38N., R. 28W. It is reported to be about 25 rods long by 15 rods wide and to consist of reddish syenite cut by an east and west trap dike. The dike is from a foot to a foot and a half wide and has fine-grained syenite on the north side and coarse-grained syenite on the south side.

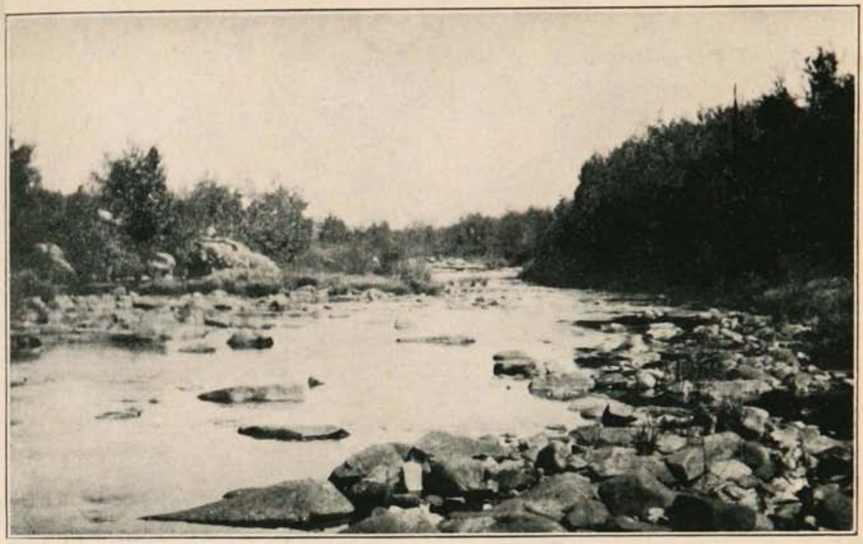
NORTHERN MILLE LACS, KANABEC, SOUTHERN AITKIN, AND WESTERN PINE COUNTIES

A number of outcrops of several different kinds of silicic igneous rock occur south and southwest of Onamia in the northern part of Mille Lacs County, some being on Rum River and some on Bradbury Brook, a tributary of Rum River.

The most northerly outcrop on Rum River is located about 5 miles south of Onamia near the ruins of an old logging dam. There is a bridge over the river at this point, and the exposures are on the east side of the river both north and south of the bridge. The principal rock is a light-colored, medium to coarse-grained granite, much of which has developed a gneissic structure and contorted, obscure banding. The banding is due in part to the arrangement of biotite in streaks and in part to a difference in size of grains of the different bands. The coarse granite is cut by several varieties of dark-colored dikes. One is a very dark, fine-grained

[55] Upham, W., *op. cit.*, p. 432.

[56] Upham, Warren, The geology of Mille Lacs and Kanabec counties: *op. cit.*, pp. 612-628.



A. GRANITE EXPOSURES ON RUM RIVER, SOUTH OF ONAMIA, MILLE LACS COUNTY

B. GRANITE EXPOSURES ALONG HAY CREEK, A BRANCH OF SNAKE RIVER, KANABEC COUNTY

biotite granite while the other is a dark, dense rock gray to greenish and fine-grained. The latter rock contains abundant pyrite.

The other outcrops on Rum River occur in section 7, T. 40N., R. 26W., and section 12, T. 40N., R. 27W. They form a series of three outcrops, two occurring in the NW¼ of NW¼ of section 7 and one in the NE¼ of NE¼ of section 12. All are found within a distance of about a half a mile along the stream.

The first of these outcrops, going down stream, consists of dark gray, fine-grained biotite granite, which has been squeezed so that the biotite has developed a parallel arrangement without segregation into bands thus giving the rock a schistose appearance. The rock, however, is quite massive.

The second outcrop consists of dense, fine-grained, mica schist. The rock has a dark greenish gray color and contains abundant flakes of muscovite, as well as biotite. It appears to be similar to the rock exposed in the outcrop last mentioned, but has suffered further deformation. Dikes of a dark-colored fine-grained feldspathic rock are found in it.

The third outcrop consists of light-colored medium coarse-grained granite consisting mainly of quartz and feldspar, but containing scattered biotite.

The exposures along Bradbury Brook consist mainly of light-colored gray or brownish granite with local gneissic phases. Three of the exposures occur on or near the South Fork of Bradbury Brook in section 25, T. 41N., R. 27W., and section 30, T. 41N., R. 26W., and another one occurs in section 13, T. 41N., R. 27W., a short distance east of the North Fork of Bradbury Brook.

The outcrop in section 13 is located on the quarter line about 1,000 feet west of the north-south township road between T. 41N., R. 27W., and T. 41N., R. 26W. The principal rock is a gray medium-grained granite with abundant biotite, which is more or less concentrated along parallel streaks due to deformation and recrystallization and gives the rock a gneissic appearance. It does not show distinct banding, however. The biotite granite is cut by several dikes of a very light-colored fine-grained to medium-grained quartz-feldspar rock (aplite) containing a little scattered biotite.

The northernmost of the exposures near the South Fork of Bradbury Brook occur along the township road between section 25, T. 41N., R. 27W., and section 30, T. 41N., R. 26W. about 1,400 feet south of the section corner. The rock here consists of medium coarse-grained light-colored granite with abundant quartz and feldspar and scattered biotite. Locally it shows a tendency to a gneissic texture, which is not very marked. This rock contains inclusions of a fine-grained, dark granite with abundant ferromagnesian minerals.

About 400 feet south of these exposures at the bridge over the South Fork of Bradbury Brook, a small outcrop of fine-grained, gneissoid granite occurs east of the road. The biotite shows in conspicuous parallel lines.

About 300 feet west of the outcrop at the bridge just mentioned, there is a dam on the South Fork of Bradbury Brook near which are found several exposures of medium-grained gray biotite granite. Some of the rock is light-colored and consists mainly of quartz and feldspar with scattered biotite, but in some of it the ferromagnesian minerals equal in amount or predominate over the quartz and feldspar and such phases are dark.

Upham[57] mentions the occurrence of several other rock exposures along Rum River and Bradbury Brook. Those on Rum River are said to be several miles above the mouth of Bradbury Brook and to consist of syenite, hornblende rock, gneiss, granite, and greenstone. Outcrops of this description have been looked for but have not been found by the writers. The outcrop on Bradbury Brook is reported to be on the South Fork 3 or 4 miles above its junction with the North Fork. As these exposures were not visited by Upham but were reported on the authority of others, it is probable that they have been confused with certain of the outcrops described above.

In the NW¼ of SE¼ of section 27, T. 42N., R. 26W., about 3 miles northeast of Onamia, exposures of granite and diorite are reported by Grout[58] to occur in the bottom of a cut along the Minneapolis, St. Paul, and Sault Ste. Marie Railroad. The outcrop rises from 2 to 3 feet above the grade and extends for 185 feet along the north side. Only a few exposures are found on the south side of the cut. The rock consists of alternate masses of fine-grained light gray biotite granite and dark gray medium coarse-grained diorite. The contacts are sharp and no change in the size of the grain is noticed on approaching them. Along one contact is a small pegmatitic band grading into the granite. A few small dark inclusions or blotches of ferromagnesian minerals are found in the granite.

About 5 miles southeast of Wahkon, Mille Lacs County, in section 3, T. 41N., R. 25W., a quarry has recently been opened in light gray granite. It is located in the northeast corner of the section in a bend of Knife River. The granite is of two kinds, one a medium coarse-grained rock, and the other finer grained. Both are very light colored and contain only a small percentage of ferromagnesian minerals. Their relation is such as to indicate that the fine-grained granite is intrusive into the

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[57] Upham, W., *op. cit.*, p. 617.
[58] Grout, F. F., Oral communication.

coarse-grained granite. The fine-grained rock resembles very closely that found at Meyers quarry west of Pierz and is hard and fresh. Dikes and irregular masses of fine-grained aplite cut both varieties of granite.

A number of granite outcrops are found in the region of Ann Lake, 4 to 7 miles northwest of Mora, Kanabec County. Near the boundary between sections 19 and 20, T. 40N., R. 24W., just north of the east and west road which runs along the south line of these sections, several exposures of medium-grained, pinkish gray biotite granite occur. They probably continue south of the road into sections 29 and 30. The principal exposure forms a small hummock overlooking a marsh a short distance north of the road. The rock here is a light pink biotite granite with abundant quartz and both white and pink feldspar.

Upham[59] reports the occurrence of ledges of gray fine-grained granite along Ann River in sections 30, 29, and 32 half a mile to a mile south of the locality mentioned above. He states that similar outcrops are reported as occurring also along Little Ann River north of Ann Lake in sections 26 and 14, T. 40 N., R. 25W.

Quarries in granite are located at Warman in the southeast corner of section 6 and the southwest corner of section 5, T. 41N., R. 23W. The granite is very light gray, medium-grained, with abundant quartz and white feldspar, and considerable amounts of scattered biotite. The rock is very even-grained and shows no abrupt changes in texture or mineral composition. Most of it is fresh and shows little or no alteration of the feldspars. At one of the quarries there are a few dikes of white feldspar-quartz pegmatite, containing scattered large thin biotite flakes.

Numerous outcrops of sedimentary and igneous rocks are found along Snake River in the northern part of Kanabec County. The southernmost of these exposures, consisting of several outcrops of flat-lying pink and red sandstone, are found in the northwestern part of section 23, T. 42N., R. 23W. The rock probably forms a part of the supposed upper Keweenawan sandstone which extends southwestward from the western end of Lake Superior. The outcrops are described later.

The next group of exposures to the north up Snake River is found beyond the big bend in the river in sections 15 and 16 of the same township. The river at this point flows eastward and the locality, which is known as Lower Falls, is a short distance west of the new iron bridge over the river. The exposures consist of gray and pink biotite granite with large included masses of biotite schist.

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[59] Upham, Warren, The geology of Mille Lacs and Kanabec counties: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 2, 1882-1885, pp. 617 and 618.

Up the river beyond this group of exposures there is a number of scattered granite outcrops as far as the mouth of Hay Creek, while north and northwest of the mouth of Hay Creek exposures again increase in abundance and cover an area of considerable size in sections 16 and 9. In this area many large outcrops occur both westward along Hay Creek and northward along Snake River. They extend up Hay Creek for nearly a mile and up Snake River from the mouth of Hay Creek about a third of a mile to a place known as Upper Falls where a reef of rocks runs across the stream. The rocks in this area are mostly gray and pink biotite granite, but locally there are pegmatitic facies and also included bands of biotite schist. There are also several fine-grained basic dikes.

Above Upper Falls only a few scattered outcrops are found along the river as far as the mouth of Cowan Brook. About 800 feet above the mouth of Cowan Brook, however, near the northern boundary of section 9, a number of small exposures of schist and granite occur on both sides of Snake River, while about a third of a mile farther up an important group of exposures is found along Snake River and east in the area between Snake River and Cowan Brook. These outcrops are in the southeastern part of section 4. They consist mostly of light-colored granite with local gneiss and pegmatite. The entire area occupied by the outcrops of Lower Falls, Hay Creek, Upper Falls, and Cowan Brook is about 2 miles wide east and west and 2½ miles long north and south.

The principal exposures at Lower Falls extend along the river for a distance of about 3,000 feet, but small scattered outcrops continue both up and down the river. By far the most important rock is gray and pink biotite granite. This rock is medium-grained and hard and fresh, containing abundant quartz. There seems to be no distinct difference in age between the gray and the pink types, the former grading into the latter with increasing pink feldspar. As far as can be determined from these exposures, there is no sharp line between them. The amount of ferromagnesian minerals in the granite is usually small, giving the rock a light color.

The schist, which occurs as large masses surrounded by granite, is principally a fine-grained, quartzose biotite schist, but some of it is coarsely crystalline. Locally muscovite occurs with the biotite and along certain streaks and bands much hornblende is developed. Garnet also is commonly disseminated through the rock, while certain hard quartzitic lenses have an interesting development of molybdenite around the borders. The larger of the schist masses have a fairly uniform strike east and west and dip to the south at angles varying between 50° and 70°. They are cut by dikes of pink granite and also locally by pink pegmatite

A. GRANITE AND MICA SCHIST OUTCROPS AT LOWER FALLS ON SNAKE RIVER, KANABEC COUNTY

B. GRANITE EXPOSURES AT UPPER FALLS ON SNAKE RIVER, KANABEC COUNTY

dikes consisting of quartz and pink feldspar with abundant muscovite. The association shows that the granite is intrusive into the schist, the masses of the latter being fragments caught in the granite. If the schist is of upper Huronian age, as is generally supposed, then the granite is post-upper Huronian and may be equivalent to certain other Keweenawan granitic rocks of the Lake Superior region. Because of the isolated situation of these rocks, however, correlation is difficult, and the age relationships are therefore uncertain.

The rock exposures along Hay Creek and along Snake River near Upper Falls, are in general similar to those at Lower Falls in that they consist largely of medium-grained gray and pink granite. There is more pegmatitic rock, however, in these exposures and locally also the granite is quite fine-grained in texture. Pegmatite is especially abundant at Upper Falls and along both sides of the river below Upper Falls. In places, large masses of véry coarsely crystalline material occur, consisting of pink feldspar, quartz, and muscovite, with locally some biotite. Usually the muscovite is in large flakes, but some of the pegmatite has suffered deformation and the muscovite is recrystallized into small flakes having a fan-shaped, foliated structure around fragments of quartz and feldspar. The granite also in a few places has suffered deformation and has developed a gneissoid texture. In one or two places it has even become coarsely schistose. Dikes of very fine-grained, dark greenish gray subsilicic igneous rock occur in the river at Upper Falls and at the dam on Hay Creek about a mile above its mouth. The one at Upper Falls shows diabasic texture while the one on Hay Creek appears to be a diorite. Masses of fine-grained quartzose biotite schist similar to that at Lower Falls occur locally in the Hay Creek and Upper Falls outcrops, but their development is not as abundant as in the former locality.

The exposures along Snake River between Upper Falls and the mouth of Cowan Brook as well as those a short distance above the mouth of Cowan Brook consist of light-colored pink and gray biotite granite with a considerable quantity of fine-grained biotite schist. Those above the mouth of Cowan Brook contain a large pegmatite dike.

The outcrops situated in the area between Snake River and Cowan Brook, about a third of a mile above the mouth of the latter, consist of light-colored biotite granite. Both the pink and gray types occur, most of the rock being very low in ferromagnesian minerals. Muscovite in small flakes is abundantly disseminated through it locally. In a few places there are gneissoid phases, showing distinct banding.

In the southwestern part of section 21, T. 43N., R. 23W., Aitkin County, about 3 miles north of the Cowan Brook exposures, there are several outcrops of schistose and banded gneiss along Snake River. The locality is known as Malloy (or Malloid) Dam. The rock seems to be a deformed and recrystallized granite. It varies from pink or white to dark gray in color. Most of it is finely crystalline biotite gneiss, biotite, quartz, and feldspar being arranged along fine laminae. The laminae of biotite are very thin, while those of quartz and feldspar are thicker and more irregular. There may be 20 or 30 thin laminae of biotite to the inch separated by thicker laminae of quartz and feldspar. Usually the successive laminae are closely similar, giving the rock a homogeneous and schistose appearance. Locally, however, there is a distinct banding of light and dark layers and the rock becomes a banded gneiss. The dip of the schistosity and banding varies from 65° to 80° north, the strike being nearly east and west. At one point a dike of pink granite cuts across the gneiss. It shows no deformation whatever. This dike rock is identical in appearance with the pink granite occurring along the Snake River in Kanabec County which contains included masses of schist. It appears that the gneiss and schist are older formations which have been rendered schistose previous to the intrusion of the granite. The granite predominates to the south in Kanabec County, while gneiss and schist predominate to the north in Aitkin, Pine, and Carlton counties.

Southwest of McGrath, a station on the Minneapolis, St. Paul, and Sault Ste. Marie Railroad east of Mille Lacs Lake, many outcrops of fairly coarse pink augen-gneiss occur on both sides of the east-west road running between section 1 and section 12, and section 2 and section 11, T. 43N., R. 24W. The outcrops extend for a mile along the road and all seem to be composed of the same kind of rock. The rock at one time was apparently a fairly coarse-grained granite with numerous prominent crystals of feldspar and some of quartz. Deformation occurred, and during this process the biotite and some of the quartz and feldspar were crushed and recrystallized. Other quartz and feldspar crystals, however, resisted deformation and remained as lentils or buttons around which the crushed material recrystallized, giving the rock a wavy, foliated texture. The buttons of quartz and feldspar are coarse-grained, many consisting of a single crystal, while the crushed and recrystallized material is fine-grained. The foliated structure is fairly regular. It strikes about N. 70° W. and the dip is vertical or steeply inclined to the south.

Augen-gneiss similar to that occurring near McGrath, as well as banded and schistose gneiss, are found cropping out at several places west and south of Denham, a station on the Minneapolis, St. Paul, and Sault Ste. Marie Railroad in Pine County, about 20 miles northeast of McGrath. The distribution of the outcrops indicates that the southern part of Aitkin County and the northwestern part of Pine County are largely underlain by gneiss, which is bounded on the south by granite and on the north by metamorphosed sediments such as schist and slate.

The most westerly of these exposures are in the southwestern part of section 35, T. 45N., R. 22W., Aitkin County, along the north and south road south of Arthyde. Two exposures occur in the road. One of them consists of pink augen-gneiss very similar to that at McGrath, while the other consists of finely laminated, dark-colored schistose gneiss, with thin lentils of crushed pink feldspar and quartz. The dark color is due to the abundance of biotite which occurs in fine laminae. The rock is probably a more metamorphosed phase of the augen-gneiss.

About 2 miles west of Denham a rock cut along the railroad in section 21 T. 45N., R. 21W., Pine County, shows dark-colored, schistose gneiss. The degree of metamorphism varies in different parts so that in places the rock is a perfect schist, finely laminated, consisting largely of biotite, while elsewhere it is more massive and contains abundant feldspar and quartz. This variation produces a rough banding more or less parallel to the foliation. The foliation or schistosity strikes roughly east and west, and dips to the north at angles varying between 70° and 80°. The rock is similar to that in one of the outcrops south of Arthyde but the "augen" structure is less marked.

About 1¼ miles south of the locality just described, on the north and south road between sections 33 and 34, T. 45N., R. 21W., pink augen-gneiss similar to that at McGrath, outcrops at several places while a mile further south between sections 3 and 4, T. 44N., R. 21W., other exposures of the same type of rock are found. In the latter locality the gneiss shows a considerable amount of muscovite.

Several exposures of gneiss with associated hornblende schist are located in the western part of the township of Bremen, T. 44N., R. 21W. The most northerly of these are found along the northern headwaters of Pine River in the northeastern corner of section 17 and adjacent parts of sections 16, 8, and 9. An outcrop on the west bank of the stream near the east quarter post of section 17 consists of pink gneiss, very coarse and containing muscovite and biotite along foliation planes. The foliation strikes approximately east and west and dips about 50° S. Along the north and south section road, near the northeast corner of section 17, and extending into the adjoining sections to the east and north, are several exposures of dark reddish gneiss with closely spaced foliation planes and of very dark, almost black, finely laminated hornblende schist. The gneiss contains abundant mica along foliation planes, the close spacing of which indicates intense deformation and metamorphism. The hornblende schist shows continuous fine laminae of hornblende alternating with laminae of quartz and feldspar. The hornblende is by far the most abundant mineral in the schist and produces a schistosity parallel to the lamination. The hornblende schist appears to be a phase of the gneiss but the relation of the two rocks could not be determined. The general dip of the foliation in these outcrops is 35° S.

The other outcrops in the township of Bremen are located along a branch of Pine River on both sides of the north and south section line between sections 19 and 20. The principal exposures are found on both the north and south banks of the stream south of the east and west quarter line. They consist of pink, fresh looking, distinctly foliated gneiss, some of which shows a somewhat indistinct "augen" texture and some the more regular interbanding of feldspar and quartz with mica. The former as a rule is more coarsely crystalline than the latter. The ferromagnesian minerals occur along foliation planes, both biotite and hornblende being present. The foliation planes as a rule are thin, irregular, and discontinuous, but locally they widen forming lense-like bunches of dark minerals. The general dip of the foliation is to the south, varying between 40° and 80°.

A group of small rock exposures occurs a short distance south of the stream near the south line of section 20 not far from the southwest corner. These are of gneiss. Hornblende and biotite schists also occur here. The gneiss varies in texture from very coarsely crystalline to medium finely crystalline and in color from gray to pink. Nearly all of it is distinctly but irregularly banded. In some places the segregation of light and dark minerals is very perfect, so that white or pink bands of intermixed feldspar and quartz ranging up to half an inch thick are interlayered with darker bands of feldspar, quartz, and ferromagnesian minerals. The hornblende and biotite schists are dark-colored, often black or greenish black and generally are finely and regularly laminated due to interlayering of fine-grained feldspar, quartz, and ferromagnesian minerals, mainly hornblende. The ferromagnesian minerals are much more abundant than the light-colored minerals, but locally layers up to a fourth of an inch in thickness, consisting almost entirely of feldspar and quartz, occur interlaminated with the dark minerals. Some of the schist shows irregular undulatory lamination and marked schistosity, usually being more coarsely crystalline and appearing to have suffered greater metamorphism than the more regularly banded schist. Most of the schist is fairly pure hornblende schist, but local phases show a considerable admixture of biotite. Interesting phases, gradational in texture as well as in mineral composition, occur between the gneiss and the schists. In some of these the light and dark-colored minerals are almost equally abundant and light-colored layers are interbanded with dark-colored layers. Some of them show gneissoid, and some show schistose textures. It seems quite clear, therefore, that the gneiss and schists belong to the same rock mass, the one representing the more silicic and the other the less silicic portions of it. The latter appear to have yielded more readily to deformational forces. The dip of the foliation and schistosity is to the south at angles varying between 40° and 70°.

A number of exposures of augen-gneiss of considerable size occur in the southeastern part of the NE¼ of section 36, T. 45N., R. 21W. The outcrops are about 1½ miles south of Denham and a short distance south of a group of exposures of interesting metamorphosed sedimentary rocks found in the southeastern portion of section 25 which is described later. An isolated exposure of dark greenish black hornblende-biotite schist is found north of the gneiss outcrops about half-way between them and the outcrops of metamorphosed sediments.

Most of the rock composing the gneiss exposures is a gray to pink augen-gneiss with distinct undulatory foliation. The large crystals forming the augen are of pink feldspar and present all stages of crushing, the foliation in the ground-mass curving around them. The ground-mass is mainly quartz, feldspar, biotite, and muscovite, all finely crystalline. In some phases muscovite is present almost to the exclusion of biotite. A small mass of biotite schist is found in one of the outcrops. It contains considerable feldspar and is probably a sheared basic inclusion.

The hornblende-biotite schist found north of the gneiss outcrops is similar to that occurring in Bremen township. It shows a distinct, irregular schistosity, but the lamination is not very marked. Hornblende predominates, while biotite and quartz and feldspar are present in minor amounts. This is the easternmost outcrop of gneiss known in central Minnesota.

OUTCROPS OF SUBSILICIC IGNEOUS ROCKS

TODD COUNTY

Outcrops of several kinds of coarse-grained, subsilicic igneous rocks occur in the northern part of Todd County. They are situated on Long Prairie River at the mouth of Fishtrap Creek and along Fishtrap Creek for about 1,300 feet above its mouth. The principal exposures consist of coarse-grained, dark greenish or brownish black gabbro. The largest outcrop of this rock is at the mouth of Fishtrap Creek, but numerous small outcrops extend southward up the creek, occurring on both banks of the stream. The last exposure up stream is an isolated outcrop found on the west bank a short distance above the first road bridge. This bridge is 1,000 feet from the mouth of the creek.

Besides the gabbro there are a few outcrops of anorthosite. One of these is on the east side of Fishtrap Creek near its mouth, and another is at the road bridge over Fishtrap Creek mentioned above.

The gabbro has suffered considerable alteration so that it consists principally of feldspar and secondary hornblende. The feldspar is more or less altered to saussurite and locally to muscovite and quartz. Apatite and magnetite are abundant in the rock and biotite also is present. The hornblende is secondary after diallage, traces of which are found in a few of the outcrops, notably in the one above the bridge. The rock in its original fresh state, therefore, consisted mainly of feldspar and diallage with biotite, apatite, and magnetite as accessory constituents. The anorthosite is composed almost entirely of feldspar, some of which has been partly altered to saussurite and some to muscovite and quartz.

A short distance east of the station of Philbrook, about 2,000 feet up Fishtrap Creek from the southernmost of the exposures just mentioned, there are a few small outcrops of coarse-grained greenish rock very much altered. Most of the rock is composed of saussuritized feldspar, green hornblende, and epidote, but some phases of it consist almost entirely of altered feldspar. Magnetite is abundant. The rock, although somewhat lighter in color, is similar in texture to the gabbro and anorthosite occurring near the mouth of Fishtrap Creek and it seems probable that it represents a further alteration phase of these rocks.

MORRISON, BENTON, AND STEARNS COUNTIES

Several exposures of subsilicic and intermediate igneous rock are found in the vicinity of Little Falls, Morrison County. One of these is at Williams' quarry in the northeast quarter of section 13, T. 129N., R. 30W., about a mile northeast of Little Falls. The rock varies greatly in texture at different points in the quarry. Some of it is dense and fine-grained and has a uniform dark gray color, while other phases are coarser grained and have a speckled appearance due to intermixed light and dark-colored minerals. The latter vary considerably in size of grain, as well as in color. In some, feldspars predominate; in others, ferromagnesian minerals. The various rocks have a fairly uniform mineral composition, except that the coarser grained varieties have suffered greater alteration.

The fine-grained type consists of feldspar and pyroxene, the former predominating. It is fairly even-grained, but occasional larger crystals of pyroxene occur. Fine particles of magnetite are scattered throughout the rock. Much of the feldspar shows partial alteration to granular kaolin, while the pyroxene shows practically no alteration. The coarser grained type consists mainly of feldspar and hornblende, the latter being secondary after pyroxene. Locally much of the hornblende shows irregular cores of pyroxene, the hornblende forming a border of varying thickness. Most of the hornblende shows pleochroism from bluish green to light yellowish green. Some of it is greenish brown. Both varieties of hornblende show pyroxene cores in places, but elsewhere the pyroxene has entirely disappeared. The feldspar is slightly altered to kaolin. A small amount of biotite (or phlogopite) is quite generally distributed through both types of rock, while locally large, very thin, flakes of phlogopite occur, giving the rock a bronzy appearance. In the phases of the rock rich in phlogopite, the pyroxene is quite fresh, and much brown hornblende occurs in irregular masses which has the appearance of being original. It is quite probable that a considerable amount of both brown and green hornblende is original. Locally the feldspar predominates over the ferromagnesian minerals to such an extent as to give the rock a very light color. Specks and irregular grains of magnetite are numerous, especially in association with pyroxene, while grains of quartz occur rarely. In general the rock has the composition of a diorite.

The diorite at Williams' quarry and the syenite occurring on the east bank of Mississippi River at Little Falls, are within a region in which slate and schist of sedimentary origin predominate. As the metamorphosed sediments have a fairly definite and regular structure throughout, it would seem that the igneous rocks are probably intrusive into them, although contacts between them have not been found.

An outcrop of hard, dark rock occurs on the west bank of Mississippi River about three quarters of a mile below the bridge of the Minneapolis, St. Paul, and Sault Ste. Marie Railroad, in section 32, T. 128N., R. 29W. It forms rapids in the river, known as Blanchard's Rapids, and outcrops of it are found on the east bank also. The rock is medium coarse grained and contains abundant pyroxene and calcic feldspar with locally phlogopite. It resembles gabbro in composition. Only a short distance above these outcrops, along the river bank, are exposures of staurolitic and garnetiferous biotite schist which are apparently the southernmost outcrops of these rocks on Mississippi River. The relation of the schist to the igneous rock could not be definitely determined. Judging from the fact, however, that the cleavage of the schist strikes in the direction of the gabbro it would seem that the latter is intrusive, as is the case with the other subsilicic or dark igneous rocks in the vicinity of Little Falls.

The occurrence of a dark-colored hornblende rock on Skunk River near the locality known as Rucker, in the northwestern part of Morrison County, has already been mentioned. The rock is dark grayish in color and contains abundant specks of granular hornblende. It is probably a hornblende syenite, but may approach a diorite in composition.

The outcrops of various rocks of intermediate composition in Benton and Stearns counties have been mentioned in connection with the descriptions of the outcrops of silicic igneous rocks of these counties, while the occurrence of gabbro also has been noted. Diorite is mentioned as occurring in the vicinity of Watab in the western part of Benton County, and near Torah (Richmond) and Cold Spring in the southern part of Stearns County. Only one group of gabbro exposures is known in this region, being located in the northeastern corner of T. 125N., R. 29W., and adjacent parts of T. 125N., R. 28W., in Stearns County. It occupies portions of several contiguous sections.[60]

AITKIN, CARLTON, AND PINE COUNTIES

Among the most important rock outcrops in central Minnesota with reference to the geology of the Cuyuna district, are those of quartzite, diorite, and diabase on the shores of Dam Lake and Long Lake in central Aitkin County, about 3 to 6 miles south of Kimberly. There are two quartzite outcrops, both located on the northwest shore of Dam Lake, one in section 34 and the other in section 35, T. 47N., R. 25W. They are described in connection with the metamorphic rocks. The diabase and diorite outcrops are southwest of the quartzite outcrops occurring on both the east and west sides of Long Lake in sections 9 and 10, T. 46N., R. 25W.

The outcrops in section 9 are by far the most extensive, occupying an area of 8 or 10 acres west of the southwestern end of Long Lake. The rock is dark green in color and is in general fine-grained. Medium coarse-grained phases, however, occur as well. All show a distinct diabasic texture. The rock appears to be less silicic in character and darker in color than that composing the outcrops east of Long Lake. It consists of pyroxene, basic feldspar, and green hornblende. Scattered quartz grains occur frequently and magnetite is disseminated through it. The rock is massive and fresh-looking.

On the east side of the lake two small groups of outcrops occur; one along the top of an elevation overlooking the northeastern part of the lake, and the other one a short distance from the mouth of a small brook which empties into the southeastern part of the lake. Both occur in section 10.

The group of outcrops at the northeastern end of the lake consists of three or four exposures, all of them quite small. The rock is medium to dark gray in color and massive, resembling diorite in appearance. It is medium to fine grained and consists of feldspar and pyroxene with some green hornblende and mica and scattered pyrite specks.

The outcrops on the southeastern side of the lake are on the banks of a small brook about 200 feet from its mouth. Two types of rock occur here. One is a gray massive rock similar to that occurring at the northeastern end of the lake, while the other is a lighter gray, schistose, micaceous rock which appears to be an alteration

[60] Bowles, O., and Grout, F. F., Unpublished map.

product of the massive rock. The schistose rock is found along irregular zones in the massive rock, all gradations occurring along the contacts. The rock is finely and distinctly laminated, white laminae, probably of crushed feldspar, being interlayered with gray laminae containing mica and other ferromagnesian minerals. The most conspicuous mineral in it is white mica which occurs in tiny flakes parallel to the lamination and produces the schistosity.

The igneous rocks at Long Lake are designated by Van Hise and Leith[61] as Keweenawan, and are believed to be intrusive into the upper Huronian metamorphosed rocks of this region. Winchell,[62] on the other hand, believed that they are equivalent to the Keewatin greenstone of northern Minnesota, and that they formed the basement on which the later sediments were deposited. The former draw their conclusions from the fact that numerous dikes of subsilic igneous rock similar to those occurring at Long Lake are found in Carlton County, and elsewhere cutting schists and slates of upper Huronian age, while the latter notes the similarity between these rocks and the greenstone of the Vermilion district and believes that the quartzite at Dam Lake overlies them.

There are a number of localities in the Cuyuna iron-ore district where subsilicic and intermediate rocks have been shown by drilling to be interlayered with the series of metamorphosed sedimentary rocks, and seem to have been deformed with them. They are evidently not basement rocks on which the metamorphosed series was deposited, nor are they later intrusives in the series. Such rocks are evidently of approximately the same age as the metamorphosed rocks, and bear a relation to them similar to that which the Hemlock volcanic rocks bear to the middle Huronian metamorphosed sediments of the Crystal Falls district of Michigan.

Subsilicic rocks of this character that have suffered considerable deformation and alteration are found outcropping at a number of localities in Carlton and Aitkin counties besides the Long Lake area already mentioned. Some of these occurrences simply exhibit schistosity while in others considerable metamorphism and recrystallization of the minerals have taken place. The rock differs distinctly from that which occurs as dikes and intrusive masses in the slate occurring along St. Louis River or in the schist and slate of the Cuyuna district. While it is not impossible that post-Keweenawan deformation may have produced changes in these rocks, it seems more logical, in view of the fact that igneous rocks are known to be associated with the schists of the Cuyuna district, to

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[61] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: *U. S. Geol. Survey Mon.* 52, Pl. 14, 1911.

[62] Winchell, N. H., The Cuyuna iron range: *Econ. Geology*, vol. 2, p. 568, 1907.

class the more altered types of subsilicic and intermediate igneous rocks with this older group.

Carlton County contains outcrops of subsilicic igneous rocks both of the older and the later types in many places.

In the NW¼ of SW¼ of section 19, T. 47N., R. 21W., a short distance north and west of Dead Moose River, and just east of the boundary line between Carlton and Aitkin counties, are several low exposures of subsilicic igneous rock. At the western end the group of outcrops is covered for the most part by large boulders. In the central and eastern parts, however, the outcrops rise a few feet above the surrounding area and slope gradually toward the river. The exposures occupy an area about 1,500 feet long east and west, by 400 feet wide north and south. The rock along the north and south sides of the group of outcrops is medium coarse-grained and of a dull grayish green color. It is made up largely of feldspar and hornblende with probably some pyroxene and small scattered crystals of magnetite and pyrite. It may be a diorite or an altered gabbro. In the center of the group of outcrops between the two areas of medium coarse-grained rock, is a dull, dark gray rock with fine-grained texture. This rock has suffered considerable alteration so that it is difficult to tell its nature without thin sections. It contains considerable carbonate, and from field relations it appears that the rock is probably derived from the alteration of the original diorite or gabbro. In the central part of the area of this rock is a light gray, crystalline, carbonate rock made up largely of carbonate and quartz with scattered pyrite crystals. Under surface conditions, the carbonate in it alters to a hydrous oxide of iron, suggesting that at least part of it is iron carbonate. Quartz veins and pegmatite dikes, vertical or dipping steeply to the south and trending about east and west, cut the other rocks. At the contact of the medium coarse hornblende-feldspar rock and the fine-grained altered rock, some shearing has taken place, giving the rock a slightly banded structure. The bands strike N. 56° W., and dip steeply to the south.

In the SW¼ of SE¼ of section 20, T. 46N., R. 21W., on the land of L. Pevon, an outcrop of fine-grained diabase occurs south and east of the farm-house. The main outcrop trends a little north of east for a distance of about 300 feet, while a smaller exposure which is badly decomposed by weathering, occurs about 100 feet farther east. The rock is a dark gray or green, massive, fine-grained, altered diabase. Small grains of pyrite occur abundantly throughout the mass. Near the center of the outcrop a belt of schistose rocks from 5 to 8 feet wide extends from north to south. Running parallel with the schistosity are narrow white bands of calcite. From the field relations, it appears that shearing has taken place between the two masses of diabase, and this schist is a shear zone product. The strike of the schistosity is about N. 40° E. and the dip is 67° southeast. At the west end of the outcrop is a quartz vein six inches wide striking east and west and dipping steeply to the south. On both sides of this vein for a few inches from the contact the rock also is schistose. All gradations can be found in the outcrop from the schistose phases to the massive diabasic phases. In this respect it resembles somewhat the exposure occurring on the southeast side of Long Lake in Aitkin County. The occurrence of the schist indicates that the rock has suffered considerable metamorphism after it was intruded.

Several outcrops of dark igneous rock occur on both sides of the north-south road between sections 14 and 15, T. 46N., R. 21W. The typical rock is a greenish black, very fine-grained diabase, but schistose phases occur intermixed with the massive rock. The southernmost exposure lies about 60 feet west of the road and about 750 feet north of the southeast corner of section 15. It consists mainly of light greenish gray hornblende schist, impregnated with specks of pyrite and containing small scattered crystals of feldspar and calcite. The strike of the schistosity is N. 70° E., and the dip is about 50° to the south. The next outcrop to the north in this group is 50 feet south of the quarter line. The larger part of the exposure lies in section 15, but it crosses the road and extends a few feet into section 14. It is a dark grayish green, or greenish black, dense, fine-grained diabase, made up principally of fine lath-shaped crystals of feldspar with associated hornblende, pyroxene, and scattered crystals of pyrite and magnetite. The central part of the outcrop is slightly sheared, developing an incipient schistosity. The original texture is still retained, but it has undergone some alteration along the shear planes where an abundance of mica has developed. A quartz vein a foot and a half wide with a vertical dip, and trending almost due north and south, cuts the west end of the outcrop, while smaller stringers of quartz and pegmatitic material are of frequent occurrence. Most of them fill north and south joints, but a few run east and west. The remaining outcrop in the group consists of two small exposures of rock similar to that described above, located about 200 feet north of this on the west side of the road, and a larger one situated about 780 feet north of the quarter line on the east side of the road. The latter outcrop occurs at the roadside and extends eastward for about 300 feet. The rock differs from that described above in being more schistose. The schistosity strikes about N. 65° E., and dips about 50° to the south. Some phases of this rock consist of well developed schist. Scattered through parts of the rock are small white spots made up principally of white feldspar, giving the rock a mottled appearance. These are elongated parallel to the schistosity. Along the shearing planes, some of which show slickensides, sericite is abundantly developed. This rock, as far as its general appearance is concerned, is similar to that in the NE¼ of NE¼ of section 4, T. 46N., R. 21W., described below.

Two small outcrops of dark igneous rock occur in the NE¼ of NE¼ of section 4, T. 46N., R. 21W., on the land of William Michalski. The outcrops lie in the cleared field between the road and the house. The rock is medium-grained, light grayish green diabase, considerably altered. In the easternmost outcrop the rock is massive, while in the outcrop to the west the rock has suffered considerable dynamic metamorphism producing a schistose structure. The schistosity strikes about N. 65° E. and dips about 45° to the south. The rock contains long, slender plagioclase crystals imbedded in a light green to gray, fine-grained ground-mass. Occurring abundantly throughout the rock are larger crystals of white feldspar largely altered to calcite, giving the rock a porphyritic appearance. Calcite occurs not only as an alteration of the large crystals, but also abundantly in the fine-grained matrix.

In section 28, T. 47N., R. 20W., about 600 feet due east of the west quarter post, an outcrop of highly altered diabase occurs on the face of an escarpment which rises about 25 feet above the bottom of the valley of Kettle River. The escarpment runs about N. 30° E. and for about 175 feet the rock is exposed along it. The diabase is massive, dull, grayish green and very fine-grained. Calcite occurs as an alteration of the feldspar, but the original diabasic texture is still retained. Besides chlorite and hornblende, which are probably mainly alteration products, there are small grains and aggregates of magnetite and pyrite. Quartz veins are abundant and thin films of quartz occur along the joint planes.

On the opposite side of Kettle River from the outcrops described above, about 100 feet south of the northeast corner of NW¼ of the SW¼, section 28, T. 47N., R. 20W., two small exposures of rock lie at the water's edge on the bank of the river. About 300 feet southwestward a low escarpment rises 20 feet above the river. Near the edge of the latter, also, rock is exposed for a distance of about 125 feet. The rock composing these exposures is a dark grayish green, finely crystalline, igneous rock, much of which shows a fine ophitic texture. In places the rock is dense, while elsewhere it shows a well-developed schistosity. The strike of the schistosity is about N. 45° E. and the dip is 70° to the southeast. The outcrops in section 28 have the appearance of being composed of fine-grained diabase which has locally suffered considerable dynamic metamorphism. The rock is very similar to other subsilicic igneous rocks exposed in the southwestern part of Carlton County which are judged to be flows or intrusive sheets interlayered with the metamorphosed sedimentary rocks of the region. This has already been discussed in connection with the description of similar rocks found at Long Lake in Aitkin County.

Another outcrop of schistose dark igneous rock occurs about 650 feet east of the northwest corner of the NW¼ of the NE¼, section 2, T. 46N., R. 20W., and continues southwestward across the forty-acre tract toward the north-south quarter line. It lies in a low, flat, glaciated ridge, partly covered by a thin mantle of soil. The rock is dark greenish gray, dense and fine-grained, and has well-developed cleavage. It is comparatively fresh and appears to have a fine diabasic texture. It is similar to that occurring in the NE¼ of SE¼ of section 15, T. 46N., R. 21W. Several sets of joints cut the rock into large polygonal blocks. The cleavage strikes about N. 45° E. and dips 17° to the southeast.

Near the center of section 5, T. 47N., R. 18W., on the south side of Park Lake River, two outcrops of dark igneous rock, occupying an area about 180 feet long and 120 feet wide, rise 10 to 15 feet above the meadow. They form two small knolls elongated in an east-west direction, one being north of the other. The rock is dark gray and medium-grained, resembling diorite. The principal minerals are feldspar, hornblende, magnetite, and pyrite. The edges of the larger feldspar crystals have been somewhat altered. Large cubes of pyrite are scattered abundantly through the rock. About a quarter of a mile north is an outcrop of similar rock which, however, is somewhat schistose and in places is mottled due to the presence of white grains of feldspar and calcite.

Small dikes or sheets of subsilicic igneous rocks occur quite commonly in the belt of slate extending along St. Louis River in northern Carlton County and thence southwestward through central and southern Carlton County, and outcrops of them have been noted in many places. They are mentioned in connection with the descriptions of these rocks. One of the larger ones of these is an outcrop of much altered diabase which lies in the bed of West Branch of Moose Horn River in the SW¼ of NW¼, section 15, T. 47N., R. 19W. It occurs intrusive into graphitic slate. Dikes of fresh gabbro and diabase cut the slates and phyllites in the valley of St. Louis River, being especially abundant near the Thomson dam and elsewhere between Carlton and Cloquet.

Dikes of dark igneous rocks have also been mentioned as occurring in various silicic igneous rocks of east central Minnesota, already described, such as those found along Snake River and Hay Creek.

A large number of outcrops of subsilicic volcanic rocks occurs at various points in eastern and southeastern Pine County. They form a part of the area of Keweenawan igneous rocks which extends southwestward from Douglas County, Wisconsin, into eastern Minnesota, forming the so-called "south escarpment." The rocks are practically all of eruptive origin, consisting of massive diabase with texture varying from medium coarse to extremely fine and of various types of amygdaloids. Locally tuffaceous layers occur, but they are not abundant. These rocks have been mentioned in the section on the general geology of east central Minnesota. They bear no direct relation to the rocks of the Cuyuna iron-ore district, and need not be discussed further here. They have been mapped and described in detail by Grout.[63]

OUTCROPS OF SLATE, SCHIST, AND OTHER METAMORPHIC ROCKS

MORRISON AND BENTON COUNTIES

The westernmost of the outcrops of metamorphic rocks in central Minnesota are chloritic schists found in the vicinity of Randall. They cover an area nearly half a mile long north and south, and about 500 feet wide. The north end of this area of outcrops is at the railway station, the rock being exposed in a cut nearly opposite the station. The outcrops are not continuous but occur at frequent intervals, southwest of the railroad and of the north branch of Little Elk River.

The chloritic schist is dark green and is essentially similar in all the exposures. It is commonly fine-grained and shows a marked but uneven cleavage which has a general direction of N. 40° E. and has dips varying from vertical to 70° northwest. No bedding is distinguishable. (Plate VI.)

The rock is essentially a fine-grained mixture of chlorite and feldspar with some quartz, which varies in abundance in different parts. Both chlorite and feldspar show parallel arrangement and elongation along the general direction of the cleavage. The quartz is in irregular grains either disseminated with the other minerals or bunched in spots. Through this fine-grained matrix are scattered somewhat larger grains of siderite. These vary in size from mere specks to perhaps one-tenth of an inch in diameter, and are abundant in all phases of the rock. Some have rhombic outlines and consist of single crystals, but most of them are irregular and consist of several individual crystals. Near the surface the siderite is oxidized to limonite and forms yellowish brown specks of ocher. Locally also the ocher is concentrated along cracks and in small openings. In some phases of the rock siderite in small irregular grains is disseminated through the matrix, along with feldspar, chlorite, and quartz.

Besides grains and little bunches of siderite, other minerals such as quartz, magnetite, and chlorite are found in the rock. Magnetite is very abundant locally, and although it is generally distributed through the rock it may be entirely absent in some places. Some magnetite grains have crystal outlines, while others are irregular. Quartz usually does not occur in large grains, but bunches of small grains are numerous.

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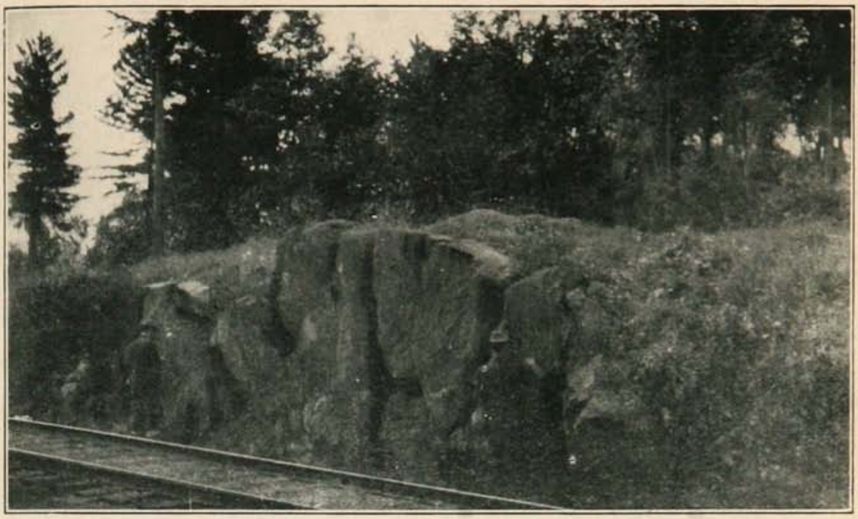
[63] Grout, F. F., Contribution to the petrography of the Keweenawan: *Jour. Geology*, vol. 18, pp. 633-657, 1910.



A. OUTCROP OF CHLORITIC SCHIST NEAR THE STATION AT RANDALL, MORRISON COUNTY
PHOTO BY CARL ZAPPFE

B. CHLORITIC SCHIST OUTCROPS AT RANDALL SHOWING CLEAVAGE
PHOTO BY CARL ZAPPFE

Chlorite generally is evenly disseminated but locally it occurs in bunches. Small grains of muscovite are found disseminated in much of the rock.

While all the rock is chloritic schist, there are local minor variations in the composition, color, and texture, as already indicated. At several points, nodular light-colored brownish masses are found which consist of quartz, feldspar, and siderite, but contain no chlorite or magnetite while elsewhere magnetite grains are closely spaced. The variation in magnetic attraction in the vicinity of Randall is attributed to this abundance of magnetite in the chloritic schist.

The Randall exposures are directly on the line of the southwest extension of the Cuyuna range. The rock is probably continuous with the chlorite schists which have been found to be so abundant in association with the iron-bearing formation in various parts of the Cuyuna range. In general appearance and composition the rock at Randall resembles closely the chloritic schist found in many of the Cuyuna range mines.

In section 3, T. 130N., R. 30W., about three miles east of Randall there are a few small exposures of chloritic schist which might readily be mistaken for boulders. They are located in the woods near the center of the section, just east of a little-used north and south wagon road that runs along the quarter line.

While most of the outcrops consist of dark green or grayish green chloritic schist, some of them have small bands of a gray porphyritic rock with large phenocrysts of white feldspar. Such bands are enclosed between chloritic schist, and there is a complete gradation between the two, showing that the chlorite schist is a dynamically metamorphosed phase of the porphyry. The direction of the cleavage is similar to that in the exposures near Randall.

About two miles north of Little Falls, Little Elk River empties into Mississippi River. Outcrops of gray slate and phyllite occur on both sides of this stream, the easternmost of the exposures being about 500 feet above its mouth. They extend along the stream for about 700 feet and within this distance several folds are found. The outcrops show beautifully both cleavage and bedding, and the relation between the two can be determined in the individual outcrops. The general strike of the bedding is about N. 50° E., while the dip varies on account of the folding. The strike of the cleavage varies between N. 32° E. and N. 61° E. The dip of the cleavage planes varies in the individual folds, but is in general about 75° southeast.

The exposures consist mainly of finely crystalline phyllite, most of which shows fine lamination parallel to the bedding. The rock is made up of fine quartz and biotite which vary in relative abundance in different layers. In some of the exposures, massive graywacke beds are interlayered with finely laminated, more highly micaceous phyllite beds. All the beds show cleavage, but the micaceous layers show it more perfectly. Thus the relation between the cleavage and the axial planes and pitch of the folds can be readily seen, and the relation of these folds to the major structure determined. The pitch of the folds is to the southwest, while the axial planes dip to the southeast, indicating that the folds are situated on the south limb of a major anticline.

In the city of Little Falls, a small island (Mill Island) occurs in Mississippi River just below the dam. (Plate VII A.) The shores around the northern half of this island consist of continuous outcrops of slate and phyllite, most of which are gray and finely micaceous. Although considerable recrystallization has occurred, the bedding is still plainly visible both on account of fine lamination and on account of an interlayering of beds of different materials. Some beds are quartzose while others are argillaceous and micaceous, the latter, however, being much the more abundant.

The beds are flexed into a number of minor folds all trending in a general northeast-southwest direction diagonally across the island. The strike of the bedding is approximately N. 30° E., parallel to the folds, while the dip varies. The schistosity is fairly regular, in general striking approximately parallel to the bedding and dipping at angles varying between 75°NW. and 75°SE. The relation of the cleavage to the bedding is clearly shown in some of the minor folds. (Plate VII B.)

The rock on Mill Island is principally dark gray, finely micaceous slate and phyllite, some portions of which are argillaceous and some quartzitic, the different phases being interlayered. Some beds are massive and quite uniform in texture, and show the bedding only by fine color lamination, while in other beds thin layers of fine argillaceous slate are interbedded with more coarsely crystalline quartzitic or micaceous phyllite. The cleavage cuts across all the laminae indiscriminately. The rock is composed of biotite and quartz with probably a considerable percentage of white mica in fine sericitic flakes. In the fine-grained slaty layers, sericite is very abundant, and distinctly visible mica flakes are almost absent, while in the coarser layers numerous fine flakes of biotite occur, disseminated in a quartzose or sericitic ground-mass. Other minerals which occur locally in the slate and phyllite are ottrelite, garnet, amphibole, and chlorite. Ottrelite occurs as small, scattered, thin, shiny black plates lying parallel to the cleavage in some of the phyllite layers, and garnet also occurs locally in the phyllite in tiny, disseminated crystals. Both are rare. Garnet, amphibole, and chlorite, however, are found more characteristically in a number of elongated, lens-shaped, concretion-like masses which occur interlayered with the slate and phyllite. Some of these masses are five or six feet long and a foot or more thick. They consist of a hard, dark, siliceous ground-mass in which are embedded

A. SLATE AND PHYLLITE OUTCROPS ON MILL ISLAND AT LITTLE FALLS, MORRISON COUNTY

B. SLATE OUTCROP AT LITTLE FALLS SHOWING THE RELATION OF CLEAVAGE TO BEDDING

abundant fibrous, black amphibole or dark red garnet with associated dark green flakes of chlorite. The amphibole crystals range up to one half of an inch in length and show no regularity in their arrangement. The garnet crystals average about one eighth of an inch in diameter, being much larger than those disseminated through the phyllite. Chlorite is commonly associated with it, and appears to be an alteration product of it. Rarely, garnet and amphibole are found together in the same concretion-like lenses, but commonly they are in separate lenses. Ottrelite also is often distinctly associated with these lenses. It does not occur within them, however, but in the phyllite or slate layers along their borders. Amphibole, on the other hand, is found only in the concretion-like masses, and not in the slate and phyllite. The origin of the concretion-like masses has not been determined.

Another outcrop of gray slate and phyllite similar to that at Little Falls is found on Swan River near Ledoux in the SE¼ of SE¼ of section 4, T. 128N., R. 30W., about 7 miles southwest of Little Falls. The exposures are on both sides of the stream near the water level and are entirely covered during high water. They are found just east of the bridge between sections 3 and 4. The rock is a finely crystalline micaceous, argillaceous, or quartzitic phyllite with well-developed cleavage striking about N.20°E., and dipping from 57° southeast to vertical. The bedding is shown by fine banding and lamination which is cut across by the cleavage lines. It strikes in general N.25°E. and dips 75°N.

Upham[64] mentions the occurrence of another outcrop of slate on Swan River in section 1, T. 128N., R. 20W., about 2½ miles below the outcrop just mentioned. It is said to crop out in the bed of the stream but was not found by one of the writers (Johnston) who visited the locality.

Scattered outcrops of garnetiferous, staurolitic mica schist are found on both banks of Mississippi River at intervals between the mouth of Swan River, about 4 miles south of Little Falls, and a point about one half mile south of the Minneapolis, St. Paul, and Sault Ste. Marie railroad bridge in section 32, T. 128N., R. 29W. The best exposures are on the west bank, but good exposures occur on the east bank also. Locally they extend partly or entirely across the river, forming rapids.

The exposure farthest north is on the west bank of the river at Pike's Rapids, a short distance below the mouth of Swan River in section 7, T. 128N., R. 29W. Southward from this locality exposures are found at Cash's Rapids in section 20, T. 128N., R. 29W. and at various points between Cash's Rapids and the railroad bridge above mentioned. Below the bridge several exposures occur as far south as Blanchard's' Rapids,

[64] Upham, Warren, The geology of Crow Wing and Morrison counties: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 2, 1882-1885, p. 600.

where are found the outcrops of gabbro, already described. (See page 51.) In one small outcrop about 1,000 feet south of the bridge, a very quartzitic phase of the schist is cut by a narrow dike of dark hornblende rock.

Most of the schist exposures are near the river's edge, and very few extend far above the level of the water on the river bank. At one or two localities, however, as at the Minneapolis, St. Paul, and Sault Ste. Marie railroad bridge, fairly large exposures are found. Because of the highly metamorphosed state of the rocks, it is only in the larger exposures that it is possible to determine the attitude of the bedding and its relation to the schistosity. Thus at the railroad bridge the schist, although strongly metamorphosed, shows interlayering of coarsely crystalline micaceous phases with finer grained quartzitic phases indicating bedding. The layers in this exposure strike N.8°E. and dip 57°NW. while the schistosity strikes N.15°E. and dips 52°NW. In the outcrops at the other localities visited, it was not possible to distinguish the bedding. The schistosity, however, was found to be perfect and fairly regular. Thus at Pike's Rapids, below the mouth of Swan River, the strike of the cleavage is N.30°E. and the dip is 65°NW., while at Cash's Rapids the strike is N.30°E. and the dip 60°NW. Above Blanchard's Rapids, south of the railroad bridge in the last schist exposure downstream, the strike of the schistosity is about north and south and the dip is 65°W. Thus there appears to be a gradual turning of the direction of schistosity from a strike of N.30°E. to nearly north and south on going southward.

The schist in all the exposures is very similar, being a micaceous or quartzose micaceous schist with abundant crystals of garnet and staurolite scattered through it. The schist, while in general similar to that at Little Falls, is much more coarsely crystalline and is more uniform in character, consisting of intermixed quartz grains and biotite flakes, the latter parallel to the schistosity. The fine interlayering which is common in the slate and phyllite at Little Falls has here been entirely obliterated, due to recrystallization. Garnet and staurolite are both abundant and occur throughout the rock. The garnet crystals are small, usually averaging about one twentieth of an inch in diameter, but the staurolite crystals range up to an inch in length and one half inch in width and frequently show cross-shaped twins. The staurolite and some of the garnet also contains abundant included quartz grains and occasional biotite flakes. The outline of the staurolite crystals as seen under the microscope is very irregular and indicates that the staurolite has grown at the expense of the quartz and biotite. The quartz grains included in the staurolite crystals are smaller than those in the remainder of the rock, showing they have probably been partly resorbed to form staurolite. A few staurolite crystals contain included garnet crystals also. Ottrelite which is present in the rocks at Little Falls has not been found in these schists. Probably it has disappeared during the more intense metamorphism which the schists have suffered. The paragenesis of minerals in the formation of garnetiferous and staurolitic schist from the original shale appears to be in the following order: quartz, biotite, ottrelite, garnet, staurolite.

It seems beyond question that the slate and phyllite on Little Elk River and at Little Falls, and the garnetiferous and staurolitic schists on Mississippi River represent different stages in the metamorphism of the same original rock. The metamorphism seems to have become more intense on going southward, due probably to the presence of the great granite mass in the St. Cloud region against which the sediments were crushed. This fact would seem to indicate that much of the granite in this region was present before the deformation of the sediments took place, probably being pre-Keweenawan in age. The alternative hypothesis is that the granite is later in age, and that the metamorphism of the sediments was due to the intrusion of the granite. It does not seem likely, however, that the metamorphic effect of such an intrusion should be felt for many miles away from the contact, especially in an argillaceous sedimentary rock. Besides, the minerals developed are characteristic of dynamic metamorphism and not of contact metamorphism.

Hall[65] notes the probable occurrence of schist in the northern part of Benton County, and on the basis of this Van Hise and Leith[66] have extended the upper Huronian slate area into Benton, Sherburne, and Stearns counties, while the granitic rocks of this region have been mapped as Keweenawan intrusives. The data on which the mapping of this schist was based are not available, so that the character and extent of the schist are not known.

CROW WING, CASS, AND AITKIN COUNTIES

In the region north of the Cuyuna district and west and southwest of the Mesabi district, no rock outcrops are definitely known, although several have been reported from different localities.

An outcrop of crystalline limestone is frequently mentioned as occurring in NW¼ of SE¼ of section 29, T. 137N., R. 28W. south of White Fish Lake in northern Crow Wing County. This supposed outcrop has been visited by the writers, who have come to the conclusion that it is a large glacial boulder. The rock rises about 15 feet above the ground and is about 20 feet by 30 feet at the base. It has a rather jagged outline and consists of light gray to pink crystalline limestone with numerous small masses and thin layers of chert. Certain layers are somewhat

[65] Hall, C. W., Keewatin area of eastern and central Minnesota: *Bull. Geol. Soc. Amer.*, vol. 12, pp. 343-376 (map), 1901.

[66] Van Hise, C. R., and Leith, C. K., *op. cit.*, Pls. I and XIV.

argillaceous and sericitic, others are quartzitic. Drilling operations not far from this locality indicate that the glacial drift in this region varies in thickness from 200 to 300 feet. It appears improbable that there should be such extreme irregularities as would result in the occurrence of rock outcrops.

Occasional references are seen in the literature[67] to an outcrop of rock in Cass County, reported as occurring along the northern edge of T. 142N., R. 27W., on Boy River, one or two miles below Boy Lake. The lithological character of the rock is not known, but it is presumed to be quartzite. The writers have not seen the outcrop, nor have they seen any person who knows definitely of its existence.

Quartzite outcrops are found near Dam Lake, Aitkin County, at two localities, one in the SE¼ of section 34, and the other in the NW¼ of section 35, T. 47N., R. 25W. The rocks composing the exposures are very similar in both localities, being hard, coarse, light gray to pink vitreous quartzite. Much of the rock is very coarse, being fine conglomerate or grit rather than quartzite. The particles composing it range up to one fifth of an inch in diameter, and all are distinctly rounded. They consist almost entirely of glassy quartz, some being perfectly transparent and colorless while others are bluish white opaline. They are all firmly cemented so that the rock breaks across the fragments rather than around them.

At both localities, several small rounded exposures protrude just above the soil. The rock is very massive and shows no trace of bedding. Even banding due to interlayering of coarser and finer material is apparently absent. A few joints cut across the outcrops and some of them may be separation planes indicating the bedding, but their character is very doubtful. Winchell,[68] who visited these outcrops, states that the exposure in section 34 shows an unmistakable bedding plane striking N.60°E. and dipping S.30°E. at an angle of 25°. This observation was not confirmed by an examination of the outcrops made by the writers. The line which connects the two outcrops, however, and the extension of which to the southwest passes over other occurrences of quartzite found by drilling, has a direction of N.50°E. which corresponds fairly well with the general strike of the sedimentary beds throughout the Cuyuna district. The general dip of these beds also is to the southeast, but at a very steep angle. It does not seem improbable, therefore, that the quartzite bed has a general northeast-southwest strike and a south-

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[67] Upham, Warren, The geology of Cass County and of the part of Crow Wing County northwest of the Mississippi River: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 4, 1896-1898, p. 65.

[68] Winchell, N. H., The Cuyuna iron range: *Econ. Geology*, vol. 2, pp. 566-567.

easterly dip, although there is apparently nothing in the individual exposures to indicate this structure.

PINE, CARLTON, AND SOUTHERN ST. LOUIS COUNTIES

Several large areas of outcrops of metamorphosed sedimentary rocks are found in the northwestern part of Pine County, south, east, and northeast of Denham, these being the southernmost outcrops of this type of rock in eastern Minnesota. The rocks are principally mica schists, but hornblende schist, quartzite, and limestone occur also.

The largest area of outcrops is that through which the Minneapolis, St. Paul, and Sault Ste. Marie Railroad passes east and northeast of Denham. The principal exposures are in the eastern half of section 19, T. 45N., R. 20W., but some are found also in the western part of section 20 and in the southeastern part of section 18. The railroad cuts through or passes over most of the outcrop.

The rock throughout this area is quite uniform, being a quartzose mica schist. It varies slightly, however, in texture and in the relative amounts of mica and quartz which it contains in different parts. Locally it is fine-grained and quartzitic, consisting of sugary quartz with abundant fine scattered biotite flakes parallel to the schistosity. Elsewhere the quartz is present in minor amount and the mica is more coarsely crystalline, producing a very marked schistosity. Local layers consist almost entirely of mica. Small disseminated crystals of garnet are scattered throughout the rock, but are more abundant in the coarsely micaceous phases. The rock in general is dark gray, the mica being mainly biotite; but white mica is intermixed with it.

Schistosity is strongly developed throughout the area so that in general it obliterates the bedding. Locally where the bedding can be distinguished by the faint interlayering of the quartzitic with the more coarsely micaceous phases, it appears to be in general parallel to the schistosity. The schistosity is quite regular in strike in the different outcrops throughout the area, being about east and west or slightly north of east. The dip, however, varies considerably in different places. In the southern part of the area it is to the north at angles varying in general between 30° and 70°. In the northern part of the area, however, both northerly and southerly dips are found. Locally the schistosity is almost horizontal.

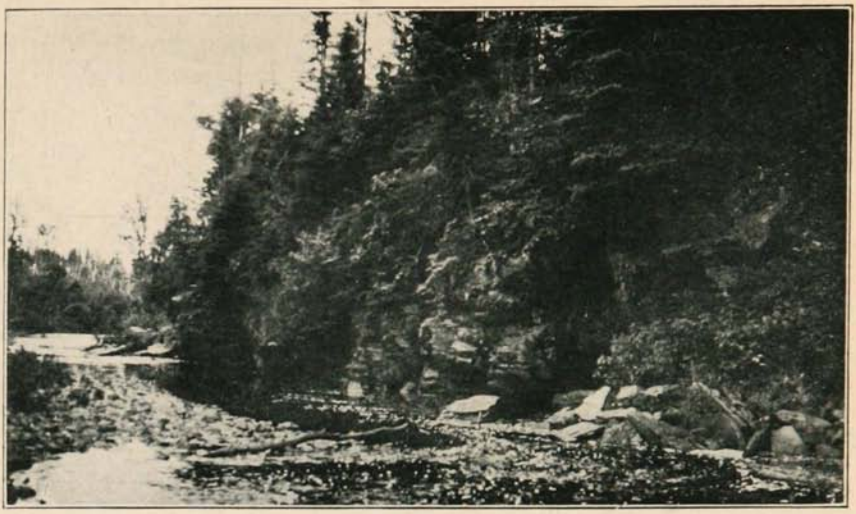
About a mile southeast of Denham is one of the most interesting groups of outcrops of metamorphosed sediments in east central Minnesota. The exposures occur principally in the E½ of SE¼ of section 25, T. 45N., R. 21W., but extend for short distances into the adjacent parts of section 30 on the east and section 36 on the south. An irregular depression with low bluffs along it runs in a southeasterly direction through this area. It varies from 200 feet to 400 feet in width, and has the appearance of being a small abandoned stream valley. The rock outcrops are found along the low bluffs on both sides of the depression. The area is wooded, the center of the depression being swampy.

The most northerly outcrops on both sides of the depression consist of hornblende schist. To the south of these, a large outcrop of quartzite is found on the west side and an outcrop of mixed quartzite and crystalline limestone on the east side. South of the quartzite on the west side are exposures of hornblende schist, followed by more quartzite and finally mica schist, while on the east side opposite to these are outcrops of mica schist and of a dark fine-grained igneous rock. The strike of the beds throughout is approximately east and west, while the dips vary 15° or 20° on either side of vertical. The dip of the cleavage of the schistose rocks is in general to the north at somewhat lower angles. In the schistose rocks the recrystallization has almost entirely obliterated the bedding, but in the quartzite and limestone the bedding is well marked. Locally rocks of different character are found interlayered.

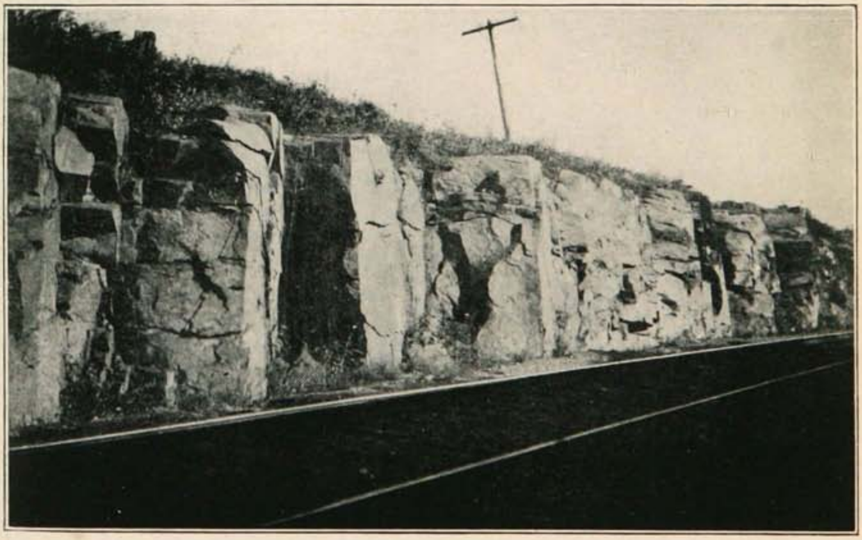
The principal exposures consist of quartzite which has suffered considerable metamorphism. It is light-colored gray, pink, or brown and is medium coarse-grained. Tiny pebbles, generally of light blue quartz, are abundantly scattered through the rock, in some places making up the larger part of the mass and forming a fine conglomerate or grit. They range in diameter up to about one fifth of an inch, although locally pebbles an inch and a half or more in diameter are found. In places fine and coarse material occur interlayered in thin beds. The quartzite has undergone considerable recrystallization so that abundant muscovite is developed throughout. Some parallel arrangement is noticeable in the muscovite, but this is not prominent enough to produce a marked schistosity. The muscovite, although generally fine, occurs in distinct flakes.

The crystalline limestone is associated with the quartzite and resembles it in appearance. It is pink to light gray in color and finely crystalline. Muscovite occurs in it abundantly in fine disseminated flakes or is segregated into thin discontinuous streaks. Some phases of the limestone are dark gray and contain thin layers consisting largely of dark hornblende. The laminae of both muscovite and hornblende are developed parallel to the bedding, suggesting that they were formed by the recrystallization of impure limestone layers.

The hornblende schist is dark grayish green and is generally coarsely crystalline when composed mainly of hornblende and finely crystalline when it contains considerable quartz. It has a well-developed cleavage which is especially prominent in the more coarsely crystalline phases. The hornblende is dark green and fibrous. Biotite is generally associated with it and in places muscovite also occurs.



A. OUTCROP OF SLATE AND PHYLLITE ON SPLIT ROCK RIVER, SOUTHWESTERN CARLTON COUNTY, SHOWING HORIZONTAL SCHISTOSITY



B. OUTCROP OF SLATE AND PHYLLITE ALONG THE RAILWAY NORTHEAST OF DENHAM, PINE COUNTY, SHOWING PARALLEL JOINTING

The mica schist is light to dark gray. In places it consists mainly of muscovite with subordinate quartz, and then shows marked cleavage and fine lamination parallel to the cleavage. The cleavage faces present a silvery sheen due to aggregates of parallel muscovite flakes. In other places, quartz predominates while both muscovite and biotite occur in abundant fine flakes. In the latter phase the bedding is still frequently recognizable, cutting across the schistosity or parallel to it. The muscovite schist is commonly associated with the crystalline limestone beds, frequently being interlayered with limestone. The quartzose mica schist with abundant biotite is similar to that exposed along the railway east of Denham.

In Carlton County, abundant outcrops of slate, graywacke, phyllite and mica schist occur in the valleys of Kettle, Moose, and St. Louis rivers and their branches, the area of outcrops extending in a general northeast-southwest direction across the county. Many exposures are found directly on the banks of streams, having been cut into by the streams during the process of erosion. Other exposures, however, occupy higher areas, in places forming prominent ridges rising above the general level and elsewhere occurring as low, flat outcrops. The ridge-like exposures are very characteristic. In some localities, as at Carlton and near Atkinson, many parallel rock ridges cover considerable areas. Some of these are 40 or 50 feet high and many hundred feet long. Nearly all of them have a general direction ranging between east-west and northeast-southwest, roughly parallel to the cleavage.

The most southwesterly outcrops of metamorphic rocks in Carlton County are those along Split Rock River, a western tributary of Kettle River. A high cliff of mica schist about 900 feet long is exposed on the south side of Split Rock River in the NW¼ of NE¼, section 29, T. 46N., R. 21W. It rises abruptly from 5 to 30 feet above the stream, trending approximately east and west. Small exposures appear at intervals west of the main cliff in the bed of the stream for a distance of several hundred feet. The rock is made up of alternate bands of fine and coarse grained quartz mica schist associated with some dark graphitic schist. Small grains of pyrite and quartz lenses occur in places. The finer grained varieties are finely plicated and consist mainly of mica, while the coarser grained varieties are rich in quartz. The average strike of the schistosity is about N.80°E. and the dip varies, due to minor folds, but is in general to the south at a low angle. The bedding where it can be observed is approximately parallel to the schistosity.

An outcrop of mica schist and phyllite similar to that described above occurs in the SE¼ of SE¼ of section 21, T. 46N., R. 21W. on the south side of Split Rock River. The outcrop begins at the east line of the section and extends westward about 1,100 feet. The eastern part appears in scattered patches above the soil and the western half stands as a vertical cliff from 2 to 10 feet above the water. The bedding in this outcrop is well marked because of the alternation of more or less massive layers rich in quartz, with finely plicated layers consisting principally of mica. The strike of the bedding is about N.75°E. and the dip 30° to the south. Locally minor folds are found, which pitch westward at a low angle, and the axial planes of which dip southward indicating that they are drag folds on the south limb of a larger anticline.

The outcrops along Split Rock River are the only exposures of schist or phyllite found in Carlton County west of the main valley of Kettle River. On Kettle River itself abundant outcrops are found at intervals, almost from its source, southward through southern Carlton County and into Pine County. The most northerly of these outcrops is said to occur near Kettle Lake. It is reported that slate was encountered during the construction of the drainage ditch heading out of Kettle Lake in the SW¼ of SE¼ of section 18, T. 48N., R. 19W. The slate is said to have been found in the bottom of the ditch a short distance from the lake. This has not been verified by the writers.

The first exposure south of Kettle Lake in the Kettle River valley is found in section 2, T. 47N., R. 20W., in the bottom and along the sides of the drainage ditch. In the SW¼ of NE¼ of this section, small exposures are found in the bottom of the ditch for a distance of about 500 feet, while in the NE¼ of SW¼, beginning about 150 feet southwest of the center post and bearing a little west of south, rock is exposed continuously in the ditch and along the sides for about 700 feet. The maximum width of the exposure east and west is about 800 feet.

The rock in both localities is made up of alternate bands of slate and graywacke. The slate is dark gray to greenish black, very fine grained, with well-developed cleavage. The bedding is brought out clearly by difference in color due to the variation in the fineness of the material. The graywacke is light gray and fine-grained, with a few small scattered pyrite grains. The general strike of the bedding is about N.75°E. and the dip varies in short distances, due to the presence of minor folds which pitch at low angles eastward. Quartz stringers occur along the crests and troughs of the minor folds and die out along the limbs. The strike of the cleavage is approximately parallel to the bedding and the dip is 73° to the south. The relations of the folds and cleavage indicate that this outcrop is on the south limb of a larger anticline.

Near the south line of the SE¼ of SW¼ of section 21, T. 47N., R. 20W., two long, narrow, parallel rock ridges rise on the west bank of Kettle River and trend southwestward. The larger or south ridge is 60 feet wide by 275 feet long and rises about 20 feet above the stream. The north ridge is about 10 feet wide and 50 feet long, and is only a few feet above the stream. The rock is a dark gray, fine-grained, dense hornblende schist which weathers to a rusty brown. Locally it has a marked schistosity, and fine mica flakes are developed along the cleavage planes. The strike of the schistosity is about N.20°E. and the dip is 80° southeastward. Much of the fresh rock has the general appearance of being dynamically metamorphosed, fine-grained, dark igneous rocks, but the original textures have been obliterated and are not recognizable in the field.

The next outcrop of schist to the south in the Kettle River valley is near the mouth of Silver Creek in the SW¼ of NW¼ of section 16, T. 46N., R. 20W. About 30 feet from the mouth, in the bed of the brook, a light gray, fine-grained phyllite crops out and is cut by a quartz vein trending a little east of north and standing almost vertical. This was explored for gold about 30 years ago, and a pit 10 feet by 10 feet was sunk on it to a depth of about 30 feet.

The formation outcrops again on the west bank of Kettle River about 130 feet below the mouth of Silver Creek, making a vertical cliff 15 to 20 feet high for a distance of about 140 feet along the river. The bedding is brought out very clearly by the difference in the coarseness of the original sediments, giving lighter and darker bands. While most of the rock is light gray, fine-grained micaceous phyllite, portions of it are highly calcareous and other portions more siliceous. On the weathered surface, the interlayering of calcareous portions with siliceous portions is clearly shown. The general strike of the bedding is about N.70°E. and the dips vary from 9° to 17° to the south, due to minor folding. These minor folds pitch eastward at an angle of about 15°.

Somewhat over a quarter of a mile below the above outcrop, or about the west central part of the NE¼ of SW¼ of section 16, T. 46N., R. 20W., on the west bank of Kettle River, near the water's edge, is an exposure of light yellowish gray, finely laminated micaceous phyllite. The rock is badly weathered and soft. It is exposed for about 100 feet. The strike of the schistosity is about N.45°E. and the dip varies. At the south end of the outcrop it is 25°N., while in the central and northern parts it is 45° to the south.

At this locality, an outcrop of the so-called "Hinckley" sandstone is reported,[69] but was not found by the writers.

In the NE¼ of section 22, T. 46N., R. 20W., several outcrops of dark, fine-grained hornblende schist occur as ridges on both sides of Gillespie

[69] Winchell, N. H., The geology of Carlton County: *Geol. and Nat. Hist. Survey of Minn., Final Rept.*, vol. 4, 1896-1898, Pl. 56 and p. 16, 1899.

Brook. At the center of this quarter section, on the north side of the brook, is a large ridge trending about east and west. It is about 250 feet wide and 800 feet long, and rises from 5 feet to 25 feet above the stream. In part it is covered by a thin mantle of soil and loose blocks. The rock is greenish gray, fine-grained, sericitic, hornblende schist. Small specks and blotches of sericite cover the cleavage surfaces. The schistosity is well developed throughout, striking about N.54°E. and dipping 35°SE.

About 600 feet north of this outcrop several small low ridges of the same kind of rock crop out. The strike of the schistosity is N.75°E. and the dip is 19°S. About 400 feet southwest of the center of the quarter section on the southwest side of the stream a triangular ridge rises from 6 to 15 feet above the stream. The rock is the same greenish gray schist. The schistosity strikes N.41°E. and dips 3° southeast. On the south side of this ridge is a fine-grained, gray, mottled rock with brown specks roughly parallel to a poorly developed schistosity. East of the above-mentioned outcrop on the south side of the brook, a long low ridge begins about 200 feet from the east line of the section and continues eastward parallel with the stream for about 300 feet in section 23. The ridge rises a few feet above the stream and is, for the most part, covered with soil. On the weathered surface the outcrops consist of a rusty brown, micaceous, schistose rock. The fresher material, however, is fine-grained gray schist with small rusty brown spots parallel to the schistosity. The strike of the schistosity is about N.75°E. and the dip 19°S. The rocks composing the group of outcrops in sections 22 and 23 are mainly fine-grained hornblende schists. All show well-developed cleavage and banding. They have somewhat the appearance of being dynamically metamorphosed dark igneous rocks, but the original texture is no longer recognizable and they are therefore grouped with the schists and slates. They resemble closely, however, many of the metamorphosed, fine-grained, dark, igneous rocks found in this part of Carlton County and may represent a more advanced stage of metamorphism.

In the SW¼ of SE¼ of section 21, T. 46N., R. 20W., about a quarter of a mile north of the mouth of Gillespie Brook, on the east bank of Kettle River, an outcrop of decomposed schist makes a cliff 10 to 30 feet above the stream, for a distance of about 400 feet. The rock is a badly weathered schist, reddish and yellowish green in color and very soft. It is broken into small irregular blocks by several intersecting sets of joints. The rock shows a fine lamination or color banding parallel to prominent, gently undulating, parting planes. Small flakes of sericite and quartz stringers lie parallel to the lamination. The color bands may be due to the original difference in the material of different layers, or it may be secondarily developed parallel to the parting planes. The strike of the parting planes varies from N.85°E. at the north end of the outcrop to N.60°E. at the south end, and the dip from 9°N. at the north end to 25°SE. at the south end.

About 700 feet south of the above exposure, on the west bank of the river, decomposed schist crops out in a vertical cliff about 20 feet high. The exposure extends for 150 feet along the stream. The rock is like that described above. At the foot of the cliff, however, it is less weathered and consists of light greenish gray schist. Near the top of this cliff is a rusty light green schist infiltrated with limonite. The rock shows undulating parting planes similar to those in the outcrop on the east bank of the river.

Just below the mouth of Gillespie Brook, Kettle River turns westward. About 500 feet west of this bend on the north side of Kettle River a low rock ridge can be traced by frequent small exposures from the bank of the river northward about 300 feet to an east-west road which crosses the river below Gillespie Brook. A small outcrop lies in the road about 125 feet farther west. On the river bank the rock forms a cliff about 15 feet high and is exposed for a distance of about 250 feet. Most of the rock in this exposure is the same rotted, light, rusty green schist as that occurring along the river above the mouth of Gillespie Brook, although some of the less decomposed material is clearly chloritic and sericitic schist. At the west end of the outcrop, however, a different type of rock occurs. It is not finely laminated and shows no color banding, but is a soft, decomposed, light yellowish green, fine-grained rock with conchoidal fracture. Judging from its structural relation to the schist, it is probably a dike or sill of decomposed igneous rock. The contact of this rock and the schist strikes N.40°E. and dips 47°SE., while the banding of the schist strikes about N.34°E. and dips 25°SE. The exposures in the road consist of decomposed, greenish brown schistose rock which appears to have been chloritic schist. The schistosity strikes about N.70°E. and dips 28°S.

The only other outcrop of greenish brown rotted schist occurring in this vicinity forms a bank 15 feet high on the south side of the above-mentioned road about 350 feet east of the mouth of Gillespie Brook, in the NW¼ of NE¼ of section 28, T. 46N., R. 20W. The strike of the schistosity is about N.70°E. and the average dip is about 50°S.

Black graphitic schist outcrops in a low mound about 600 feet southwest of the mouth of Gillespie Brook and about 300 feet from the south bank of Kettle River, in the NE¼ of NW¼ of section 28, T. 46N., R. 20W. This mound is about 50 feet wide east and west and about 80 feet long. A small cut 10 by 20 feet, and 6 feet deep at the face has been excavated in it. The rock has well-developed schistosity and shows crumpled and crenulated foliation planes along which graphite is developed abundantly. The strike of the schistosity is about N.85°E. and the dip about 35°S. Near the surface the parting planes are stained with limonite. Pyrite crystals and small cavities, from which pyrite has been dissolved, are disseminated through the schist. Quartz stringers occur in some places.

Below the outcrops of graphitic and other schist near the mouth of Gillespie Brook, no outcrops are found along Kettle River for a distance of about three fourths of a mile. Beyond this, however, a group of exposures occurs in the southwestern part of section 28 and the southeastern part of section 29, T. 46N., R. 20W., forming escarpments along the river. The main escarpment on the east side of the river begins in the NW¼ of SW¼ of section 28, about 300 feet east of the river, and continues with frequent exposures, southwestward across the southeast corner of NE¼ of SE¼ of section 29, into the SE¼ of SE¼ of section 29, where it forms a vertical cliff 20 feet high and about 350 feet long on the south side of a big bend which occurs in the river at this place. The outcrop varies in width from a few feet at the north end to 400 feet at the south end. Exposures also occur on the west side of the river about 600 feet north of the big bend near the south line of the NE¼ of SE¼ of section 29. A rounded hill of rock about 230 feet wide east and west and about 260 feet long rises from the water's edge to a height of about 30 feet.

The principal rock in this group of exposures is a dark greenish gray, banded, fine-grained, micaceous hornblende schist. There is an alternation of bands of coarser and finer grained material. The schistosity is parallel to the banding or lamination. Stringers and lenses of quartz and quartz and calcite, varying from a fraction of an inch up to several inches in thickness in places lie parallel to the lamination. Generally in the larger lenses the quartz occupies the middle zone with calcite on either side. Quartz and calcite also form thin films along the joint planes. Pyrite occurs abundantly as small stringers along the banding and joint planes, and as crystals disseminated through the rock. At the north end of the escarpment the banding and schistosity strike about N.75°E. and dip 40°S., and at the south end they strike about N.85°E. and dip 27°S. Gentle undulations occur between these points. At the outcrop on the west side of the river the strike of the banding and schistosity is about N.85°E. while the dip is to the south at low angles.

In the northeastern part of the NW¼ of NE¼ of section 32, T. 46N., R. 20W., a low narrow outcrop lies at the water's edge on the west bank of Kettle River. The rock consists of alternate layers of coarse- and fine-grained, light gray phyllite. The surface is stained a rusty brown.

The fine-grained layers are much contorted. Quartz lenses parallel to the lamination and schistosity are found in the fine-grained bands. The strike is about N.70°W. and the dip is to the southwest at a low angle.

About a quarter of a mile below the exposure in section 32, Split Rock River flows into Kettle River from the northwest. A precipitous cliff of rock forms the southwest bank of Split Rock River from its mouth up stream for a distance of about 300 feet. Below the mouth, the cliff continues southward along the west bank of Kettle River for about 1,200 feet. The rock is light to dark gray, fine-grained, micaceous phyllite. Alternations of fine-grained micaceous with coarser grained more siliceous layers bring out the original difference in the sediments. The bedding and schistosity are parallel and gently undulating. The finer grained layers are minutely crenulated. Small lenses of quartz occur locally parallel to the schistosity. A small pegmatite dike parallel to the schistosity is exposed for a few feet in a pit about 50 feet south of the mouth of Split Rock River. Several sets of intersecting joints cut the rock into polygonal blocks of various sizes. The average strike of the schistosity and lamination is about N.80°E. and the dip varies from 15° to 35°S.

A rock similar to that found at the mouth of Split Rock River is exposed over a large area in the center of the SE¼ of section 32, T. 46N., R. 20W. It outcrops along the west bank of Kettle River for a distance of about a quarter of a mile and extends westward from the river about the same distance. The outcrops occur on a burnt-over tract as three large, flat, irregular mounds or ridges. The rock is light to dark gray, fine-grained, banded mica schist and phyllite, with marked schistosity in general parallel to the banding. The more micaceous or finer grained layers are crenulated. Quartz occurs in lenses parallel to the schistosity and also in veins from a few inches to several feet wide cutting across the schistosity. These quartz veins strike about N.10°E. and stand vertically. The strike of the bedding and schistosity is about east and west and the dip varies from 3° to 25° south, due to the broad low undulations.

The phyllite and mica schist can be traced southward by frequent outcrops along the escarpment on the west side of the river to the southeast corner of section 32, T. 46N., R. 20W., where they form an overhanging cliff about 20 feet above the water. This cliff continues southeastward along the river for about 600 feet into Pine County, cutting across the northeast corner of section 5 and ending in the NW¼ of NW¼ of section 4, T. 45N., R. 20W. The average strike of the schistosity in this area is east and west and the dip is about 20°S.

Farther south along Kettle River in northern Pine County, a number of scattered exposures of phyllite and mica schist occur extending through section 4 and thence southward as far as the south line of section 9, T.

45N., R. 20W., below which point no schist outcrops are known on Kettle River. In the southwestern part of the SE¼ of NW¼ of section 4, T. 45N., R. 20W., and extending southward into the NE¼ of SW¼ of section 4, a long narrow outcrop of schist occurs on the east side of Kettle River. It forms a steep cliff along the river bank for about 400 feet and then extends southeastward as a high escarpment, a short distance from the river, for about 800 feet, with frequent outcrops. The rock consists of alternate layers of quartzitic and micaceous, light to dark gray phyllite and mica schist. The darker micaceous bands are crenulated, while the quartzitic layers are evenly schistose. Lenses of quartz, with scattered hornblende and garnet, occur parallel to the schistosity. Near the south end a vertical northwestward striking quartz vein about 10 feet wide cuts the schist. The strike of the layering of the mica schist is about east and west, and the dip varies from 2°N. to 30°S., due to minor folding.

About a quarter of a mile to the southwest, in the northeast corner of the SW¼ of SW¼ of section 4, T. 45N., R. 20W., are two small outcrops of mica schist on the west bank of Kettle River near the water's edge. The larger one is exposed for about 120 feet and rises from 2 to 5 feet above the river. The smaller one is exposed for about 10 feet at the water's edge. The strike of the schistosity is about N.80°E. and the dip is 18°S.

In the E½ of NW¼ of section 9, T. 45N., R. 20W., on the east bank of Kettle River, about 800 feet south of the Minneapolis, St. Paul, and Sault Ste. Marie Railroad bridge over Kettle River, an outcrop begins which continues southward along the river for about 650 feet. The outcrop lies at the water's edge. The rock is a light gray, garnetiferous, mica schist. Some layers are very siliceous and contain abundant small flakes of biotite and muscovite in a sugary quartz matrix. These alternate with layers in which the mica occurs in coarser folia and quartz is present in minor amount. Lense-like inclusions of sugary quartz containing abundant greenish black hornblende and some garnet are found parallel to the schistosity. The strike of the schistosity is about east and west and the dip varies from 20° to 30°S.

A similar schist outcrops in the south central part of the NE¼ of SW¼ of section 9, T. 45N., R. 20W., on the southeast bank of Kettle River for a distance of about 600 feet. The strike is N.80°E. and the dip is 30°S. This is the southernmost known outcrop of this series of rocks on Kettle River. About a mile and a quarter below it, sandstone blocks and boulders are abundant in the drift. With the exception of a small outcrop reported to occur near Willow River, however, there are no outcrops of the so-called Hinckley sandstone along Kettle River for more than 10 miles below the southernmost mica schist outcrop, and it is possible that the schist forms the bedrock over a part of this area.

In the central and eastern parts of Carlton County, east of the Kettle River valley, outcrops of schist, phyllite, graywacke, and slate are more abundant than in the Kettle River region. They extend as scattered exposures and groups of exposures from Moose Lake in the south central part of the county to Cloquet in the northeastern part. In some places outcrops cover many acres while elsewhere small isolated exposures are found. For the most part, however, the mantle of glacial till is thin and the bed rock is probably not far below the surface throughout this region even where outcrops are small and scattered.

At Moose Lake mica schist is found northeast, north, west, and southwest of the town along both the Minneapolis, St. Paul, and Sault Ste. Marie, and the Northern Pacific railroads. The scattered outcrops cover an area roughly 2 miles long and ranging up to perhaps 1,000 feet in width. In the NE¼ of section 20, T. 46N., R. 19W., the Minneapolis, St. Paul, and Sault Ste. Marie Railroad runs in a rock cut from a few feet up to 15 feet deep for a distance of about 2,000 feet. The rock is light to dark gray, finely to coarsely crystalline phyllite and mica schist. The lighter gray layers are siliceous and fine-grained, while the darker layers are rich in mica and are more coarsely crystalline. The micaceous layers show fine crenulation and give shining, glossy, cleavage surfaces. Quartz occurs in lenses parallel to the schistosity and also as veins and thin films along some of the joint planes. About 800 feet from the north end of the cut, a vertical dike of fresh, grayish black, fine-grained, massive, igneous rock about 11 feet wide cuts the schist, striking about N.75°W. At the contact with the schist, the rock is extremely fine textured but becomes coarser toward the center of the dike. The contact is sharp and the schist is hardened within a few inches of the contact and its schistose structure is destroyed. The schistosity shows low, broad, undulations along the walls of the cut. The average strike is about N.60°E. and the dip varies from 5° to 40°SE.

The phyllite and mica schists continue as a ridge southwestward from the railroad cut for about a mile, where they are cut through by the Northern Pacific Railroad in the NE¼ of NW¼ of section 29. The ridge lies between the tracks of the two railroad lines, and rises about 30 feet above the grade of the Northern Pacific Railroad. Small outcrops are abundant along it. To the southwest it is lower and gradually disappears beyond the Northern Pacific railroad tracks. In the rock cut on the Northern Pacific Railroad in the southeast corner of SE¼ of SW¼ of section 20, and in the northeastern part of the NE¼ of NW¼ of section 29, the rock is exposed continuously for about 500 feet on the northwest side of the railroad. It shows low, broad, undulations in the schistosity which has a general low dip to the east.

Just northeast of Moose Lake in the north central part of the NE¼ of NW¼ of section 21, T. 46N., R. 19W., is a low, rounded mound 50 by 60 feet, about 170 feet northwest of the Northern Pacific Railroad tracks. The mound consists of interlayered quartzitic and micaceous schists. The light gray siliceous layers are thicker than those in the rock forming the ridge northwest and west of Moose Lake; individual layers reach a thickness of 2 feet. The strike of the layering is about N.85°E. and the dip 15°S.

About one third of a mile farther northeast, an outcrop of mica schist occurs in the bed of a small stream in the north central part of the SW¼ of SE¼ of section 16, T. 46N., R. 19W. The rock is exposed for about 40 feet and is similar to that in the cut at Moose Lake. The strike of the layers is about N.42°E. and the dip is 6°SE. Loose boulders and irregular blocks of the same kind of rock occur abundantly in the drift for several hundred feet to the southwest.

The next important group of outcrops to the northeast is that near Barnum. At the railroad station and extending westward from it is a large flat area of irregular outline in which rock exposures are abundant. The area is in the western part of the NW¼ of section 1, T. 46N., R. 19W., the NE¼ and the northeastern part of the NE¼ of NW¼ of section 2, T. 46N., R. 19W., the southeastern part of the SE¼ of SW¼ and the southern part of the SE¼ of section 35, T. 47N., R. 19W. It rises as a small upland 3 to 10 feet above the surrounding low land, and in places forms a vertical escarpment along the borders. Parts of it are concealed by a thin veneer of soil. The rock is phyllite and mica schist. Thin layers of glossy, dark gray, micaceous rock with wavy cleavage planes are interbedded with heavy, massive, layers of fine-grained lighter gray graywacke. These massive beds are from 2 to 10 feet thick and some of them are highly calcareous. Scattered stringers and lenses of quartz parallel to the schistosity are abundant in the micaceous layers, and calcareous concretions or lenticular rusty brown cavities from which they have been dissolved, are found in some of the massive beds. The average strike of the bedding is about east and west and the dip varies from 0° to 35°S. Small drag folds pitching from 0° to 35° to the east are abundant in the micaceous layers. The outcrop as a whole appears to be on the south limb of a larger eastward pitching anticline.

About 5 miles west of north from Barnum on the West Branch of Moose Horn River, in the SW¼ of NW¼ and the NW¼ of SW¼ of section 15, T. 47N., R. 19W., black slate and associated altered diabase crop out along the river bed for a distance of about one half mile. The exposures are practically continuous for this distance and rise on either side of the stream from a few inches up to about 5 feet. The southern part of the outcrop is black carbonaceous slate, probably largely graphitic, the strike and dip of which vary in short distances due to minor folding. Large crystals of pyrite occur in it abundantly. A well-developed fracture cleavage has been superimposed on the slaty cleavage and is almost at right angles to it. The large structural feature indicated by the slate outcrop is a southward dipping monocline, with minor drag folds, forming the south limb of an eastward pitching anticline. The northern part of the outcrop consists of dark, grayish-green, medium-grained, altered diabase, containing abundant scattered pyrite. The contact of the diabase and slate is not exposed, but it seems probable that the diabase forms a large intrusion in the black slate.

About 6 miles northeast of Barnum near Mahtowa, a station on the Northern Pacific Railroad, are numerous exposures of schist and slate and some of dark igneous rock. They are found chiefly along Moose Horn River and its branches from Mahtowa northward to Park Lake. Throughout most of the region the bedrock where not exposed is comparatively near the surface.

In the NW¼ of SE¼ of section 8, T. 47N., R. 18W., in a meadow about 1,000 feet southeast of the center of the section, two pits, 100 feet apart, pass through a thin mantle of glacial drift into bed rock. The pits are 8 by 12 feet and are reported to be 30 feet deep. The rock consists of layers of a light gray and dark gray, fine-grained phyllite and slate, black carbonaceous slate, and grayish black, dense, finely laminated amphibole schist or amphibolite. Small quartz lenses and stringers of carbonate occur parallel to the cleavage. Crystals of pyrite are abundant. In the west pit the cleavage and lamination strike about N.77°W. and dip 16°S., and in the east pit they strike about N.70°W. and dip 85°N. About 700 feet northeast of these pits is another pit, partly filled, which has black carbonaceous slate on the dump.

In the northwestern corner of this 40-acre tract are several small, low, shattered outcrops of a light gray, fine-grained phyllite. No satisfactory observations could be made as to strike and dip.

Another outcrop of phyllite, slate, and amphibolite occurs in the northeastern part of section 8 in a low round knoll on the north-south line between the NE¼ of NE¼ and NW¼ of NE¼, about 80 feet south of the north line of the section. The knoll is 250 feet wide east and west and about 300 feet long, lying west of Moose Horn River. The outcrop is mainly fine-grained laminated amphibole schist, but includes some layers of finely micaceous phyllite and slate. The cleavage is well developed in the micaceous phases, but less so in the amphibolitic phases. Some micaceous layers show crenulated cleavage. The weathered amphibole schist, or amphibolite, is speckled with abundant minute spots of light brown ocherous limonite, the decomposition product either of ferrous carbonate or of some ferrous silicate. Some of the rock has a rusty brown color due to the abundance of limonite. The slate and phyllite layers are subordinate to the amphibolite layers. All are comparatively thin-bedded. The rock lies in a series of small anticlines and synclines forming a larger westward pitching anticline. The axis strikes about N.75°E. and pitches about 60°W.

About 250 feet southwest of the northeast corner of the SW¼ of SE¼ of section 5, T. 47N., R. 18W., two pits were sunk about ten years ago in black carbonaceous slate, probably largely graphitic. The pits are 10 by 15 feet, and about 30 feet deep. The north pit passes through 20 feet of black slate into a glossy, light gray, micaceous slate and phyllite. The strike of the schistosity of the black slate is N.70°E., and the dip is 26°S. The south pit was sunk on a quartz vein about 2½ feet wide. The vein strikes about north and south and stands vertically, while the schistosity of the slate strikes N.66°E. and dips 37°S. Pyrite occurs abundantly in the black slate as narrow stringers parallel to the schistosity and also as large cubical crystals, an inch or more along the side, which have grown without reference to the cleavage. In many cases the cleavage of the slate is shown by parallel lines cutting across the crystals of pyrite, and thin parallel folia of slate are frequently included within the pyrite crystals. This shows that the pyrite is secondary, having developed during or after the metamorphism of the black slate in the same manner that the staurolite crystals are developed in the garnetiferous schist of the Little Falls region. (See page 62.)

A small, low outcrop of black slate is found 450 feet south of the pits in the same 40-acre tract.

In the E½ of SE¼ of section 5, T. 47N., R. 18W., small exposures of black slate occur frequently on both sides of the northwest road and in the bed of Park Lake River. These outcrops are low and shattered. A small pit on the east side of the road, about 800 feet north and 300 feet west of the southeast corner of the section, was dug in black slate, as shown by the material on the dump. Much pyrite occurs in this slate along cleavage planes. About 50 feet east of the pit is a shallow trench, 2 feet wide, trending north and south, exposing the black slate for a distance of 60 feet. The rock is covered by only a few inches of soil. The cleavage strikes N.70°E. and dips 75°S. About 200 feet north of the pit on the west side of the road black slate crops out over a small area, while 400 feet farther northeast on the east side of the road, light gray micaceous quartzite or graywacke crops out along the east section line and continues into section 4. The rock is massive and in general has a poorly developed cleavage. The strike of the layering is N.70°E. and the dip is 50°S. Several small exposures of black slate occur a short distance north and northwest of this outcrop on both sides of the road.

In the SW¼ of NE¼ of section 5, T. 47N., R. 18W., farther northwestward along the road, black slate is exposed at frequent intervals for a distance of about 700 feet. The rock occurs in low ridges on both sides of the road and has also been exposed in the grading. The strike of the cleavage at the south end of this area is about N.75°E. and the dip is 40°S.; at the north end the strike is about N.75°E. and the dip is 75°S.

A number of outcrops of graywacke, slate, and phyllite occur along the west line of section 4, T. 47N., R. 18W. south of the west quarter corner. As has been mentioned, some of these extend westward into section 5 and most of them also continue for a short distance eastward into section 4.

An outcrop of light gray phyllite and black slate occurs near the center of section 4. It lies on the west side of the north-south road running along the east line of the NE¼ of SW¼ of the section. The outcrop begins at the northeast corner of this 40-acre tract (at the center of section 4) and continues southward along the road for about 800 feet. The outcrop extends westward from the road 50 feet at the north end of the outcrop, and 200 feet at the south end. It is a low flat exposure, the west margin forming a westward facing escarpment 6 to 8 feet above the general level of Moose River, which is a short distance west. The outcrop is made up of alternate layers of light to dark gray phyllite and black slate. The dark bands contain carbonate minerals and are mottled with small porous specks of limonite. The outcrop is a large anticline with small drag folds on both limbs. The strike of the axis is N.80°E. and the pitch is 20°E.

A number of scattered outcrops of light gray phyllite and dark gray slate occur in the E½ of NE¼ of section 4, T. 47N., R. 18W. The rock is badly broken and rises only a few inches above the soil. No satisfactory observations could be made on the attitude of the rock in most of the outcrops. Near the southeast corner of the NE¼ of NE¼ of the section, however, dark gray slate striking about N.86°E. and dipping 45°S. crops out in a low ridge about 200 feet long, east and west and about 60 feet wide.

Three and one-half miles north of east from Mahtowa near the center of NE¼ of SE¼ of section 1, T. 47N., R. 18W., is a small outcrop of light gray, fine-grained graywacke. The outcrop is broken and covered with loose blocks. No satisfactory observations could be made as to strike and dip.

Several rock exposures of varying size are found in the SE¼ of section 31, T. 48N., R. 18W. The northern and easternmost of these is a low outcrop of a light gray, medium-grained graywacke occurring near the center of the east-west line along the north side of the NE¼ of SE¼ of the section. The attitude of the graywacke is uncertain.

In the W½ of the quarter section, several outcrops are found consisting mainly of slate, phyllite, and graywacke. The most northerly of these is about 400 feet west and 350 feet south of the northeast corner of the NW¼ of SE¼ of section 31. It is 5 feet wide and 10 feet long and rises only a few inches above the surface. The rock is dense, light gray, fine-grained graywacke. The weathered rock is full of minute brownish yellow specks of limonite. The graywacke has a poorly developed schistosity, which strikes N.84°E. and dips 64°S.

About 400 feet southwest of this outcrop, a 3-inch vertical hole was drilled to a depth stated to be 330 feet. No accurate log was kept of the drilling, as far as known. The information available, however, and an examination of the core, indicates that the upper part of the hole is in dense, dark gray, finely micaceous graywacke and that below this, black, carbonaceous (probably largely graphitic) slate was encountered. The cleavage in both rocks is well developed. The cleavage surface of some of the black slate has a mottled appearance caused by small, scattered, shiny, black particles. The dip of the cleavage is 50°, probably to the south.

About 450 feet somewhat east of south from the drill hole there are several small outcrops of light gray, medium-coarse graywacke. In some there is a slight orientation of the flaky minerals producing a poorly developed schistosity. Similar rock in small scattered exposures is found about 1,000 feet west of this exposure in the southeastern part of the NE¼ of SW¼ of section 31.

In the western part of the SE¼ of SE¼ of section 31, T. 48N., R. 18W., about one third of a mile southeast of the drill hole, are several long, low, narrow, parallel ridges consisting of alternate layers of phyllite, slate, and graywacke. The ridges vary in length from 50 to 300 feet and in width from 10 to 50 feet, their longer axes being parallel to the strike of the rocks. The slate and phyllite are dark gray and occur as narrow beds from a few inches to a foot thick in the heavy-bedded, lighter gray, fine-grained graywacke. These rocks lithologically are similar to those south of Park Lake, which are described later. The strike of the bedding is N.53°E. and the dip is 42°SE. Minor drag folds in the slate pitch northeastward at low angles. The rocks appear to be on the south limb of a larger anticline.

About ten years ago, in prospecting for coal, two pits were sunk just west of the dwelling house of J. P. Peterson in the SW¼ of NW¼ of section 32, T. 48N., R. 18W. The larger pit is 350 feet south and 70 feet east of the northwest corner of this 40-acre tract, on the east side of Park Lake Creek. It is 15 feet by 20 feet, and 30 feet deep. In the bottom a 3-inch vertical hole was put down 80 feet. The pit is now caved and partly filled with water. The small pit, 75 feet to the south, is 5 feet by 5 feet and was sunk to a depth of 8 feet. The surface material is from 2 feet to 10 feet in thickness. The rock in both pits is black carbonaceous slate, much fractured and impregnated with pyrite and quartz. The more highly carbonaceous phases of the slate are dull, earthy, and soft. Other phases are harder and show slickensides in several directions. Some graphite in shiny films is developed along the slickensides and along fracture planes. On account of the caving and water, the attitude of the slate could not be determined. The cleavage in a piece of core taken from the larger pit shows a dip of about 45°. This dip is probably south, judging from the structure of slate outcrops nearby.

In the region south and southwest of Park Lake are extensive outcrops of slate and graywacke, covering considerable areas in sections 29, 30, and 31, T. 48N., R. 18W. The northernmost of these exposures are found on the south shore of the lake in the SE¼ of NW¼ of section 29. They rise about 10 feet above the level of the lake and slope out into the lake beneath the water. Near the shore they form several small, low rock islands. Most of the rock is massive, medium-grained, light gray graywacke, with small bands of fine-grained, darker, slaty material, with well-developed cleavage. Glacial grooves and striations trending N.60°W. are seen on outcrops of the coarser phases. The strike of the formation varies from east and west to N.70°W. and the dip varies due to minor folding. Drag folds show that the outcrops are on the north limb of an anticline.

About 350 feet south of the center of section 29, T. 48N., R. 18W., on the north-south road running southward from Park Lake, graywacke and slate exposures occur as low, narrow ridges crossing the road in an east-west direction. The width of the group of exposures where it crosses the road is more than a quarter of a mile, and it extends eastward into the W½ of SE¼ of section 29 for a maximum distance of 250 feet. The group is at the northeast end of a large area of exposures which continues from this point southwestward across the SW¼ of section 29, the southeast half of the SE¼ of SE¼ of section 30, the northwest half of NE¼ of NE¼ of section 31, T. 48N., R. 18W. Throughout this area exposures are more or less continuous. South of its west end, small scattered rock ridges occur for a distance of about 800 feet farther, being partly in the SE¼ of NE¼ and partly in the SW¼ of

NE¼ of section 31. The main belt of exposures consists of many parallel rock ridges of varying size. They range from 5 feet to 600 feet in width and from 10 to 2,100 feet in length, and rise above the surrounding soil from a few inches up to 15 feet. The ridges are separated from each other by lower marshy ground, the distance between the ridges varying from 20 feet to 400 feet. Their longer axes strike east-west or a few degrees south of east.

The outcrops throughout the area are made up mainly of alternate bands of medium coarse-grained graywacke and fine-grained slate. These bands vary in thickness from a fraction of an inch up to several feet; the graywacke is more abundant than the slate and occurs in thicker, more massive beds. Locally fine micaceous phyllite occurs where deformation has been somewhat more intense, or where shearing has taken place. The slate is darker than the graywacke and has a well-developed cleavage. Some of the coarser graywacke phases, also, show a slight schistosity. Small, elongated, nodules or concretions of calcareous material occur in broken bands in the graywacke, and appear as cavities on the weathered surface. Quartz occurs sparingly as stringers between the bedding in the minor folds and as thin films along some of the joint planes. Small grains of pyrite are abundant in the coarser material, and on weathering leave small cavities with a rusty stain. Several sets of joints cut the rocks into polygonal blocks of various sizes.

The rocks are folded into a series of small anticlines and synclines of several orders, with the axes at the crests and troughs horizontal or pitching up to 5° either to the east or to the west. The average strike of the axial planes is about N.77°W. From a study of the drag folds and the relation of cleavage to the bedding, it appears that the Park Lake series of outcrops forms a low flat anticlinorium.

A short distance south of the main Park Lake area of slate and graywacke outcrops is a small exposure of phyllite. It is located on the north side of the east-west road between sections 29 and 32, T. 48N., R. 18W., about 100 feet east of the southwest corner of the SE¼ of SW¼ of section 29, T. 48N., R. 18W. The rock is light gray, and on the weathered surface is mottled, the mottling being due to small cavities containing limonite derived from the weathering of some disseminated iron-bearing mineral. The schistosity strikes N.82°W. and dips 35°S.

Numerous outcrops of slate and graywacke are found in the region between Park Lake and Atkinson, most of them are ridges trending approximately east and west. The most westerly of these is about a mile south of east from Park Lake in the southeastern part of section 28, T. 48N., R. 18W. Two long, low, narrow ridges are situated along the east-west road on the south line of the NW¼ of SE¼ of section 28.

The south ridge, about 30 feet wide, lies about 200 feet west of the southeast corner of the 40-acre tract, and extends westward along the road for about 470 feet. Ten feet north on the roadside is a smaller ridge about 200 feet long and 25 feet wide. The outcrop in the road consists of gray, medium fine-grained graywacke cut into polygonal blocks, 1 to 4 feet long by intersecting joints. Cavities formed from the more easily weathered carbonate nodules occur in bands bearing about east and west. Locally there is a poorly developed schistosity striking N.80°W. and dipping 34°S. The outcrop north of the road is made up of alternate bands of fine-grained, dark gray slate and medium fine-grained, lighter colored graywacke. These bands vary in thickness from 2 inches to a foot or more. Single bands can be followed the entire length of the outcrop. The strike of the layers is N.88°W. and the dip 56°N.

About a mile east of the exposures in section 28, a series of more or less parallel east-west rock ridges occurs in the east central part of the E½ of SE¼ of section 27, T. 48N., R. 18W., and continues eastward across the central part of the SW¼ of section 26. The ridges vary up to 600 feet in length and from 10 to 300 feet in width, and rise from 2 to 20 feet above the intervening depressions. Prominent ridges are found on both sides of the east-west road leading to Atkinson, the largest being on the south side. The rock is slate and fine-grained graywacke occurring in alternate beds. The beds are from a fraction of an inch to 10 feet or more thick. The slate beds have well-developed cleavage and are darker than the graywacke. Some layers are calcareous. Much of the rock is finely mottled for a few inches below the weathered surface, due to an abundance of small specks of limonite. Carbonate concretions or nodules, or cavities from which they have been weathered out, are found in some of the graywacke bands. Spongy quartz with soft earthy limonite in the cavities, occurs as veins along some of the joint planes and also parallel to the bedding. The limonite is a weathering product of siderite and perhaps of pyrite. The average strike of the bedding is about east and west, and the dip varies from 30° to 70°N. due to drag folds. The strike of the cleavage is about east and west and the dip is about 70°S. These rock ridges are structurally on the north limb of a larger anticline.

The next group of outcrops to the east is west, north, and east of Atkinson. It extends from the east central part of section 26, T. 48N., R. 18W., eastward through the central part of section 25, the last outcrops to the east being in the east central part of section 25. The exposures form a belt of more or less parallel east-west trending ridges occupying an area about a mile long east and west and about one fourth of a mile wide. A few outlying exposures are found west and north of the main belt. The individual outcrops vary from mere knobs to ridges 600 feet long and 300 feet wide. Several of the ridges west of Atkinson are 10 to 30 feet high. The rock consists of alternate layers of light to dark gray graywacke, and dark gray to black slate. The beds vary in thickness from a few inches to several feet. The weathered phases are mottled with fine specks of limonite. Quartz veins and quartz siderite lenses are common along the axes of the small folds and pinch out along the limbs. The siderite locally has been entirely altered, and the lenses consist of a spongy mass of quartz and earthy limonite. Several pits have been sunk in prospecting for gold in different parts of the area where these lenses are abundant. In two pits in the northeast corner of the NW¼ of SW¼ of section 25, a small brecciated zone is exposed in the dark-colored slate. Quartz, siderite, pyrite, and some calcite cement the breccia and extend into the wall rock for several feet as stringers between the laminae of the slate. The rocks in the central part of the area lie in a series of folds, with smaller folds down to minute plications superimposed on their limbs. The axes of the larger folds strike about east and west, and are either horizontal or pitch at a low angle to the east. At the western end of the main belt of outcrops in the northeast corner of the NE¼ of SE¼ of section 26, there is a low, flat exposure about 250 feet east and west and 100 feet wide. The average strike of the beds at this place is about N.75°E. and the dip varies due to minor folding. The axial lines of the minor folds strike about N.85°E. and pitch 8°E. The rock is light gray graywacke, some of which shows well-developed cleavage. Locally tiny flattened particles of dark gray slate are embedded in the lighter colored graywacke. Another small outcrop in the western part of the main belt of exposures occurs on the northwest-southeast road in the southern part of the SW¼ of NW¼ of section 25. The strike of the beds is about N.85°E. and the dip is 80°N.

Outlying exposures of graywacke and slate occurring northwest of the main belt of outcrops form two long, low, narrow, parallel ridges in the SE¼ of NE¼ of section 26, and the SW¼ of NW¼ of section 25. The ridges extend east and west for nearly a quarter of a mile and vary from 20 to 80 feet in width. They rise only a few feet above the surrounding flat area. The rock is mainly light gray, mottled graywacke with a few thin interbedded layers of slate. The strike is about N.85°E. and the dip varies from 40° to 60°S.

An outlying exposure north of the main belt of outcrops at Atkinson occurs in the north central part of the SW¼ of NE¼ of section 25, forming two low, flat, parallel, east-west ridges. They are about 250 feet long and 50 feet wide. The rock is light gray, siliceous graywacke in heavy layers with thin interbedded layers of dark gray slate. The beds strike about east and west and dip 45°S.

About half a mile east of Atkinson on Black Hoof River, is the easternmost outcrop of graywacke and slate in this vicinity. It is located in the west central part of the NE¼ of SW¼ of section 30, T. 48N., R. 17W., and consists of several low knobs of fine-grained, light gray graywacke. The outcrop rises near the north-south road on the west side of this 40-acre tract and extends eastward for about 650 feet. Knobs occur on both sides of the river rising 8 to 10 feet above the water and sloping gently toward the east. The rock is in places schistose and is cut into irregular blocks by several sets of joints. Concretions or nodules of carbonate minerals occur sparingly. The beds strike east and west and dip south at a low angle.

The belt of exposures extending from Park Lake eastward through sections 28, 27, 26, and 25, T. 48N., R. 17W., which is described above, includes the principal rock outcrops of this region. A more or less parallel belt composed of fewer and more scattered exposures, occurs south of this larger belt, extending in an approximately eastward direction from the eastern part of section 34, T. 48N., R. 18W. through sections 35 and 36, T. 48N., R. 18W., into section 31, T. 48N., R. 17W. The exposures of the northern belt have structures indicating that in general they are situated on the north limb of a large anticline, those in the southern belt appear to be either near the crest or on the south limb of an anticline.

The westernmost of the exposures on the southern belt consists of a large irregular knoll of rock located in the east central part of the E½ of NE¼ of section 34, T. 48N., R. 18W., and extending for about 200 feet into the southwest corner of the NW¼ of NW¼ of section 35. The knoll is about 1,000 feet long east and west and about 800 feet wide north and south and rises about 60 feet above the surrounding country. It is made up of thick beds of a light gray, fine-grained graywacke separated by thin layers which are more slaty and darker in color. The slaty layers are micaceous and have well-developed schistosity. Locally they are crenulated and contain lenses of quartz parallel to the foliation. Intersecting sets of joints cut the rock into large irregular blocks, and some of the joints are filled with quartz. Lenticular depressions, stained black or rusty brown, from which nodules of carbonate minerals have been dissolved, occur parallel to the strike of the bedding in some of the coarser layers. The outcrop appears to represent an eastward pitching anticline, the strike of the axial line being about N.85°E. and the pitch 10°E. Small drag folds occur on both limbs of the anticline.

In the northeastern part of the SW¼ of NE¼ of section 35, T. 48N., R. 18W., just south of the north line and about 100 feet west of the Northern Pacific tracks, is a low glaciated ridge of phyllite. The ridge is about 150 feet long east and west and 75 feet wide, and rises a few feet above the surrounding meadow. Thick, light gray, fine-grained, arenaceous layers alternate with dark gray, slaty layers. Some of the slaty layers show a considerable development of fine mica along cleavage planes. Concretions of carbonate minerals are abundant in some of the layers. At the east end of the outcrop they are more resistant than the enclosing rock and stand out as tiny knots, while at the west end they have been dissolved, leaving rusty brown or black pod-like depressions. Several sets of intersecting joints cut the rock into large irregular blocks. The strike of the schistosity is about N.85°E. and the dip is 45°S. The bedding strikes N.82°W. and the dip varies in short distances, due to minor folding. This outcrop is on the south limb of a larger anticline.

About a mile northeast of the exposure in section 35, near the north quarter corner of section 36, T. 48N., R. 18W., rock is exposed in several small areas. It is mainly light gray, fine-grained graywacke, much weathered and shattered. The beds appear to lie almost flat.

The easternmost rock exposures of the southern belt of outcrops occur in the SW¼ of section 31, T. 48N., R. 17W., along Black Hoof River and west of it, where there are three or four separate outcrops of graywacke and slate. An exposure of graywacke and slate in a low flat ridge is found in the northeastern part of the SW¼ of SW¼ of the section. It lies on a northward facing slope and rises about 10 feet above a swamp to the north of it. The ridge is 600 feet long east and west and 300 feet wide. Small, shattered exposures lie to the east, south and west of the main outcrop for several hundred feet. In the main exposure, layers of light gray, fine-grained graywacke, hard and siliceous, and with poorly developed cleavage, alternate with darker slaty layers having well-developed cleavage. The layers vary from a few inches to several feet thick, the graywacke beds being thicker. The slaty layers show fine mica developed along cleavage planes. Lenses and stringers of quartz occur parallel to the bedding. The rock lies on the crest of a large anticline with small anticlines and synclines on either limb. The axial line of the anticline strikes about east and pitches about 10°E.

About a quarter of a mile to the north of this exposure, in the NW¼ of SW¼ of the section, is a ridge of dark gray slate trending northwest. The ridge rises only a few feet above the surrounding flat, swampy country. It is about 500 feet long and about 200 feet wide. The rock is uniform, dark gray slate with fine mica developed locally along cleavage planes. Thin laminae and specks of limonite lie parallel to the cleavage and also occur as small spots throughout the rock. In the fresher phases pyrite is abundant, indicating that the limonite is derived from pyrite by weathering. The slate forms a synclinal trough that pitches a little south of east at a low angle.

A. OUTCROPS OF SLATE ALONG ST. LOUIS RIVER BELOW THOMSON DAM, CARLTON COUNTY. LOOKING NORTHWESTWARD

B. OUTCROPS OF SLATE AT THE NORTHERN PACIFIC RAILROAD BRIDGE OVER ST. LOUIS RIVER BELOW THOMSON DAM, CARLTON COUNTY. LOOKING SOUTHWESTWARD

West of these two ridges in the western part of the SW¼ of section 31, and extending into the SE¼ of section 36, T. 48N., R. 18W., are small, low, badly broken exposures of dark gray slate. No outcrop showing the attitude of the rock was found.

About a quarter of a mile east of the outcrops described above in the NW¼ of SE¼ of section 31, several small exposures of light gray, medium-grained graywacke are found along Black Hoof River. The rock is hard and siliceous and shows no cleavage.

The next group of exposures northeast of the Atkinson–Park Lake region are those in the vicinity of Otter Creek in sections 16, 17, and 20, T. 48N., R. 17W. Most of these exposures occur along the Northern Pacific Railway which runs northeastward from Atkinson to Carlton. Some are found along Otter Creek.

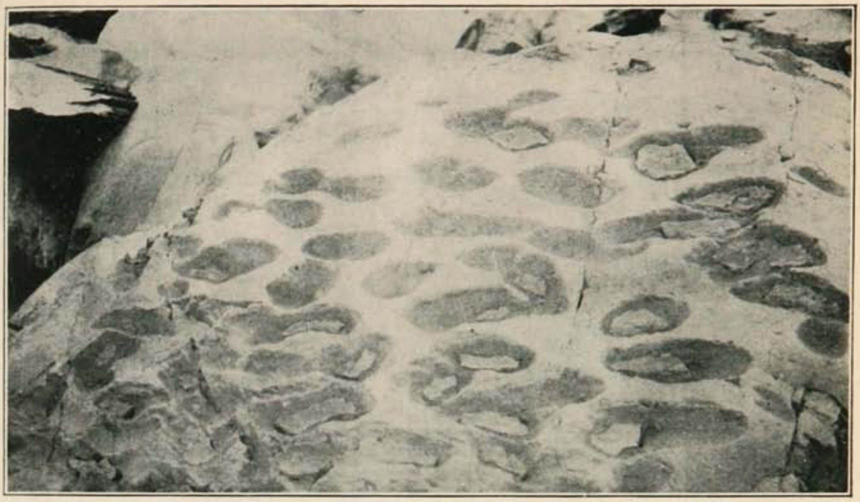
A short distance northeast of the center of the SW¼ of NW¼ of section 20, T. 48N., R. 17W. are two small low ridges of slate and graywacke. The outcrop begins along the northeast-southwest road which runs parallel to the Northern Pacific railway tracks, northeastward from Atkinson, and continues southeastward across the Northern Pacific tracks. It is about 300 feet long and about 40 feet wide. Thin bands of dark gray slate are interlayered with thick beds of lighter gray graywacke. The rock is broken into large blocks by intersecting joints. Quartz, with small crystals of pyrite, occurs in narrow veins and lenses. The bedding strikes about N.85°W. and dips 47°N.

About a fourth of a mile northeast of this outcrop in the east central part of the NE¼ of NW¼ of section 20, several low east-west rock ridges occur along the Northern Pacific tracks and along the highway. They vary in length from 50 to 300 feet and in width from 30 to 100 feet. The rock consists of dark gray slate, some layers of which are very siliceous and have poorly developed cleavage, while other layers are less siliceous and show good cleavage. The layers range in thickness from a fraction of an inch to several inches. Small crystals of calcite and siderite are abundant in the more siliceous layers. In one layer small flattened oval particles of black slate are embedded in the lighter-colored siliceous slate. The rocks lie in a series of small anticlines and synclines, the axial lines of which strike about N.80°E. and pitch from 10° to 20°E.

About 200 feet southwest of the Northern Pacific Railway bridge over Otter Creek, in the northeastern part of the SE¼ of SE¼ of section 17, T. 48N., R. 17W., the railway passes through a rock cut for about 110 feet. This cut is through the northwest corner of a high east-west rock ridge about 500 feet long and 175 feet wide which rises about 50 feet above Otter Creek. Layers of slate and schistose graywacke are exposed along the cut, striking N.80°E. and dipping 30°N. The following succession of beds is found. At the bottom, with 5 feet exposed, is a dark gray, fine-grained, siliceous slate. On the cleavage surfaces are seen a few rounded, flat, black particles, probably squeezed slate fragments. Specks of pyrite and some carbonate are disseminated through the rock. Above this layer are 3 feet of uniform, dull, black, dense slate; above that 4 feet of dark gray siliceous slate and schistose graywacke which in places contain pebbles of fine-grained, darker slate, flattened transversely to the cleavage. The pebbles range from a fraction of an inch to several inches in the longer diameter. Alternating thin layers of slate of different coarseness of grain and color are clearly visible in this bed, the coarser layers carrying the slate pebbles. The cleavage cuts transversely across the layers and has fine flakes of mica developed along it. The coarser layers are finely mottled, due to abundant limonite specks, probably derived from the alteration of siderite. The next 5 feet consist of dark greenish phyllite finely mottled with tiny specks of limonite. A few small oval flattened particles of dark slaty material are found on the cleavage faces. Above this bed is a layer of dark gray, coarse-grained, schistose graywacke 3 feet thick. It is similar to the bed below it, but coarser, containing abundant small rounded particles of dark slaty material, as well as numerous grains of quartz. Small specks of limonite and of white carbonate minerals are scattered through the rock. Pyrite is found locally and fine mica is developed along cleavage planes. The cleavage is well developed. The top layer in the cut is a dark gray to black, uniform, fine-grained slate. The thickness could not be determined, but about 15 feet are exposed in the cut. The cleavage strikes about N.87°E. and dips 75°S.

Northeastward from Otter Creek to Carlton a few ridges of slate and graywacke are found both north and south of the Northern Pacific tracks. The ridges trend about east and west and rise from a few feet to 50 feet or more above the surrounding flat region. These ridges have not as yet been examined in detail. To the northeast they connect with the extensive exposures of rock along St. Louis River in the vicinity of Carlton, Thomson, and Cloquet.

In the St. Louis River valley slates and graywacke with a few dikes of dark igneous rock are exposed almost continuously along the river from the center of section 1, T. 48N., R. 16W. on the southeast, to the eastern part of section 15, T. 49N., R. 17W. on the northwest, a distance by river of about 15 miles. These rocks rise as high steep escarpments on both sides of the river for much of the distance and within this gorge are numerous falls and rapids. They also rise as long, narrow, east and west rock ridges, that extend from a few hundred feet to several miles on either side of the river gorge. These ridges are very numerous



A. CALCAREOUS CONCRETIONS WEATHERING OUT OF SLATE AT CARLTON

B. SMALL DIKE OF DIABASE INTRUDING SLATE AT CARLTON

locally. In the region around Carlton and Thomson they cover several square miles and continue southwestward from Carlton for some distance in the direction of Otter Creek.

In the southeastern part of the region the slate and graywacke are associated with younger rocks such as the sandstones, conglomerates, and basic lavas of the Keweenawan. In sections 1 and 2, T. 48N., R. 16W., a coarse quartzose Keweenawan conglomerate lies unconformably on the upturned edges of the slate and graywacke. In the bed of Mission Creek and its tributaries, in sections 30 and 31, T. 49N., R. 15W., north of Fond du Lac, are several exposures of slate north of the overlying Keweenawan sandstone. Outcrops of slate and graywacke also occur along Midway Creek in sections 5 and 6, T. 49N., R. 15W., a short distance west of the border of the lava flows extending northward from Duluth.

The outcrops throughout the St. Louis River valley are made up of alternate layers of slate and graywacke, varying in coarseness of grain and ranging from light gray to black in color. Locally dikes of dark igneous rocks are abundant. The common rocks are fine-grained, dark gray to black slate, some of which is highly siliceous; gray, somewhat micaceous slate with well-developed cleavage, and fine-grained to medium coarse-grained graywacke, some showing cleavage and some being massive bedded and siliceous with little or no schistosity. In some of the coarser beds quartz grains are abundant and a few fragments of slate are locally present. Concretions or nodules of carbonate minerals occur both in the slate and graywacke. They are generally parallel to the bedding and locally they merge into each other, forming continuous bands. In places the longer axes of the concretions are parallel to the cleavage and stand at an angle to the bedding. On weathering they leave pod-like cavities, stained a rusty brown or black. (Plate X A.)

Several sets of intersecting joints cut the rock into polygonal blocks of various sizes. Faulting has taken place along some of the joints, as shown by breccia zones and slickensided surfaces. Thin films of quartz and in places calcite, coat some of the joint planes. Quartz occurs as veins from a fraction of an inch to several feet in width in many parts of the area and also as lenses between slate beds on the crests of smaller folds pinching out along the limbs. Pyrite and siderite are often associated with the quartz and they also occur as small crystals disseminated in the rock.

Dikes of dark igneous rock, varying from a few inches to 60 feet or more wide, cut the slate series in many places. Several are well exposed at the Thomson dam. The rock is mainly a fine-grained, greenish black diabase. At the contact with the slate or graywacke it is extremely fine-grained and dense. Away from the contact it becomes coarser and takes on a marked ophitic texture. The dikes strike, in general, a few degrees east of north and stand vertically. At the contact the metamorphosed sediments have been hardened and their cleavage destroyed, while a new cleavage is developed in them parallel to the contact of the dike. This condition extends out from the dikes on either side for a few inches to several feet. The dikes are more readily broken down by weathering than the slate or graywacke, and are generally found in depressions.

The rocks in the Carlton-Cloquet region lie in a series of low, broad folds, with minor folds and crenulations superimposed on the limbs of the larger folds. The major structure consists of several large, gently eastward pitching anticlines and synclines. The east-west trending rock ridges so characteristic of the area around Carlton, are usually formed along the limbs of folds, one of the slopes being approximately parallel to the dip of the bedding and the other slope cutting across the bedding and being steep and ragged. Occasionally ridges are found which are structurally crests of anticlines or troughs of synclines. The strike of the bedding varies with the position of the bed with reference to the fold, but in general it ranges between N.80°W. and N.80°E. The dip of the beds varies from horizontal to vertical both north and south. The strike of the major cleavage varies a few degrees on either side of east and west and the dip is at varying angles both north and south, but is nearly always steeper than the bedding. The axial lines of the minor folds trend about east and pitch at low angles either eastward or westward.

The northernmost outcrop of slate in east central Minnesota, as described by Spurr,[70] occurs in the vicinity of Brookston in southern St. Louis County. The outcrop is said to be located south of St. Louis River, in NW¼ of SW¼ of section 27, T. 51N., R. 19W. The rock is described as consisting of alternate layers of siliceous slate, fine-grained slate, and sericite schist or slate, the layering being due to the difference in coarseness of the original sediments. The schistosity or cleavage is about at right angles to the bedding. The cleavage strikes about N.70°E. and has a steep dip. The outcrop has not been seen by the writers.

OUTCROPS OF SANDSTONE AND OTHER CLASTIC ROCKS

KEWEENAWAN SANDSTONE AND RELATED ROCKS

Outcrops of pink and red sandstone are abundant in east central Minnesota, occurring at intervals along a belt extending southwestward from the southwestern end of Lake Superior through Carlton, Pine, and Kanabec counties. These rocks have been generally described as belonging to the Lake Superior sandstone, the character and age relations of which have already been discussed. (See pages 13 and 14.)

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[70] Spurr, J. E., The stratigraphic position of the Thomson slate: *Am. Jour. Sci.*, 3d ser., vol. 48, p. 164, 1894.

The most southwesterly of the sandstone exposures is described by Upham[71] as occurring on Snake River in the NW¼ of section 3, T. 39N., R. 24W., Kanabec County. The sandstone is said to be exposed along the southwest side of the river for a distance of 300 feet with a width of 75 feet. It rises from 5 to 10 feet above the river, in places having a vertical outcrop. It is a coarse-grained sandstone of gray to brown color, showing thin layering and containing local beds of dull red sandstone. Pebbles varying up to several inches in thickness occur scattered through it. Fossils have not been found. The rock has a low dip to the east, 15° being the maximum.

The next sandstone outcrop to the north is one reported as occurring in the southern part of T. 40N., R. 23W.[72] It is mapped as extending along Snake River and is said to consist of interbedded red sandstone and ash-colored clay.

Aside from these two exposures, no sandstone is known along Snake River south of that mentioned on page 43 as occurring in section 23, T. 42N., R. 23W., just south of the big bend in the river. The largest exposure in this locality is found on the west bank of the river and forms a small cliff for a distance of about 300 feet along the stream. It consists of interlayered coarse-grained sandstones of slightly varying texture and color. Most of the rock is light-colored pinkish gray to pink, and massive; but near the base of the cliff a thin layer of dark red shaly sandstone occurs. Locally small pebbles of quartzite and other material are found in some of the layers. The general dip of the beds is 10° to 15°SE. A second outcrop occurs about 500 feet farther downstream on the east bank. This exposure is small and consists of sandstone similar to that described.

The sandstone outcropping along Snake River was all mapped by Upham as "Potsdam" sandstone. Although no fossils were found in it which might aid in determining its position, it was believed to underlie the Upper Cambrian and to be of Lower Cambrian age.

Numerous exposures of sandstone are mentioned by Upham[73] as occurring along Kettle River southward from Willow River in the western part of Pine County, and also along St. Croix River in the southern part of Pine County. Most of these outcrops were designated as "Hinckley" sandstone, but one or two were mapped as "Potsdam" sandstone. The term "Hinckley" sandstone was applied by Winchell, Upham, and others of the Geological and Natural History Survey of Minnesota to sandstone beds which are not definitely a part of the Upper Cambrian series, but

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[71] Upham, Warren, The geology of Mille Lacs and Kanabec counties: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 2, 1882-1885, pp. 621-622.

[72] Upham, W., *op. cit.*

[73] Upham, Warren, The geology of Pine County, *op. cit.*, pp. 637-642.

which are stratigraphically above the so-called "Potsdam" sandstone. In some reports it is considered as the lowest member of the "St. Croix" and in other reports as the uppermost member of the "Potsdam." The "St. Croix" sandstone of the early reports embraced the lower portion of the Upper Cambrian.

Exposures of the same sandstone are mapped by Winchell as occurring along the upper part of Kettle River west of Moose Lake in Carlton County, while the abundant exposures of sandstone and conglomerate occurring along St. Louis River west of Fond du Lac in southern St. Louis County are designated by Winchell as Puckwunge conglomerate and "Western" sandstone.[74] All of these beds are believed to be stratigraphically below the lowest fossiliferous "St. Croix" beds which are found along St. Croix River above and below Taylor's Falls, the Puckwunge conglomerate, which was classed as "Potsdam," being the lowest.

The sandstone which is found in numerous exposures along Kettle River in Pine County is described by Upham as occurring in bluffs along the river banks, and also forming the river bed in many places and producing rapids. For a long distance north and south of Sandstone the river flows through a great gorge in which sandstone is exposed both along the river banks and along the tops of bluffs 75 to 100 feet above the river. The rock is mostly fine-grained sandstone, but coarse-grained phases occur which, however, are rarely conglomeratic. It generally crumbles easily, and as a rule varies in color from buff to gray, though red and brown phases occur also. The beds lie flat or dip in various directions at low angles.[75]

Exposures of sandstone are found along St. Croix River in the southeastern part of Pine County, above and below the mouth of Snake River, as well as a short distance above the mouth of Kettle River. The exposures near the mouth of Snake River are mapped as "Hinckley" sandstone, and are said to be of friable gray and white sandstone with locally beds of conglomerate and of red, green, and yellow shale. The rocks are distinctly bedded, being horizontal, or having a slight inclination to the south. They are believed to belong to a higher stratigraphical horizon than the sandstone found along Kettle River. The outcrops north of the mouth of Kettle River are designated as "Potsdam," and are said to consist of red sandstone with underlying conglomerate.

The sedimentary rocks found along St. Louis River in Carlton and St. Louis counties are divided by Winchell[76] into two stratigraphic horizons. The lower beds are designated as Puckwunge conglomerate, and

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[74] Winchell, N. H., The geology of southern St. Louis County: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 4, 1896-98, Pl. 66.
Winchell, N. H., The geology of Carlton County, *op. cit.*, pp. 13-16.
[75] Upham, W., *op. cit.*

are believed to be of Lower Cambrian age. Exposures occur along St. Louis River and north of it at various points. The formation is said to be about 100 feet thick, and to grade from coarse conglomerate at the base upward into white sandstone and light-colored shale, and then into red shale which is overlain by rocks of eruptive origin.[77] The latter are designated as the "Manitou" eruptives of late Keweenawan age, and are said to stratigraphically underlie the so-called "Western" sandstone. This rock consists mainly of red sandstone and conglomerate which grade upward into lighter-colored sandstone. Its upper portion is believed to represent the so-called "Hinckley" sandstone. In the recent work by Thwaites already referred to (see pages 13 and 29), the sandstones along St. Louis River have all been placed in the Bayfield group of the upper Keweenawan.

Besides the sandstone outcrops mentioned by Winchell and Upham, a number of scattered occurrences of sandstone in southern Carlton and northern and western Pine counties are mapped by Hall.[78] No descriptions of the localities, however, are given.

The relative stratigraphic positions of the various beds of sandstone occurring in St. Louis, Carlton, Pine, and Kanabec counties is unknown. If the fossiliferous Upper Cambrian series rests conformably upon the red clastic series in southern Minnesota, as seems probable, and if the latter is supposed to be equivalent to the Keweenawan pink and red sandstone of east central and northern Minnesota, which in earlier reports has been called "Hinckley" sandstone, "Western" sandstone, "Lake Superior" sandstone, etc., then the rocks exposed in the southern part of Pine County can probably be regarded as showing the transition from the lower part of the Upper Cambrian into the upper part of the Keweenawan sandstone (red clastic series?). The question as to whether the so-called "Hinckley" sandstone belongs to the Upper Cambrian series or to the Keweenawan can not yet be answered, nor, as has been mentioned before, do we know whether the sandstone southwest of Lake Superior is Cambrian or Keweenawan in age, although the latter view seems to be the more probable.

CRETACEOUS SEDIMENTS

Besides the outcrops of the older sandstones just described in the eastern portion of the region under consideration, there are a number of scattered outcrops of slightly consolidated sediments occurring in the southwestern portion of the region. These, because of their softness,

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[76] Winchell, N. H., The geology of Carlton County, *op. cit.*

[77] Winchell, N. H., *op. cit.*, p. 13.

[78] Hall, C. W., Keewatin area of eastern and central Minnesota: *Bull. Geol. Soc. Amer.*, vol. 12, Pl. 29, 1901.

do not yield extensive exposures, but locally, as along Mississippi River and in the region to the west, scattered outcrops show their presence. Mosasaur teeth and other fossils have been found in them in places and indicate that they are of Cretaceous age.

Only one of these outcrops was examined by the writers, this occurring on the west bank of Mississippi River, just above the mouth of Two Rivers in the southern part of Morrison County. Much of the material at this locality consists of unconsolidated or slightly consolidated gray clay locally yellow or brown iron-stained. Some beds of fairly compact shale and siliceous shale occur, however. These are light gray to dark gray in color and locally greenish. Very commonly they are impregnated with limonite so that they have a yellow to dark brown color. Much of the material has curious little concretionary pellets scattered through it. In places these are so abundant as to make up most of the rocks, while elsewhere they are entirely lacking. Where the rock is iron-stained the pellets are dark brown. Elsewhere they are green or gray.

Other occurrences of Cretaceous sediments described by Upham[79] are in the southern part of Stearns County near Torah (Richmond). Three miles north of Torah (Richmond) in a ditch dug for drainage, yellow and blue clay were encountered with three seams of lignite from 1 to 6 inches thick. Locally pyrite was found in the blue clay. Southwest of Torah (Richmond) along Sauk River, considerable prospecting is said to have been done for lignite. Several shafts were sunk ranging in depth up to 125 feet. Most of the material encountered consisted of blue, white, and yellow clays in which were local beds of gray to black shale and seams of lignite several inches thick. Fossil fragments of mollusks and fishes were found in some of the shale beds. In places, crystals of selenite were found in the blue clay near the lignite seams. Granite was found to underlie the Cretaceous sediments.

THE CUYUNA IRON-ORE DISTRICT

LOCATION OF THE DISTRICT

The Cuyuna iron-ore district is located in the central part of Minnesota, trending southwesterly from the center of Aitkin County through Crow Wing and Morrison counties, into Todd County. The most important part of the iron-bearing belt is in Crow Wing County. This part has a course approximately parallel to Mississippi River and lies southeast of it. In the southwestern part of the district, between Brainerd and Little Falls, Mississippi River, changing its course from

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[79] Upham, Warren, The geology of Stearns County: *Geol. and Nat. Hist. Survey of Minn., Geol. of Minn.*, vol. 2, 1882-1885, pp. 459-461.

southwest to south, crosses the ore-bearing belt. Southwest of this point the ore-bearing belt continues in the same general direction through Morrison County and into Todd County, beyond which it is not known. Northeastward, the iron-bearing belt runs from Crow Wing County into Aitkin County and disappears beyond Rice River.

The district has a length northeast and southwest of about 65 miles, and ranges in width from a mile or two to as much as 12 miles, not including the Emily area in northern Crow Wing County where iron-bearing rocks have been found in scattered localities. The region presented for exploration amounts to approximately 40,000 acres.[80] Much of this area is under cultivation, farms being scattered throughout. Forested and brush lands also occupy large areas, and locally swamps occur along the iron-bearing belts.

Although Mississippi River flows through the district, the drainage is very imperfect. Lakes are very abundant throughout the region. The largest of these is Mille Lacs Lake, 14 miles wide by 16 miles long, situated about 14 miles southeast of Deerwood. The lakes are especially numerous in the eastern part of the district, where extensive moraines occur, and decrease in number toward the southwest where outwash plains predominate over moraines.

The valley of Mississippi River is narrow and in general is not very deep, although locally as at Brainerd there is a distinct gorge. Its only large branch in the region under discussion is Crow Wing River, which empties into it from the west about 10 miles below Brainerd. Small side streams, however, are abundant, but these, as a rule, have worn their valleys only short distances back from the Mississippi.

The topography of the district is predominantly morainic. Over large areas it is hummocky, numerous small hills being interspersed with swampy areas and lakes. In other places there are extensive outwash plains and the surface is level or gently undulating. The greatest difference in elevation is about 200 feet. The elevations vary from 1,150 feet above sea level, which is approximately the elevation of Mississippi River in the western part of the district, to about 1,350 feet, which is the elevation of some of the higher hills in the eastern part of the district. The highest point in the region adjacent to the Cuyuna district is Warren Hill, just west of Mille Lacs Lake, the summit of which is 1,450 feet above sea level. Mille Lacs Lake has an elevation of 1,249 feet.

The principal towns along the ore-bearing belt from northeast to southwest are Kimberly and Aitkin in Aitkin County; Deerwood, Cuyuna, Crosby, Ironton, Manganese, Trommald (formerly Iron Mountain),

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[80] Zapffe, Carl, The Cuyuna iron-ore district of Minnesota: *Supplement to Brainerd Tribune*, July 1, 1910.

Riverton, Woodrow, Brainerd, and Barrows in Crow Wing County; and Randall in Morrison County. Of these towns, all those located in Crow Wing County except Deerwood and Brainerd were built since the beginning of the development of the iron mines. The oldest of these, Cuyuna, is about nine years old. The largest city in the district is Brainerd, which has a population of about 8,000 and which at one time was one of the lumber centers of northern Minnesota. It was also here that the general offices of the Northern Pacific Railway were located before they were moved to St. Paul. At the present time Brainerd is the center of a fairly prosperous and constantly growing farming community. Of the other cities on the range, Aitkin also is well established and is independent of the iron-mining industry. Kimberly, Deerwood, and Randall are smaller towns, built before iron ore was discovered in the region. All the other towns mentioned are more or less dependent on the iron-mining industry to which they owe their establishment.

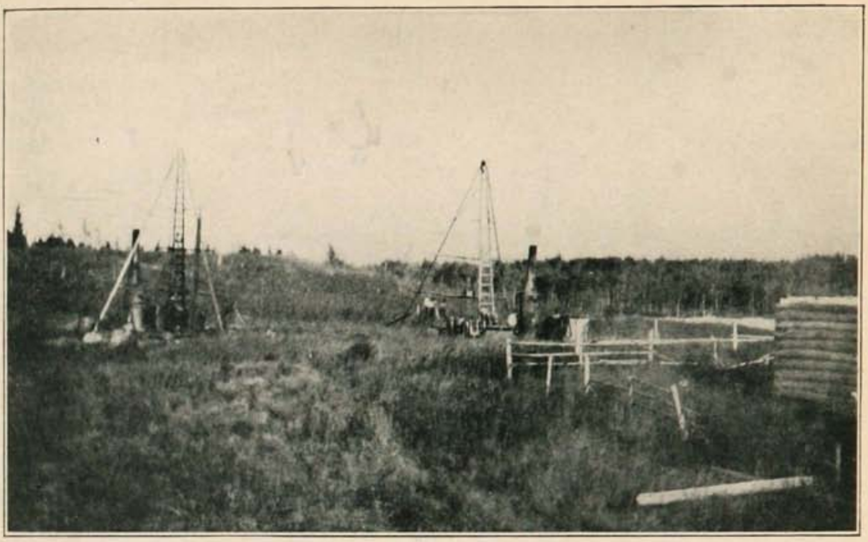
Two railroads serve the Cuyuna district, the Duluth-Brainerd branch of the Northern Pacific Railroad, built in 1870, and the Cuyuna Range branch of the Minneapolis, St. Paul, and Sault Ste. Marie Railroad, built in 1910. The former runs from Duluth and Superior westward through Carlton, Aitkin, Deerwood, and Brainerd, to Staples where it joins the main line of the Northern Pacific to the West Coast. In its passage through the iron-ore district, it runs approximately parallel to the ore-bearing belts. A branch line of the Northern Pacific also runs along the east side of Mississippi River between Brainerd and Little Falls connecting at the latter point with the main line to Minneapolis and St. Paul. A number of small branches run to various mines in the iron-ore district.

The Cuyuna Range branch of the Minneapolis, St. Paul, and Sault Ste. Marie Railroad leaves the Duluth-Winnipeg branch of this road at Lawler and runs westward through Aitkin to Iron Hub. Here it divides, a northern branch going to Manganese and a southern branch through Cuyuna, Crosby, and Ironton, to Riverton. Various mines are connected with the main lines by branch railways.

HISTORY OF THE DISTRICT

That iron ore might be found in east central Minnesota was suspected long before its actual discovery. It is said that when the Northern Pacific Railway surveys for the present road were being made previous to 1870, through what is now the Cuyuna district, indications of the presence of iron ore were found,[81] due probably to compass disturbances being noted. Mention of variations in the direction of the compass needle

[81] Kellogg, L. O., Notes on the Cuyuna range, I and II: *Eng. and Min. Jour.*, vol. 96, pp. 1199-1203, Dec. 27, 1913; vol. 97, pp. 7-10, Jan. 3, 1914.



A. EXPLORATION BY DRILLING IN THE CUYUNA DISTRICT

B. STARTING EXCAVATION WITH STEAM SHOVEL AT THE MAHNOMEN OPEN-PIT MINE, NEAR IRONTON

PHOTO BY CARL ZAPPFE

in parts of Crow Wing County are said to be found also in the notes of the government land surveyors made in the 70's, at which time the Marquette Range of northern Michigan was the only iron-ore producing district in the Lake Superior region.

It was about 1890 when the first magnetic surveys were made in east central Minnesota for the purpose of locating areas of abnormal magnetic attraction, such as are assumed to indicate the presence of iron ore. From this time until the actual discovery of the existence of iron-bearing formation in the Cuyuna district, during the summer and fall of 1904, magnetic surveys were made at intervals in different parts of the region. Some time elapsed, however, before the regularity and extensiveness of the magnetic variations were realized, and after this, systematic exploration work progressed rapidly. Most of the early magnetic work was done by Mr. Cuyler Adams to whom belongs a large share of the credit of discovering and developing the range. It was Mr. Adams also who started the first drilling operations on the range; in fact, it was not until he had encountered iron-bearing formation with a churn drill that the existence of the new iron range became common knowledge.

Mr. Adams first became interested in the region now known as the Cuyuna district early in the 90's, when the Mesabi district was still a wilderness.[82] His attention had been drawn to the area by the fact that he noted magnetic variations on certain lands which he had purchased, and at various times he made magnetic surveys with dial compass and dip needle in attempts to locate lines of maximum magnetic attraction.[83] In this he was successful, and eventually two such lines were located, both having northeast-southwest trends. One of these lines was 12 to 15 miles long and was located south of Deerwood, in general running parallel to and south of the Northern Pacific Railway. It extended from the west line of section 10, T. 46N., R. 28W., southwesterly across the corners of T. 46N., R. 39W., and T. 45N., R. 29W., to the center of the west line of section 29, T. 45N., R. 30W. The other line was found about 7 miles north of Deerwood, running in a northeast-southwest direction across section 30, T. 47N., R. 28W. south of Rabbit Lake. Both lines seemed to feather out at the ends.

Drilling was begun in the district in May, 1903,[84] the first holes being put down in the SW¼ of the SE¼ of section 16, T. 46N., R. 28W., near the northeast end of the southern line of attraction, while later holes were put down in sections 21, 20, and 10, T. 46N., R. 28W., also on the

[82] Thomas, Kirby, A new promising Lake Superior iron district: *Min. Wld.*, vol. 21, pp. 446-448, Nov. 5, 1904.

[83] Adams, Cuyler, Personal correspondence.

[84] Thomas, Kirby, *op. cit.*

southern line of attraction. Exploration work was begun in section 30, T. 47N., R. 28W., south of Rabbit Lake on the northern line of attraction, in July, 1904. Five drills were active throughout the summer of 1904, and by October, 1904, twenty-two holes, more than half of which encountered iron-bearing formation or lean iron ore, had been drilled, and the information gained was first given to the public. When the information began to spread, much interest and excitement was created, even though ore in commercial quantity had not yet been found.

Besides this drilling in the central part of the district, it is stated that drilling was done also during the summer of 1904 in the Dam Lake region about three miles south of Kimberly.[85]

Magnetic exploration work progressed very rapidly after the discovery of iron-bearing formation, and soon the district in which abnormal magnetic attractions were found to occur was greatly enlarged by extensions to the northeast and southwest. Various mining companies from the other iron ranges took options on favorably located properties and started exploration work. Among the first of these to come into the district was the Oliver Mining Company of the United States Steel Corporation, which took options on large tracts of land and started drilling operations. After considerable drilling and exploration, however, this company withdrew from the district and has not since then been identified with any of the Cuyuna range operations. Other companies that came into the district from other ranges are Pickands, Mather and Company, Rogers-Brown Ore Company, Tod-Stambaugh Company, M. A. Hanna and Company, Inland Steel Company, Ogelbay, Norton and Company, and Jones and Laughlin Steel Company. Some of these companies have become permanently identified with the district, while others withdrew after preliminary exploration work.

Not long after the discovery of the existence of iron-bearing formation in the Cuyuna district, the possible connection between the iron-bearing formation of the western end of the Mesabi district and that of the Cuyuna district became a subject of considerable interest, and soon drilling was started in the region southwest and south of Grand Rapids and north and northwest of Aitkin. This drilling has continued to the present time, and ore has been found locally in this region.

The first attempt at underground work in the Cuyuna district was made by the Hobart Iron Company of Pickands, Mather and Company, which sunk a 120-foot shaft with several hundred feet of cross cuts in the SW¼ of the SE¼ of section 8, T. 45N., R. 29W. This work was done in 1905 and the early part of 1906, but the operation was abandoned after some months.

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85 Thomas, Kirby, Notes on the geology of a new iron ore district in **Minnesota**: *Mines and Minerals*, vol. 25, p. 27, August, 1905.

The first permanent mining shaft in the Cuyuna district was sunk by Rogers-Brown Ore Company. During the summer of 1907 this company started drilling on lands on which they had secured options in sections 29 and 30, T. 47N., R. 28W.[86] south of Rabbit Lake. Some of these lands had been previously drilled by other companies, including the Oliver Mining Company, the latter having secured an option on the properties, but having released them because the results of exploration were considered unsatisfactory. The indications of the presence of ore, as shown by the Rogers-Brown Ore Company exploration work, appeared so favorable, that this company took a lease on the properties and started sinking its shaft, which has developed into the present Kennedy mine. The Oliver Mining Company had already attempted sinking a shaft on the tract, but this had caved in at a depth of 25 feet. Previous to starting their permanent shaft, the Rogers-Brown Ore Company, therefore, sunk an exploration shaft less than 100 feet south of the old Oliver Mining Company's shaft in order to test the surface. This was put down to a depth of 50 feet, and as no great difficulty was encountered, the permanent shaft was started near the southeast corner of lot 5 of section 30, T. 47N., R. 28W., about half a mile northeast of Cuyuna. The shaft was begun as a 10 by 16 foot lath shaft, but considerable quicksand was encountered, and it was changed to a drop shaft, which after great difficulty and nearly a year of uncertainty was finally ledged at a depth of 112 feet in October, 1908.[87]

In the meantime exploratory drill work had been carried on throughout the region so that the district had been greatly extended both to the northeast and southwest. By 1909, 2,000 holes had been drilled, and iron-bearing rocks with associated ore had been proved to exist in two parallel northeast-southwest belts, one north of the Northern Pacific Railway, known as the north range, and the other south of the railway, known as the south range.[88] In the south range iron-bearing formation had been shown to occur as far northeast as Rice River, T. 48N., R. 26W., and southwest as far as Mississippi River, T. 43N., R. 32W., a distance of about fifty miles. In the north range, iron-bearing formation had been found at various localities in T. 47N., R. 28W., T. 47N., R. 29W., and T. 46N., R. 29W. In addition to this, iron-bearing formation had been found also west of Mississippi River in T. 133N., R. 32W., southwest of Staples.[89] However, exploration work was actively continued,

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[86] Woodbridge, D. E., Iron ore in Crow Wing County, Minnesota: *Eng. and Min. Jour.*, vol. 84, pp. 775-776, Oct. 26, 1907.

[87] Anon., A difficult shaft sinking operation at Deerwood, Minnesota: *Iron Tr. Rev.*, vol. 43, pp. 772-774, Nov. 5, 1908.

[88] Adams, F. S., The iron formation of the Cuyuna Range: *Econ. Geology*, vol. 5, pp. 729-740, 1910; vol. 6, pp. 60-70, 156-180, 1911.

[89] Adams, F. S., *op. cit.*

and during the fall of 1910 forty drills were at work in various parts of the range.

When the iron-bearing rocks in the district were first discovered, Brainerd, Deerwood, and Aitkin were the only towns of importance in the region, and Deerwood was the only town located in the area where the first important deposits of iron ore were discovered. It was not long, however, before new townsites were established and Cuyuna, Crosby, and Ironton became active, growing towns. Cuyuna was settled in 1908, Crosby was platted in 1909 and settled in 1910, while Ironton was established in 1910. Later the towns of Riverton, Manganese, Woodrow, Barrows, and, more recently, Trommald were settled.

It was not long after the completion of the Kennedy shaft to bed rock, that the construction work on the Minneapolis, St. Paul, and Sault Ste. Marie Railroad branch line into the Cuyuna range was started and by December, 1910, it had reached the town of Cuyuna near the Kennedy mine, and the grading had been completed into Crosby and Ironton.[90] A spur had also been constructed to the Kennedy mine, where the shaft had been sunk to the lowest level (262 feet) and where a stock pile of 45,000 to 50,000 tons of ore was awaiting shipment. The first trainload of ore from the Cuyuna range was shipped over this road from the Kennedy mine in May, 1911.

Meanwhile other shafts were being sunk in the north range, and in 1912 the Armour No. 1 and Armour No. 2 mines near Ironton, and the Thompson mine near Crosby, made their initial shipments, increasing the list of producers to four.

The Armour No. 1 mine was opened by the Iroquois Iron Company, which sank a circular concrete shaft south of the ore body during 1910 and 1911. During 1912 and 1913, 159,859 tons of ore were produced from this mine, but in July, 1913, all operations ceased.[91] The property remained idle during 1914, but in January, 1915, the lease of the Iroquois Company was assigned to the Inland Steel Company, who decided to strip the western part of the ore body. Stripping operations were commenced in the spring of 1915 and were continued during the summer, remarkably rapid progress being made. A total of about 800,000 cubic yards of overburden was removed, much of which was taken through the Pennington open pit with which the Armour No. 1 pit is directly connected. Mining operations in the open pit began in August, 1915, and 79,773 tons of ore were shipped before the end of the year. During the season of 1916, the Armour No. 1 mine was steadily operated.

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[90] Anon., The Cuyuna range, Minnesota: *Eng. and Min. Jour.*, vol. 90, p. 1214, Dec. 17, 1910.

[91] Anon., Armour mines on Cuyuna range: *Iron Tr. Rev.*, vol. 57, p. 1223, Dec. 23, 1915.

A. REMOVING OVERBURDEN BY HYDRAULIC METHOD AT THE ROWE MINE, NEAR RIVERTON. SHOWS STREAM OF WATER ISSUING FROM GIANT NOZZLE WASHING DOWN SAND AND CLAY

B. REMOVING OVERBURDEN BY HYDRAULIC METHOD AT THE HILLCREST MINE, NEAR IRONTON. SHOWS GIANT NOZZLE, CENTRIFUGAL PUMP, AND DISCHARGE PIPE
PHOTO BY CARL ZAPPFE

The Armour No. 2 mine was leased and drilled by the Iroquois Iron Company.[92] Exceptionally good ore is said to have been shown up in the drilling, and it was soon discontinued and a concrete shaft was sunk during 1910 and 1911. Mining was started in 1912, and 524,825 tons of ore were shipped during the seasons of 1912, 1913, and 1914, by the Rogers-Brown Ore Company, which operated the property. In January, 1915, the lease was assigned, together with that on the Armour No. 1 property, to the Inland Steel Company, which shipped 333,856 tons of ore from this mine during 1915. The Armour No. 2 mine has been in steady operation since it was first started, and some of the best ore shipped from the district has come from this mine.

The Thompson mine was started as an underground mine by the Inland Steel Company in 1911. A shaft was sunk between two ore bodies, one on the north and one on the south, and small quantities of ore were shipped during 1912 and 1913. It was then decided to strip the south ore body, and mine the upper part of it by open pit methods. The underground workings were closed in June, 1913,[93] and stripping operations were in progress during the latter part of 1913 and the early part of 1914, the first ore being shipped from the open pit during the summer of 1914. Since then the Thompson mine has been operated steadily. In the fall of 1916 the steam shovels were removed from the pit and milling was inaugurated. At about the same time stripping operations were started on the north ore body and continued during the spring of 1917.

In 1913 five new mines joined the ranks of producing mines. They are the Pennington, Ironton, and Cuyuna–Mille Lacs mines near Ironton, the Iron Mountain (now Algoma) mine near Manganese, and the Barrows mine near Barrows. These mines, with the exception of the Barrows mine, are located on the north range, and two of them, the Cuyuna–Mille Lacs and Iron Mountain mines, are manganiferous iron-ore mines. The Barrows mine is located in the western part of the south range.

The Pennington mine was the first open-pit mine in the Cuyuna district. Excavation was started in January, 1913, and before the end of the year 1,500,000 cubic yards of overburden had been removed and 101,136 tons of ore had been mined.[94] The first carload of ore was shipped August 2, 1913, and shipping continued until the close of lake navigation, about the middle of November. During 1914 the Pennington mine was idle, but shipments recommenced in August, 1915, after the

[92] *Op. cit.*, pp. 1223-1224.

[93] Swanson, August, Annual report of Inspector of Mines, Crow Wing County, Minn., Year ending June 30, 1914, p. 8.

[94] Woodbridge, D. E., Changes and outlook in the lake iron-ore trade: *Iron Age*, vol. 93, pp. 15-18, Jan. 1, 1914.

Anon., The Dean-Itasca and Pennington mines: *Iron. Tr. Rev.*, vol. 57, pp. 1140-1141, Dec. 9, 1915.

completion of the Armour No. 1 open pit, and were continued during 1916.

The Ironton and Cuyuna-Mille Lacs mines both made small initial shipments in 1913. The Ironton mine is located in the northern part of the village of Ironton on the southwest extension of the Armour No. 2 ore body. It was opened in 1912,[95] and 49,150 tons of ore were shipped during 1913 and 1914. In 1915 the mine was idle and recommenced operations only during the latter part of the season of 1916.

The Cuyuna-Mille Lacs and Iron Mountain mines were the first shippers of manganiferous iron ore in the Cuyuna district. The Cuyuna-Mille Lacs mine is situated just south of Menomin Lake about a mile northwest of Ironton. The shaft was started in October, 1911, and reached bed rock after penetrating about 50 feet of surface drift. In 1913, 27,300 tons of ore were shipped, and shipments have continued to the present time. Until 1916 the Cuyuna-Mille Lacs mine was the only important shipper of manganiferous iron ore in the district, only small shipments being made from the Iron Mountain mine and from one or two of the iron-ore mines. Ore, ranging from about 10 per cent to 30 per cent in manganese,[96] and between 35 and 40 per cent in iron has been shipped from the Cuyuna-Mille Lacs mine, several grades with different manganese and iron content being produced. At present the lower grade ores are being produced in larger quantities.

The Iron Mountain mine, located about half a mile south of Manganese, was opened by the Iron Mountain Mining Company. The first shaft was sunk during 1911 and 1912, but was closed down and a second shaft was started in May, 1913.[97] The first ore was shipped in 1913, consisting of a few carloads used for experimental purposes.[98] The mine was idle in 1914, but operations were recommenced in 1915, 8,600 tons of ore being shipped during the season. In the winter of 1916 the Iron Mountain mine was taken over by the Hoch Mining Company and renamed the Hoch mine. A large tonnage was mined and shipped during the season of 1916. At the present time (summer 1917) the mine is being operated by the Algoma Mining Company and is known as the Algoma mine.

The Barrows mine, located 4 miles southwest of Brainerd, was the first of the south range mines to join the list of producers. It was

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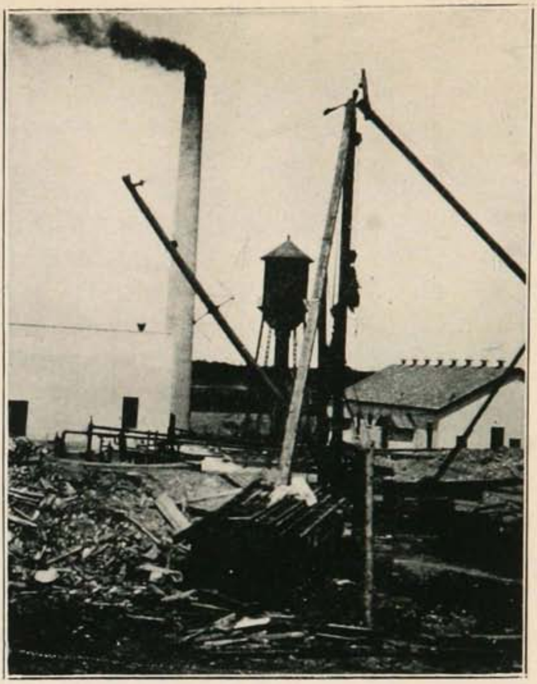
[95] Swanson, August, Annual report of Inspector of Mines, Crow Wing County, Minnesota. Year ending June 30, 1914, p. 11.

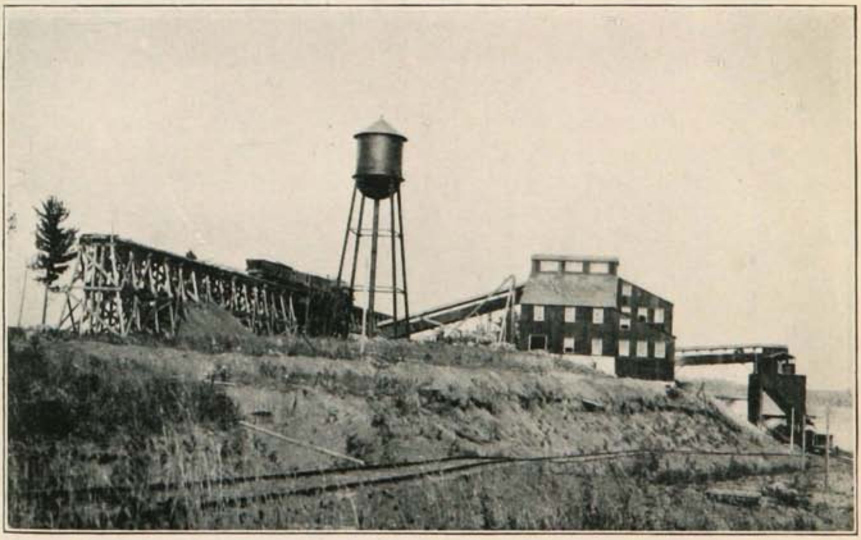
[96] Zapffe, Carl, Matters of interest to operators regarding the Cuyuna district: *Proc. Lake Sup. Min. Inst.*, vol. 20, pp. 196 et seq., Sept. meeting, 1915.

[97] Swanson, August, Annual report of Inspector of Mines, Crow Wing County, Minnesota. Year ending June 30, 1913, p. 11.

[98] Zapffe, Carl, *op. cit.*, p. 197.



A. SINKING A CONCRETE SHAFT AT THE CROFT MINE, NEAR CROSBY
PHOTO BY CARL ZAPPFE



B. IRON-ORE CONCENTRATING PLANT AT THE ROWE MINE, NEAR RIVERTON
PHOTO BY CARL ZAPPFE

soon followed, however, by the Adams mine and more recently by the Wilcox and Brainerd-Cuyuna mines.

At the Barrows mine considerable difficulty was encountered in shaft sinking on account of bad ground. A test shaft was sunk during 1911 to a depth of 80 feet, and the conditions encountered were so serious that the second shaft was started as a timber drop shaft. This was abandoned after reaching a depth of more than 50 feet. A third shaft, also a timber drop shaft, was started early in 1912 and was finally ledged. The Barrows mine was operated by the Virginia Ore Mining Company, of M. A. Hanna and Company, the first ore being shipped from the mine in 1913. Shipments continued until the summer of 1914 when the lease was abandoned and the mine ceased operating. The Barrows mine is owned by the Brainerd Mining Company.

During the shipping season of 1914 only two new mines were added to the producing list, viz., the Rowe mine, near Riverton, on the north range and the Adams mine, 3 miles southwest of Deerwood, on the south range. Several new shafts, however, were started during the year, including the Sultana shaft about a mile northwest of Ironton, the Croft shaft near Crosby, the Wilcox shaft near Woodrow, and the Rowley shaft half a mile south of Barrows.

The Rowe open-pit mine of the Pittsburgh Steel Ore Company was excavated during 1913 and 1914, the first ore being shipped in the autumn of 1914. Sluicing and hydraulic stripping were successfully applied in the removal of the overburden which covered the ore, this being the first instance of such methods being employed in the removal of overburden in the Lake Superior district.[99] The operations were begun in August, 1913, and for a short time the sluicing method was used. The location is near the shore of Little Rabbit Lake, and a hill rising to an elevation of 50 feet above the level of the lake covered the ore body. Water was therefore pumped from the lake up to the hill and turned loose, the returning stream carrying a full burden of material down to the lake. This was continued until the slope became too low for the effective removal of material. A hydraulic giant and a centrifugal sand pump were then installed. The stream from the hydraulic giant undercut the banks of sand and clay, and the material was washed by the water down to a sump where it was picked up through suction by the sand pump and discharged through a 12-inch pipe into the lake. The stripping operations continued

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[99] Kellogg, L. O., Stripping with the hydraulic giant: *Eng. and Min. Jour.*, vol. 97, pp. 166-167, Jan. 17, 1914.

McAuliffe, P. J., Stripping a mine by hydraulic methods: *Coal Age*, vol. 5, pp. 568-569, Apr. 4, 1914.

McCarty, E. P., Hydraulic stripping at Rowe and Hillcrest mines on the Cuyuna Range, Minn.: *Lake Sup. Min. Inst.*, Sept. meeting, 1915. See also *Iron Tr. Rev.*, vol. 58, pp. 136-139, Jan. 13, 1916.

into the summer of 1914, a total of about 1,581,000 cubic yards of earth being removed, of which 81,000 cubic yards were removed by the preliminary sluicing. The final clearing up of boulders and other material not removed by hydraulicking was done with steam shovels.

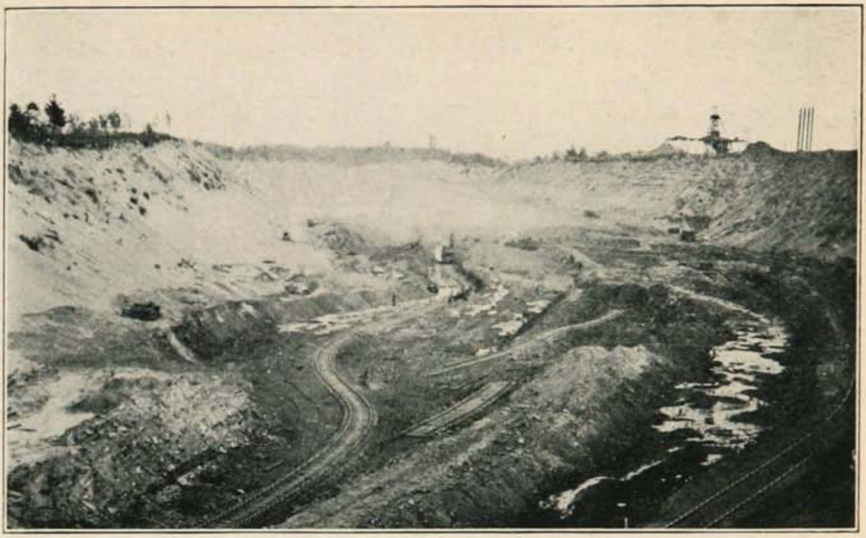
During 1914, 80,000 tons of ore were shipped from the Rowe mine. But it was found that in many parts of the ore body the "direct-shipping" ore was irregularly mixed with low-grade material which could not be shipped profitably without concentration. Concentration tests were made on this material during the following winter and during the spring and summer of 1915, a concentrating plant was erected. No ore was mined during this time, but in August, 1915, upon the completion of the concentrating plant, operations recommenced and 143,163 tons were shipped before the season closed. A large part of this tonnage consisted of concentrates.

The Adams mine is the easternmost mine on the south range. The area in which it is located was one of the first to be explored in the Cuyuna district. In 1908-9, a shaft was sunk on the property by Rogers Brown Ore Company, but was abandoned at a depth of 52 feet before it had penetrated the surface drift.[100] A few years later the property was leased by Cuyler Adams and a concrete shaft was sunk for him by the New York Foundation Company in 1912. The ore body was opened during 1913, and some ore was shipped in 1914, but during the fall of the latter year operations ceased and the mine has since then been inactive.

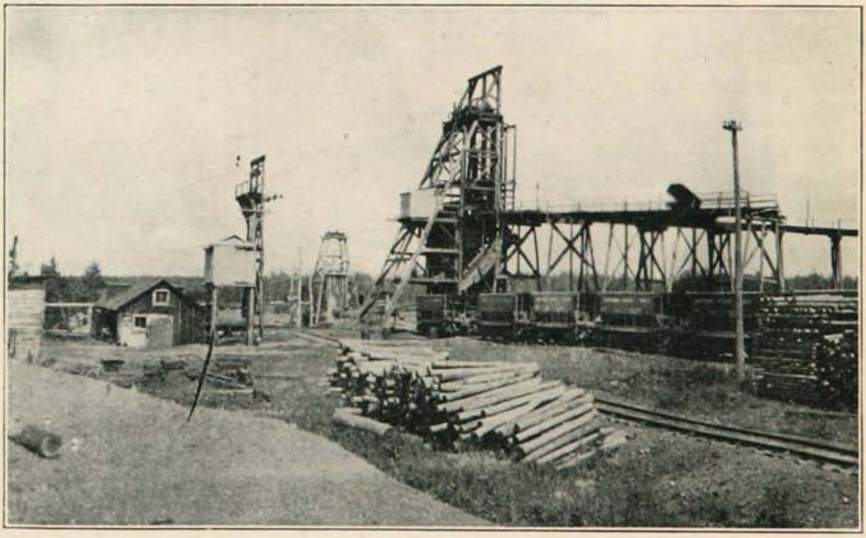
The year 1915 was one of considerable activity in the Cuyuna district. Early in the year the concentrating plant at the Rowe mine was started, stripping operations were begun at the Hillcrest mine, about a mile west of Ironton, and at the Armour No. 1 mine north of Ironton, while shaft-sinking was in progress at the Croft mine near Crosby, and at the Rowley mine of the Barrows Mining Company, south of Barrows. A little later stripping operations were begun on the Mahnomen open-pit mine of the Mahnomen Mining Company, north of the Pennington open pit. Toward the latter part of the summer, the Hopkins shaft was sunk by Breitung and Company, Ltd., a short distance east of the Cuyuna-Mille Lacs mine, while in the fall the Tabbert shaft of the Adbar Development Company was started in the south range between Brainerd and Woodrow.

Only three new mines made their initial shipments in 1915, these being the Sultana mine north of Ironton on the north range, the Wilcox mine near Woodrow, and the Brainerd-Cuyuna mine near Brainerd, both on the south range. The Sultana mine of the Sultana Mines Company,

[100] Zapffe, Carl, Personal communication.



A. PENNINGTON–ARMOUR NO. I OPEN-PIT MINE NEAR IRONTON. LOOKING NORTHEASTWARD
PHOTO BY CARL ZAPPFE



B. HEAD-FRAME AND TRESTLE OF CUYUNA–MILLE LACS MINE, NEAR IRONTON LOOKING EASTWARD
PHOTO BY CARL ZAPPFE

formerly the Cuyuna-Sultana Company, is located in the southern part of section 3, T. 46N., R. 29W., about half a mile east of the Cuyuna-Mille Lacs mine, and like the latter is a manganiferous iron-ore mine. The first exploration shaft, which is now Shaft No. 1, was begun June 25, 1914, and the permanent hoisting shaft was begun October 1, 1914. Both were ledged during the fall of 1914. A small quantity of ore was shipped in the fall of 1915, and during the spring and summer of 1916 a considerable tonnage was mined. A small experimental concentrating plant for treating the lower grade ore was erected in the spring of 1915, but tests were unsuccessful.

The sinking of the Wilcox shaft was begun early in 1914 and continued during the summer and fall.[101] The ore body was opened during the winter and the following spring, shipments beginning during the summer. The Wilcox mine is the only one of the south range mines which has produced steadily since it was opened. It was operated by the Canadian-Cuyuna Iron Mining Company during 1915 and 1916. In 1917 it was taken over by the Paterson Construction Company which is operating it at present.

The Brainerd-Cuyuna mine had difficulty in shaft-sinking on account of quicksand. Two shafts were sunk, but were abandoned before reaching bed rock, the first one being started in August, 1913, and the second one in February, 1914.[102] A third one, however, started late in 1914, reached bed rock with difficulty in the spring of 1915. The first ore was raised during the summer, the shipments amounting to 3,000 tons.

During 1916 there was much activity among the manganiferous iron-ore mines, and considerable tonnages of this ore were shipped from the Cuyuna-Mille Lacs, Sultana, Hoch (now Algoma), and Ferro mines. Three new manganiferous iron-ore mines, the Ferro, located near Iron Mountain, the Mangan No. 1 mine situated just northeast of the Cuyuna-Mille Lacs mine, and the Mangan No. 2 mine about one fourth of a mile north of the Armour No. 1 mine near Ironton, joined the list of producers. During the late fall, several new shafts were started on manganiferous iron-ore bodies in different parts of the north range, among them being the shaft of the Merritt interests near Iron Mountain, the McKenzie shaft of the Donohue interests near Manganese, and the Joan shaft of the Joan Mining Company, east of Menomin Lake.

The Ferro mine, formerly known as the Duluth-Brainerd, is located about half a mile southwest of the Algoma mine already mentioned. A shaft was sunk on this property by the Duluth-Brainerd Iron Company during the fall of 1913, and a little ore was taken out.[103] There were

[101] Swanson, August, Annual report of Inspector of Mines, Crow Wing County, Minn. Year ending June 30, 1914, p. 13.

[102] *Ibid.*, p. 12.

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

no important operations, however, during 1914 and 1915. Early in 1916 the property was taken over by the Onahman Iron Company, and a large tonnage of high-grade manganiferous iron-ore was shipped during the season.

The Mangan No. 1 mine of the Mangan Iron and Steel Company was begun in December, 1915, and a considerable quantity of ore was taken out during the summer and fall of 1916.

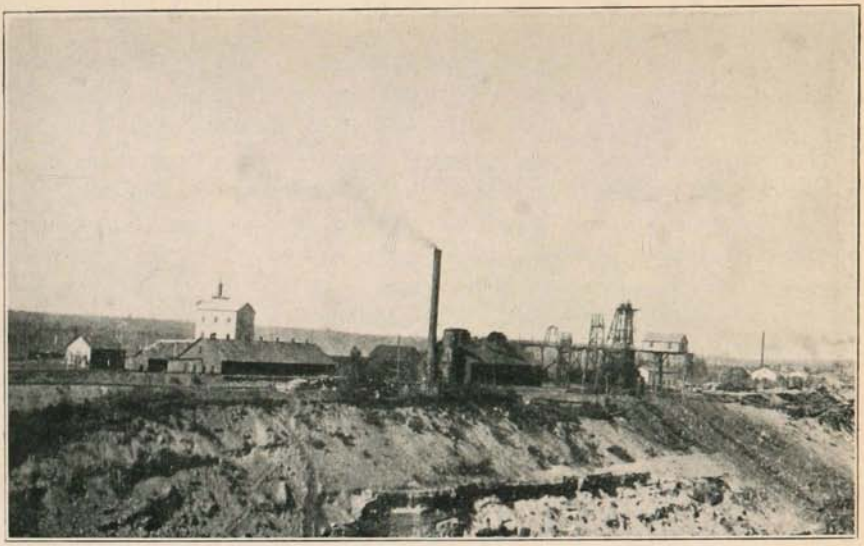
The Mangan No. 2 mine, also of the Mangan Iron and Steel Company, contains both iron ore and manganiferous iron ore. Shaft sinking was begun in June, 1916, and a small quantity of manganiferous iron ore was mined during the autumn.

Not only were the manganiferous iron-ore mines active during 1916, but more iron ore was produced in the district than during any previous year. Four new iron-ore mines joined the producing list during 1916, these being the Mahnomen and Hillcrest open-pit mines near Ironton and the Croft and Meacham underground mines near Crosby. A second shaft was started by the Adbar Development Company on the Tabbert property near Woodrow, the first having been abandoned on account of bad ground. This shaft, as well as that at the Rowley mine, near Barrows, had not reached bed rock in the autumn of 1916. Late in the autumn of 1916, the Cuyuna Realty Company started sinking a shaft on the Feigh property, located between the Pennington and Hillcrest open pits.

The Mahnomen ore body was stripped of its overburden by means of steam shovels, operations being started early in the summer of 1915. The work continued during the summer and fall of 1915, and the spring of 1916. As the ore body was underneath a swampy area, considerable difficulty was encountered in excavating on account of water. However, comparatively rapid progress was made, and ore was shipped during the summer and fall of 1916.

The stripping operations at the Hillcrest mine were commenced in April, 1915,[104] with hydraulic giant and sand pump, such as had been used in removing the overburden from the ore body at the Rowe mine. The average thickness of the overburden overlying the ore body was about sixty-five feet, and it was calculated that approximately a million cubic yards of material had to be removed. The work progressed rapidly during the summer and fall, with an operating force of only six men to a shift, and it continued through the extremely cold weather of January, 1916. During midwinter, however, operations ceased, but were recom-

[104] Anon., Stripping the Hillcrest iron mine with a sand pump: *Eng. and Min. Jour.*, vol. 101, pp. 211-215, 1916.



A. HEAD-FRAME, CONCENTRATING PLANT, AND PART OF OPEN PIT AT THOMPSON MINE, NEAR CROSBY. LOOKING NORTHEASTWARD
PHOTO BY CARL ZAPPFE

B. HEAD-FRAME AND POWER HOUSE OF ADAMS MINE, NEAR DEERWOOD
PHOTO BY CARL ZAPPFE

menced in the spring. In the summer the boulders and coarse debris left by the sand pump were removed by means of a steam shovel, and the first ore was shipped from the mine in October. The Hillcrest mine is operated by the Hill Mines Company.

The Croft mine of the Merrimac Mining Company (John A. Savage and Company), is located about half a mile north of Crosby. Shaft sinking was begun at this mine during the fall of 1914 and continued through the summer of 1915. In the fall of 1915, cross cuts were driven from the shaft northward into the ore body, and during the winter and spring the ore body was opened up in preparation for the shipping season. A considerable amount of ore was shipped during the summer and fall of 1916.

The Meacham mine is situated a short distance southwest of the Croft mine near the edge of the Thompson open pit. The shaft was sunk during 1910 and 1911 at approximately the same time that the shafts for the Armour No. 1, Armour No. 2, and Thompson mines were being sunk, but the mine was idle until the spring of 1916, the first shipment being made by Rogers-Brown Ore Company in May.

The iron ore and manganiferous iron ore production from the Cuyuna district to the end of 1916 aggregated 5,116,358 tons, of which 4,747,268 tons were iron ore and 369,090 tons were manganiferous iron ore. This ore was produced by 21 mines, the bulk of it coming from the Kennedy, Armour No. 2, Thompson, Pennington, Rowe, and Armour No. 1. Three mines which contributed to this production, viz., the Adams, Barrows, and Brainerd-Cuyuna mines, were idle in 1916. The remaining 18, however, were actively operated, seven of them making their first production in 1916. The seven new mines are the Croft, Ferro, Hillcrest, Mahnomen, Mangan No. 1, Mangan No. 2, and Meacham. The accompanying table shows the production of the mines of the Cuyuna district to the end of 1916, as reported to the Division of Mineral Resources of the United States Geological Survey.

GENERAL GEOLOGY OF THE DISTRICT

GENERAL STATEMENT

The only known outcrops of bed rock in the Cuyuna iron-ore district are the quartzite and greenstone occurring near Dam Lake and Long Lake, a short distance south of the northeastern end of the iron-bearing belt, and the chlorite schist at Randall near the southwestern end of the iron-bearing belt. Both of these have already been described. Over the rest of the region there is a covering of glacial till varying in thickness from 0 to 400 feet. The variation in thickness of the mantle of glacial material is due in part to the present surface topography and in part to the irregularity of the bed-rock surface. The least thickness

Total Production of Iron Ore and Manganiferous Iron Ore in Cuyuna District†

	1911	1912	1913	1914	1915	1916	TOTAL
Adams	......	......	......	5,505	......	......	5,505
Algoma (Iron Mountain; Hoch)*	......	......	1,000	......	8,600	23,000	32,600
Armour No. 1	......	66,526	93,333	......	79,773	76,799	316,431
Armour No. 2	......	73,089	213,309	238,427	333,856	327,023	1,185,704
Barrows	......	......	18,216	33,540	......	......	51,756
Brainerd-Cuyuna	......	......	......	......	3,000	......	3,000
Croft	......	......	......	......	......	85,033	85,033
Cuyuna-Mille Lacs*	......	......	27,200	55,000	45,000	90,000	217,200
Ferro*	......	......	......	......	......	17,210	17,210
Hillcrest*	......	......	......	......	......	22,143	22,143
Ironton	......	......	5,150	44,000	316	35,000	84,466
Kennedy	181,224	205,363	251,984	196,225	202,082	209,777	1,246,655
Mahnomen*	......	......	......	......	......	148,000	148,000
Mangan, Nos. 1* & 2*	......	......	......	......	......	39,572	39,572
Meacham	......	......	......	......	......	56,427	56,427
Pennington	......	......	101,136	......	117,068	206,085	424,289
Rowe	......	......	......	80,000	143,163	174,002	397,165
Sultana*	......	......	......	......	13,152	31,844	44,996
Thompson	......	24,761	32,679	178,354	202,640	197,157	635,591
Wilcox	......	......	......	......	38,708	63,907	102,615
Totals	181,224	369,739	744,007	831,051	1,187,358	1,802,979	5,116,358

* Manganiferous iron ore mines.
† Statistics compiled by United States Geological Survey, published by permission of mining companies.

known in the principal part of the iron-ore district is 15 feet. Because of this drift mantle the study of the occurrence, structure, and distribution of the various rocks in the Cuyuna district is of necessity based on information gained by drilling and mining operations.

The rocks in the Cuyuna district which have been found up to the present time can all be grouped under three classes, (1) metamorphosed sedimentary and igneous rocks interlayered with each other in beds and lenses, usually with steep dip due to extensive folding, (2) igneous rocks intruded into the metamorphosed rocks subsequent to their metamorphism and deformation, and (3) younger rocks which lie horizontally on the eroded surfaces of the older rocks.

The age of the various rocks is not definitely known. Because of their metamorphosed and folded state, the first group mentioned above has usually been classed as Huronian, and on account of their general relation to the rocks of the Mesabi district and the occurrence of iron-bearing formation in them, it has generally been supposed that they are of the same age as the iron-bearing rocks of the Mesabi district, i.e., upper Huronian.[106]

In accordance with this view all the slates, schists, and other metamorphosed rocks in east central Minnesota have been grouped under the name of Virginia slate, which term was originally applied to the slate overlying the iron-bearing Biwabik formation in the Mesabi district. In view of the facts that no rock outcrops exist in the region between the southwestern end of the Mesabi district and the northeastern end of the Cuyuna district, a distance of nearly 40 miles, and that only scattered drilling has been done in this region, it seems premature to correlate definitely the rocks of the two districts. It is possible that the metamorphosed rocks of the Cuyuna district may belong to either a higher or a lower horizon than the upper Huronian rocks of the Mesabi district, or possibly rocks of several different geologic ages are present. It is undoubtedly true that in most areas of pre-Cambrian rocks in northern United States and Canada, where detailed work has been possible, the occurrence and distribution of the rocks has been shown to be much more complex than is at present supposed to be the case in east central Minnesota. Our present knowledge of the details of the structure and stratigraphy of the rocks of the region is still too meager to allow the substitution of a definite classification for the one now in use. In fact there is no evidence to show that this classification may not be correct. However, it would doubtless have been better had a local term been used for

[106] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: *U. S. Geol. Survey Mon.* 52, pp. 212 et seq., 1911.

the metamorphosed rocks of the Cuyuna district pending the accumulation of more evidence. In the text of this report general terms preferably are used.

The old metamorphosed rocks are principally slates and schists of various kinds associated with beds and lenses of iron-bearing formation. Locally quartzite also has been found, and at one or two places limestone is reported to occur. The slates include gray argillaceous slate, finely micaceous gray phyllite, black carbonaceous slate and dark green amphibolitic slate. The schists are principally quartzose and argillaceous sericitic schists, which are probably of sedimentary origin. With these is associated green chloritic schist, much of which appears to be of igneous origin, although the original texture has almost entirely disappeared. Metamorphosed chloritic igneous rocks, in which the schistosity is but slightly developed, however, and in which igneous textures are still clearly visible, have also been found in drilling operations in different parts of the district.

The rocks of second class, viz., igneous rocks which are intrusive into the metamorphosed rocks and have not themselves been metamorphosed, are generally supposed to be of Keweenawan age. If the metamorphosed rocks are of upper Huronian age this is a reasonable assumption. These rocks occur as dikes or irregular intrusive masses of different sizes, cutting the older rocks, and in many instances causing further metamorphism along the contacts. All rocks of this class found in the district up to the present are subsilicic, and are usually medium fine-grained or porphyritic.

The rocks of the third class occur only locally and in minor quantity. They are of two types, (1) horizontal flows of igneous rocks, probably of Keweenawan age, which have been found at one or two places underlying the glacial drift and overlying the metamorphic complex, and (2) isolated patches of ferruginous conglomerate and other sediments supposed to be of Cretaceous age, and probably to be correlated with similar patches of sediments occurring in the western portion of the Mesabi district.[106] The rocks of the first type may perhaps be correlated with the Keweenawan trap rocks found in the region of St. Croix River in eastern Minnesota. No outcrops of them have, however, been found in the central part of the state. The second type of rocks is probably a phase of the clayey and calcareous rocks of Cretaceous age, beds of which occur outcropping along Mississippi River south of Little Falls and elsewhere in central Minnesota.

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[106] Zapffe, Carl, The Cuyuna iron ore district of Minnesota: *Amer. Ass'n. Adv. Sci.*, Dec. meeting, 1910. See also *Supplement to the Brainerd Tribune,* July 1, 1910.

STRUCTURE OF THE ROCKS

The rocks of the Lake Superior region suffered folding at several periods in their history. As far as is known, however, the forces causing the deformation at the different periods have been applied in approximately the same directions, i.e., northwest-southeast, so that the results, as apparent in the rock structure, are superimposed upon each other. The final outcome of these various deformational activities has been that all the pre-Cambrian rocks of the Lake Superior region have been folded into a great complex synclinorium trending approximately northeast-southwest. The Keweenawan rocks have suffered the least folding of all, and form a broad trough with a gently dipping northwest limb and a more steeply dipping southeast limb. The older rocks have suffered successively greater deformation, the upper Huronian having many minor folds within the main synclinorium, while the lower Huronian and Archean are in places so intensely deformed that it is almost impossible to decipher their relation to the general structure of the region.

Because of the dominance of the northwest-southeast deformation, the general strike of the rock structures, such as bedding, cleavage or schistosity, and folds, throughout the Lake Superior region, varies between east-west and northeast-southwest. It is this general similarity of secondary structures in all the rocks which most strongly points to the conclusion that the deformational movements at different periods have varied but little in direction.

Conforming with the general structure of the Lake Superior region, the rocks of the Cuyuna district are folded into a complex series of anticlines and synclines trending northeast-southwest.[107] In the Cuyuna district the dip of the limbs of the folds is usually vertical or very steep, and may be either to the southeast or northwest, the former dip predominating. Very often close folding has resulted in producing an approximate parallelism of both limbs of a fold. This is probably the explanation for the great predominance of southeast dips in the district, which are characteristic both in the north and south ranges. The pitch of the folds is usually very low and may be either to the northeast or to the southwest. Pitches in one or the other direction usually predominate in different parts of the district. Thus at the southwestern end of the north range the pitch of the folds is in general to the northeast, while along the central part of the north range it is to the southwest. Frequently the pitch is so low that the crests of anticlines are practically horizontal for miles. Because of this low pitch of the folds, the various rock layers appear on

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[107] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: *U. S. Geol. Survey Mon.* 52, pp. 620 et seq., 1911.

Zapffe, Carl, The Cuyuna iron ore district of Minnesota: *Amer. Ass'n. Adv. Sci.*, Dec. meeting, 1910. See also *Supplement to the Brainerd Tribune*, July 1, 1910.

the erosion surface as approximately parallel northeast-southwest trending bands. Locally, where the pitch brings rock layers below the erosion surface, sharp turns occur and the bands double back on themselves. Elsewhere minor drag folds cause local irregularities in their trend.

On account of the lack of exposures and as yet insufficient drilling and underground development, it has not been possible to work out the details of the structure. Drag folds and other secondary structures point to the existence of several major and many minor folds in both the north range and the south range. Ultimately, by means of these structures, it may be possible to determine the relationship between the rocks in different parts of the district. The apparent absence of any definite stratigraphic succession, however, is a serious drawback in working out the geologic relations.

The general distribution and structure of rocks in east central Minnesota indicates that the Cuyuna district is situated near the axis of the southwestern extension of the Lake Superior synclinorium. The close folding, such as exists in this district, would thus be naturally accounted for as well as the very gentle folding along the Mesabi range which is supposed to be on the north limb of the synclinorium. The south limb, represented by the Penokee-Gogebic district in northern Michigan and northern Wisconsin, is as yet unknown in Minnesota. The extensive areas of granitic rock in the Saint Cloud and Mille Lacs Lake regions may be south of the south limb of the synclinorium, or, as believed by Zapffe,[108] they may represent intrusions within the synclinorium. It is known that some of these granites do intrude metamorphosed sediments, but the age of the latter is not definitely established. If the granite is lower-middle Huronian or Laurentian in age and represents the basement upon which the metamorphosed sediments of the Cuyuna district rest, then the south limb of the synclinorium may be expected to run northeastward from Little Falls through the northern part of Mille Lacs Lake toward Kettle River. On the other hand, if the granite is of later age than the metamorphosed sediments and represents intrusions within it, the south limb of the synclinorium may be far to the southeast.

LITHOLOGY OF THE ROCKS

OLDER METAMORPHOSED ROCKS (VIRGINIA SLATE)

Geologic relations.—The principal constituents of the metamorphosed rocks of the Cuyuna district are chloritic, micaceous, and quartzose schists. Associated with these are extensive layers of iron-bearing rock and locally lenses of quartzite and masses of metamorphosed igneous rock. Black, carbonaceous slate and dark green amphibolitic slate also

[108] Zapffe, Carl, *op. cit.*

occur in many places, and limestone has been encountered locally. These rocks are irregularly interlayered with each other. They all have a general northeast-southwest strike, and usually a steep dip to the southeast or northwest, the former dip being by far the more common. On the horizontal surface the different rock layers appear as discontinuous bands of varying width all approximately parallel.

Up to the present time it has been impossible to work out any definite stratigraphic succession for the metamorphosed rocks of the district. The only horizontal markers of any considerable extent are the layers of iron-bearing rock. These, however, are unsatisfactory since several distinct bands of iron-bearing rock run through different parts of the district, and it is not known as yet whether they are the surface expressions of a single layer which has been complexly folded, or whether several different layers and lenses of iron-bearing rock exist at different stratigraphic horizons. The different bands of iron-bearing rock differ in the character of materials which they contain and in the nature of the wall rock which bounds them. This would indicate that they are not portions of the same layer. On the other hand, the same band of iron-bearing rock may show distinct and even abrupt changes in the nature of the materials composing it, both along the strike and across it. Thus certain bands of iron-bearing rock show highly manganiferous ore along one side and ferruginous chert or hematite with only a trace of manganese along the other side. Other bands of iron-bearing rock consist almost entirely of red or brown hematite and hematitic or limonitic chert in one locality, while at another locality the same band may consist largely of black magnetic ore and magnetitic slate. It is thus difficult to correlate the different bands on the basis of lithology.

Some geologists believe that probably the different bands of iron-bearing rock of the north range may be referred to a single layer, but that the bands in the south range represent a different and probably higher stratigraphic horizon. This assumption is based on the fact that the ore and iron-bearing rock in the two ranges present rather distinct lithologic differences. The south range ore is usually black or yellow and is associated largely with slaty, argillaceous rocks, many of which are magnetitic. Ferruginous chert does not occur as abundantly as on the north range and manganese oxide is present only in small amounts in a few places. The north range ores on the other hand are usually brown, red, or blue, and are abundantly associated with ferruginous chert and only locally with amphibole-magnetite rock or magnetitic slate. They also contain much manganese oxide in places which may be present in distinct bodies or may be disseminated through the iron ore. In view of the facts, however, that much of the north range iron-bearing rock has associated with it slaty, magnetitic rocks, and that the manganese oxide is only local in its occurrence and apparently increases in amount toward the north, it does not seem that the lithologic differences noted between the north range and south range iron-bearing rocks are sufficient to justify their assignment to separate horizons. On account of the unique character of the iron-bearing beds, it is believed that somewhat peculiar conditions attended their deposition. That such conditions were frequently repeated in the course of sedimentation does not seem probable in the absence of definite data to the contrary. It is, therefore, more reasonable for the present to assume that only one main iron-bearing horizon exists in the Cuyuna district. Cheney[109] has recently made an interpretation of the rock structure of the district on this supposition.

What is true of the layers of iron-bearing rock as horizon markers is also true of the associated rocks, and as these in general are much less continuous and less uniform, they are of but little value in this respect. The chloritic schist, which is perhaps the most nearly uniform of these associated rocks, occurs in lenses, which, although of considerable width, are rarely of great longitudinal extent. Such lenses are found at various horizons, frequently being interlayered within the iron-bearing rock itself.

Carbonaceous slate is frequently used as a local horizon marker as it has often been found to occur along the boundary of iron-bearing beds. However, single layers are rarely continuous for long distances along the strike. On the south range, black carbonaceous slate is much more characteristic than on the north range, being so commonly associated with the ore bodies that its presence is considered a good indication for ore.

It might be supposed that quartzite would form a definite stratigraphic unit in this district as it does in most of the other Lake Superior iron-ore districts. However, in the Cuyuna district, quartzite lenses and layers have been encountered in only a few places, and it has not yet been possible to determine any relationship between the scattered occurrences.

It is possible that, as exploration work progresses, and individual beds of different rocks are traced along the strike, some orderly arrangement of layers may be found to exist. For the present, however, any attempted correlation is largely speculative.

Deerwood iron-bearing member.—The iron-bearing rocks of the Cuyuna district present a variety of lithologic types. Among the more common types are hematitic and limonitic chert, hematitic and limonitic slate, cherty and argillaceous ferrous carbonate, siliceous magnetitic slate, amphibole-magnetite rock, green amphibolitic slate, jaspilite, dark blue,

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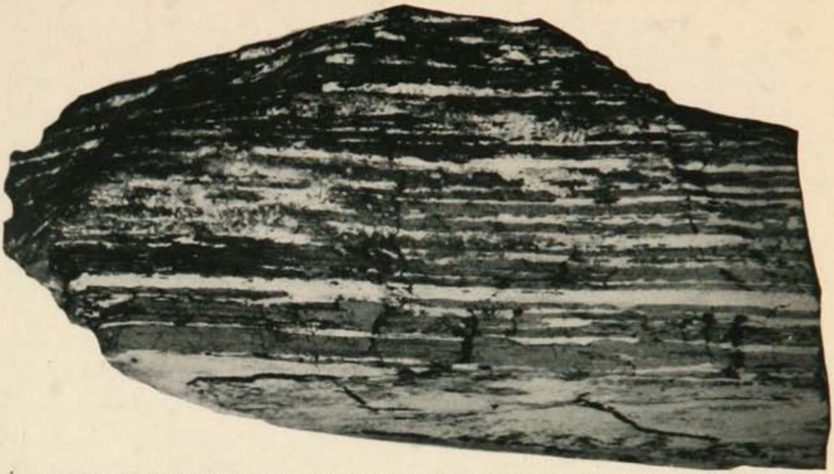
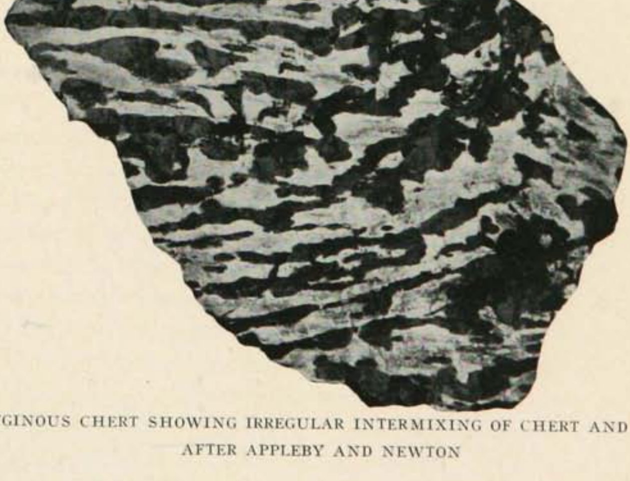
[109] Cheney, C. A., Jr., Structure of the Cuyuna iron-ore district of Minnesota: *Eng. and Min. Jour.*, vol. 99, pp. 1113-1115, June 26, 1915.



A. FERRUGINOUS CHERT SHOWING REGULAR INTERBANDING OF CHERT AND IRON OXIDE
AFTER APPLEBY AND NEWTON



B. FERRUGINOUS CHERT SHOWING IRREGULAR INTERMIXING OF CHERT AND IRON OXIDE
AFTER APPLEBY AND NEWTON

red, brown, black, and yellow iron ore, black, red, and brown manganiferous iron ore, green chloritic schist, and dark red hematitic schist.

Limonitic and hematitic chert are the most characteristic iron-bearing rocks in the Lake Superior region. In the Cuyuna district they are most abundant in the north range where they compose the principal part of the iron-bearing layers. However, they are common on the south range as well. They usually consist of interlaminated white, pink, or gray chert and hematite or limonite, the chert and iron oxide occurring in alternate layers. (Plates XVII and XVIII.) In some parts of the rock the hematite or limonite laminae are fairly pure, and elsewhere they are very siliceous. In many places the iron oxide present is merely a stain or an impregnation. Thus there are all gradations of ferruginous chert from siliceous iron ore to chert containing only a small percentage of iron oxide. Much of the ferruginous chert, instead of being banded, presents a blotchy appearance due to the irregular distribution of chert and iron oxide or to the irregular staining of the chert by the iron oxide. The more siliceous iron-stained chert usually shows a more irregular distribution of chert and iron oxide. In many places, however, very siliceous ferruginous chert shows an even brown or red color throughout, the entire mass of chert being impregnated with iron oxide.

The chert laminae in ferruginous chert are typically fine-grained, dense, and flinty, but locally they have suffered partial disintegration and present a fine sugary appearance. When completely disintegrated they break up into fine sand, giving rise to what is known as wash ore. Wash ore is soft ferruginous chert from which the disintegrated chert can be removed by washing while the iron oxide remains behind and becomes concentrated.

A microscopic examination of ferruginous chert shows it to consist of little else than silica and iron oxide. A large proportion of the silica present is in the form of slightly recrystallized chert, while the rest is sufficiently coarsely crystalline to be called quartz. Very little chert is amorphous as are cherts of recent geologic age. Most of it has a microcrystalline texture, the coarseness of which varies so that all gradations occur between chert and quartz. The iron oxide is usually amorphous, generally occurring thickly bunched along layers, but at many places also being disseminated through the chert as tiny specks. Locally phases of the ferruginous chert contain iron oxide in the crystalline form.

Hematitic and limonitic slates are not as abundant in the district as ferruginous chert, but occur locally as beds and lenses interlayered with ferruginous chert or iron ore. They are usually dark red or light to dark brown and present a thinly laminated appearance. Red hematitic slate is by far the most abundant. It is dark red, soft, and in general is finely and regularly laminated. The brown limonitic slate is usually more hydrated than the red slate and in places has a soft, clayey consistency. Siliceous phases of the slates which show gradation into ferruginous chert occur also. These are thinly laminated, but are hard and in places contain thin chert layers. The ferruginous slates represent stages in the deposition of the iron-bearing rocks when fine, argillaceous sediment rather than silica was being deposited with the iron. They are generally not slates in the proper sense of the word, as they rarely show slaty cleavage but are rather indurated, ferruginous shales or ferruginous argillites. They are not as abundant in the Cuyuna district as in some of the other Lake Superior iron-ore districts, especially in the Mesabi.

The ferruginous slates differ from the hematitic schist, described on page 119, in that they are sedimentary, having been deposited at the same time as the ferruginous cherts, and having suffered the same alterations. The hematitic schist on the other hand results from the alteration and impregnation with iron oxide of the green chloritic schist, a rock of probable igneous origin, which is commonly associated with the iron-bearing rock. Most of the ferruginous slates cleave parallel to the original bedding laminations; hematitic schist cleaves parallel to the schistosity. Certain ferruginous slates, however, which are derived from the oxidation of green amphibolitic slates also have well-developed secondary cleavage.

Cherty and argillaceous ferrous carbonates are believed to be the original rocks from which the iron-bearing beds of the Cuyuna range in their various phases are largely derived. Such rocks have been reported from many parts of the district, having been found in the deep drilling, and also in the deeper workings of some of the mines. Several different types occur with gradational phases between them. They vary in composition and texture. Some have a banded, laminated appearance while others are massive. Nearly all of them are dense and fine grained. They range from light gray to dark green or black according to the associated minerals present. Usually they consist of interlayered chert or argillaceous material with amphibole and iron carbonate. Magnetite is a common constituent, and with increasing magnetite and recrystallization of the other constituents these rocks grade into amphibole-magnetite rock and magnetitic slate.

The banding of the cherty and argillaceous ferrous carbonate is largely due to interlayering of different constituents. The laminae of chert and siderite are usually light gray or greenish, while those containing argillaceous material or amphibole are darker and with increasing magnetite become almost black. Some phases of iron carbonate rock are light gray and consist almost entirely of chert and siderite which may be interlayered or may be irregularly intermixed. Grains of magnetite often occur along lamination planes, making the banding more marked. Other phases of iron carbonate rock contain considerable amphibole, and these show interbanding of light gray and somewhat darker green layers. Still other phases are very dark gray or green and consist mainly of amphibole and argillaceous material, mixed with more or less siderite but containing little or no chert. Such phases are usually very fine-grained and show no marked lamination. All these varieties of iron carbonate rock are interbedded with each other and grade into each other.

The siliceous magnetitic slate and amphibole-magnetite rock are phases of the original iron-bearing formation which have suffered metamorphic alteration and recrystallization. They are banded or laminated rocks usually very dark colored with a tinge of green. They consist mainly of amphibole and magnetite associated with chert or quartz. The fine-grained, finely laminated types with slaty structures are known as magnetitic slates, while the more coarse-grained and coarsely-layered types are known as amphibole-magnetite rock. As is the case with ferruginous slate, magnetitic slate rarely, if ever, shows slaty cleavage and might perhaps be more properly designated magnetitic argillite. The banding in these rocks is due to the segregation of the different minerals into layers and also to a difference in the coarseness of crystallization. Thus layers of fairly pure magnetite alternate with layers of amphibole or of quartz and amphibole. Some bands are very fine-grained, especially those consisting mainly of magnetite, while other bands as those of amphibole are often medium coarse-grained. The segregation of minerals in the amphibole-magnetite rocks and magnetitic slates is never perfect. Small amounts of magnetite are usually disseminated through quartz and amphibole layers, while quartz, and amphibole occur intermixed with magnetite along the borders of magnetite bands.

There is considerable variation in the composition of these rocks. Some consist largely of magnetite and amphibole and others contain a considerable amount of silica, either as chert or quartz, with amphibole, but with little magnetite. There is also some irregularity in the texture, such as the thickening or pinching out of laminae. These irregularities, however, are much less marked than they are in the ferruginous cherts.

The amphibole-magnetite rock and magnetitic slate of the Cuyuna district differ from the typical amphibole-magnetite rock of some of the other Lake Superior iron-ore districts, such as the Mesabi, Gogebic, and Marquette districts. These rocks in the Cuyuna range are fine-grained, more perfectly laminated, and in general they contain less quartz and more ferromagnesian minerals. The typical amphibole-magnetite rock of the Cuyuna district is a finely banded rock consisting of alternating bands of magnetite and amphibole with a minor amount of quartz. That of the eastern part of the Mesabi district, on the other hand, is an irregularly banded rock consisting of alternating layers of fine-grained magnetite and coarse-grained quartz and amphibole. In the Cuyuna district, quartzose and cherty phases of the amphibole-magnetite rock and magnetitic slate are also common, however, and are characteristic, more especially, of less highly magnetitic phases of these rocks.

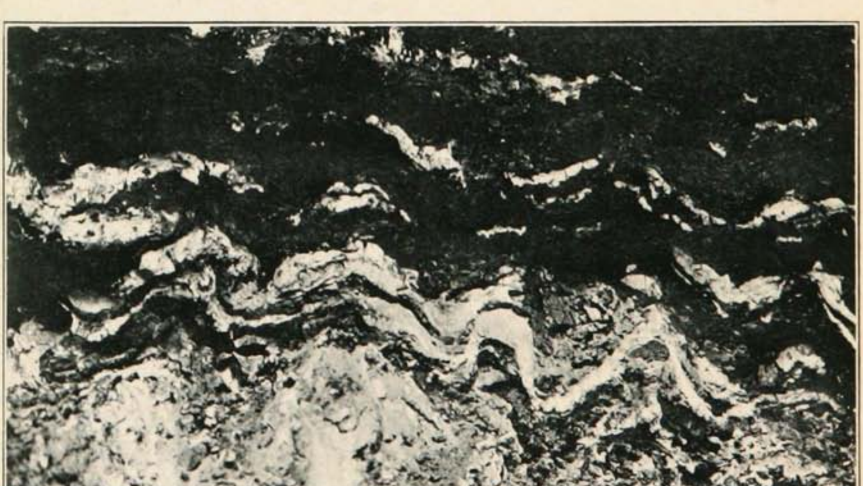
With decrease of magnetite and iron carbonate, the slaty iron carbonate rocks and magnetitic slates grade into green amphibolitic slates. These are dark green rocks, nearly always finely and regularly laminated and with well-developed slaty cleavage at varying angles to the lamination. They consist mainly of a network of finely crystalline amphibole, but usually considerable iron carbonate is present and locally magnetite as well. Green amphibolitic slate occurs interbedded with other iron-bearing formation rocks or in areas adjacent to them.

Jaspilite is of rather rare occurrence in the Cuyuna district, but well defined beds of it are found in several of the mines. Thus at the Cuyuna-Mille Lacs mine both the hard red-banded jasper and the specular, schistose jasper occur along the south wall of the north ore body, where they are interlayered between typical banded hematitic chert on one side and lean manganiferous iron ore on the other side.

Jaspilite is metamorphosed and recrystallized ferruginous chert. Where the metamorphism has not been very intense a hard, dense rock, bright red to reddish black, is formed. This is the more common phase, while the crystalline, specular form which results from pronounced recrystallization is more local in its occurrence. Some of the hard, red jaspilite shows oolitic texture. In places in the Cuyuna district there is a very hard, dense, siliceous, ferruginous chert to which the term jasper is sometimes applied. This rock, however, varies in color from brown or reddish brown to black, and is simply a very siliceous ferruginous chert.

The iron ore of the Cuyuna district is associated with different phases of the iron-bearing rock, varying in color, texture, and composition according to the type of iron-bearing rock with which it is associated. Seven or eight main belts of the iron-bearing rocks run in a northeast-southwest direction through the district, and bodies of iron ore or manganiferous iron ore occur at intervals along nearly all of these belts. Both hard and soft ores are found, locally one being more abundant and elsewhere the other. They have suffered varying degrees of hydration. Some consist of typical blue or reddish blue hematite, while others consist of yellow, ocherous limonite. All gradations between these two extremes are found. Some of the rich hematite ore like that at the Armour No. 2 mine is finely crystalline, but most of the ores and especially the more hydrated forms are amorphous. Locally fibrous, botryoidal limonite or goethite occurs in veins and geodes, but does not constitute an important ore.

A. WASH ORE SHOWING POROSITY DUE TO DISINTEGRATION AND REMOVAL OF CHERT
AFTER APPLEBY AND NEWTON



B. MINOR PLICATIONS IN THE IRON-BEARING ROCKS AT THE WEST END OF THE
ROWE OPEN PIT

The manganiferous iron ore consists mainly of some form of iron oxide mixed with manganite, pyrolusite, or wad. In most of the manganiferous iron ore bodies, local masses of pure black manganese ore occur but are usually present in minor quantity and are irregularly intermixed with manganiferous iron ore or manganiferous iron-bearing rock. The manganiferous iron ores vary in color from dark red or brown to black, and are usually fine-grained to finely crystalline in texture. In a few places vugs of needle ore consisting either of pyrolusite or manganite have been encountered.

The green and gray chloritic schist, commonly known as green schist, and the dark red hematitic schist do not belong to the iron-bearing rocks proper, but are closely associated with them. They generally occur as small lenses within the iron-bearing layers, or they may bound such layers on either side. The dark red hematitic schist usually occurs along the borders of the lenses where the schist is in contact with the iron-bearing rock or iron ore and has become impregnated with iron oxide for varying distances from the contact, while the green or gray chloritic schist occurs in the center of such lenses, or forms entire layers where they are not in contact with iron-bearing rock.

As will be mentioned later, it is believed that the chloritic schists represent original masses of subsilicic igneous rock which were intruded as sills into the iron-bearing rock and associated sedimentary rocks, while these were still largely in an unmetamorphosed condition. Some of it may be of volcanic origin, having been formed as local irregular flows, or as beds of ash or agglomerate. Subsequent metamorphism and deformation were suffered alike by igneous rocks and sediments.

Analyses have been made for the writers by the School of Mines Experiment Station, University of Minnesota, of type specimens of different phases of the iron-bearing and associated rocks with the view of comparing the composition of the different varieties of rock, as well as of determining approximately the range in composition of some varieties. These are given in the accompanying table.

Schist, slate, quartzite, and associated igneous rocks.—The beds of iron-bearing rock practically throughout the Cuyuna district, are inclosed between layers of schist or slate. Generally the schist or slate on one side of the iron-bearing layer is identical with that on the other side. Locally, however, the rocks forming the two walls present marked differences, but such differences are rarely constant over large areas.

A number of distinct types of schist and slate are found in the Cuyuna district, among which are (1) white, greenish or brownish, light-colored, quartzose, sericitic schist or slate, (2) gray, finely micaceous schist, phyllite, or slate, (3) dark green, laminated, amphibolitic slate, (4) dark green or gray chloritic schist, commonly micaceous and locally quartzose, *Analyses of Type Specimens of Iron-Bearing and Associated Rocks of the Cuyuna District Dried at 212° F.**

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Fe_2O_3	50.90†	36.38†	55.50†	32.23†	23.93†	5.27	16.00	1.51	29.57	28.97†	3.70	43.31	12.15	12.24
FeO	.....	.....	.....	.....	.....	31.34	17.33	16.42	17.09	.....	23.70	0.43	24.54	2.41
Mn_2O_3‡	0.27	0.33	.....	1.49	0.36	2.53	1.28	2.27	0.95	0.43	0.50	0.77	6.44	0.23
SiO_2	43.22	59.20	37.68	51.70	47.83	30.15	32.10	59.32	43.24	42.85	28.52	42.70	40.70	37.20
Al_2O_3	0.48	0.27	1.53	8.92	16.62	0.40	4.85	0.79	1.12	18.94	16.78	8.96	2.24	27.39
CaO	0.02	0.02	.....	0.20	0.23	1.25	5.73	0.41	1.56	0.20	1.59	0.28	1.28	0.45
MgO	0.08	0.11	.....	0.03	0.73	4.77	5.74	4.38	2.23	0.03	11.22	0.10	2.77	1.00
K_2O	.....	.....	.....	.....	3.24	.....	.....	.....	.....	.....	.....	.....	.....	.....
P_2O_5	0.073	0.169	0.267	.....	0.176	0.665	4.019	0.057	1.090	0.224	0.987	0.077	0.572	0.316
TiO_2	.....	.....	.....	.....	2.62	0.02	0.13	Trace	0.04	2.06	3.18	0.48	Trace	3.68
CO_2	.....	.....	.....	.....	.....	24.65	8.68	14.06	0.40	.....	.....	0.10	10.21	0.51
Graphite	.....	.....	.....	.....	.....	.....	.....	.....	0.45	.....	.....	.....	0.40	3.75
H_2O (combined)	4.68§	3.92§	5.56§	5.33§	2.74	0.36	3.14	0.25	3.88	6.42	8.48	3.64§	.....	9.14§
Total....	99.72	100.40	100.54	99.90	98.84	101.40	99.00	99.47	101.62	100.12	98.66	100.85	101.30	98.32
Fe { solub. in HCl	35.63	25.15 }	38.85	22.56	{ 16.04	28.06	24.68	13.83	33.91	20.04	21.02	30.50	26.80	8.80
Fe { insol. in HCl	none	0.32 }			{ 0.71	none	none	none	0.08	0.24	none	0.08	0.79	1.65
Mn	0.19	0.23	.....	1.05	0.25	1.76	0.89	1.58	0.66	0.30	0.35	0.27	2.24	0.08
P	0.032	0.074	0.117	.....	0.077	0.290	1.755	0.025	0.476	0.098	0.431	0.034	0.250	0.138
Loss on ignition	4.68	3.92	5.56	5.33	3.66	20.65	8.60	12.06	1.05	7.05	7.15	3.64	9.00	9.14

* Analyses by J. H. McCarthy, School of Mines Experiment Station, University of Minnesota.

† Total iron calculated as Fe_2O_3.

‡ Total manganese calculated as Mn_2O_3.

§ Loss on ignition, essentially molecular H_2O.

1. Banded ferruginous chert from Kennedy mine, near Cuyuna, Minnesota (Plate XVII A).
2. Ferruginous chert consisting of irregularly intermixed chert and iron oxide from Thompson mine, near Crosby, Minnesota (Plate XVII B).
3. Hard, dense, ferruginous chert from Rowe mine, near Riverton, Minnesota.
4. Dark red, laminated ferruginous slate from Sultana mine, near Ironton, Minnesota.
5. Soft, red, laminated ferruginous slate from Rowe mine, near Riverton, Minnesota.
6. Fine-grained, light gray, siliceous iron carbonate rock from Kennedy mine, near Cuyuna, Minnesota.
7. Dense, dark gray, argillaceous iron carbonate rock from Kennedy mine, near Cuyuna, Minnesota.
8. Greenish gray, banded, cherty iron carbonate rock from Kennedy mine, near Cuyuna, Minnesota.
9. Greenish black, laminated amphibole-magnetite rock from Adams mine, near Deerwood, Minnesota.
10. Dark red, hematitic schist from Kennedy mine, near Cuyuna, Minnesota.
11. Grayish green, chloritic schist from Kennedy mine, near Cuyuna, Minnesota.
12. Dark red, hematitic slate from Mangan No. 2 mine, near Ironton, Minnesota.
13. Green amphibolitic slate from Mangan No. 2 mine, near Ironton, Minnesota.
14. Black graphitic slate from drill hole north of Blackhoof Lake, near Ironton, Minnesota.

as already described in connection with the iron-bearing rocks, (5) dark red hematitic schist derived from green chloritic schist by impregnation with hematite, (6) dark red hematitic slate derived by oxidation or impregnation with hematite from amphibolitic slate, and (7) black carbonaceous slate, generally containing more or less pyrite. The distribution of these various schists and slates is irregular, but some are more abundant in one locality and others elsewhere. Thus quartzose sericitic schist is especially abundant in the region lying south of the north range, chloritic schist is very common in association with the iron-bearing belts running from Riverton northeastward to Crosby and Cuyuna, while black carbonaceous slate is conspicuous locally in the northeastern portion of the south range and in the northern part of the north range.

Although most of the slate and schist of the Cuyuna district is undoubtedly of sedimentary origin, there are certain types, as the green chloritic schist, which in their occurrence and relation to the associated rocks strongly suggest an igneous origin. The chloritic schist generally occurs in comparatively short thick lenses, which are interlayered with other rocks without any apparent order or regularity, although they generally lie parallel to the bedding of the enclosing rocks. The chloritic schist rarely shows lamination or other sedimentary characteristics, and its contact with the associated rocks is sharp and without gradational phases. Its chemical and mineral composition has not yet been studied in sufficient detail to allow its definite classification, but indications point toward an igneous origin. Much of the light-colored, quartzose, sericitic schist or slate is siliceous, and local phases of it might be termed schistose, sericitic quartzite. The gray phyllite on the other hand is usually very fine-grained and silky in texture and rarely contains much quartz. The green amphibolitic slate consists mainly of a network of finely fibrous amphibole, but contains a considerable percentage of carbonate minerals. This rock is closely associated with the manganiferous iron-bearing rocks north and south of Menomin Lake.

Quartzite has been reported as occurring in several parts of the district, notably in the northeastern portion of the south range and near the southwest end of the north range. In the latter locality, beds of typically fine-grained, vitreous quartzite have been encountered in drilling operations along a belt more than a mile long, beyond which it seems to disappear in the schist areas. Locally iron-bearing rock and black slate are associated with it, but in general chloritic and micaceous schists occur on both sides of the quartzite belt. In the northeastern part of the south range also quartzite has been found by drilling in a number of localities, especially in the neighborhood of Cedar Lake. About 10 or 12 miles east of this region are the quartzite outcrops at Dam Lake. Some connection may exist between the rocks of the two regions.

Igneous rocks, in which the original constituents have been largely altered and which have suffered considerable deformation locally, have been encountered in drilling operations in different parts of the district. Most of them seem to have been originally of a subsilicic character and now consist mainly of chlorite. Some still show the original igneous textures, while others have been rendered schistose and grade into chloritic schist. Gradations between the schistose and non-schistose phases have been found locally.

These rocks are believed to be of approximately the same age as the associated metamorphosed sediments, namely upper Huronian. The less schistose phases are usually medium to fine-grained. When comparatively fresh they are difficult to distinguish from the later igneous intrusives which are believed to be of Keweenawan age. Of the many bodies of igneous rock found in the district, very few except the schistose types can be definitely classified with the earlier or the later group. The relations can be determined only by a careful study of the shape of the igneous rock masses, of the degree of metamorphism which they have suffered, and of their relation to the enclosing rocks.

The form of the masses of igneous rock associated with the metamorphosed sediments has rarely been determined by the drilling, although a few of the masses have been found to be irregularly interlayered with rocks of sedimentary origin. Probably many of them represent intrusions, but some have textures that resemble those of extrusive igneous rocks. In general, however, the alteration has progressed to such an extent that the original character is not determinable from the texture.

LATER INTRUSIVE ROCKS

Later intrusive rocks which are believed to be of Keweenawan age and which have themselves suffered little or no deformation or dynamic metamorphism, are known to occur in many parts of the district. They are practically all of the type usually classed as greenstones, including diorite, diabase, gabbro, and perhaps even less silicic varieties. Most of them are fine-grained dark green rocks of granular or ophitic texture such as occur at the Barrows mine. At one or two localities, as at the Adams mine, a porphyritic rock has been encountered. Many of these intrusive rocks have been altered so that at present they consist mainly of chlorite and decomposed feldspar. Some, however, are still comparatively fresh, having suffered weathering only for a short distance downward from the lower surface of the glacial drift.

The shape of most of the intrusive bodies is not known, as drilling has been conducted so as to avoid them rather than to outline them.[110] Some are known to be in the form of dikes, others are irregular.

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[110] Zapffe, Carl, The Cuyuna iron-ore district of Minnesota: *Supplement to the Brainerd Tribune*, July 1, 1911.

The metamorphic effect of the intrusions along their contact with the older rock is in most places clearly noticeable. Where the igneous rocks have been intruded into the original iron-bearing rocks, they have usually caused a recrystallization. Chert is changed to quartz, and lime, magnesia, and other constituents are changed to amphibole. The iron oxide is in many places altered to magnetite. Thus typical magnetitic slate and amphibole-magnetite rock have been developed under the action of intrusions. Whether or not most of the rocks of this type in the district have been produced in this manner, or whether they were more generally formed during the deformation is not known. Doubtless the intrusions were locally effective, but from present indications they do not appear to have been sufficiently wide-spread to account for much of the metamorphism over large areas.

LATER VOLCANIC AND SEDIMENTARY ROCKS

Volcanic rocks which lie on the eroded surface of the older rocks are reported by Van Hise and Leith[111] to occur at several localities a short distance south and southwest of Brainerd and also about six miles east of Brainerd. They are said to be silicic and to have amygdaloidal texture. The beds range up to 15 or 25 feet thick and seem to occupy depressions in the underlying rock surface.[112] These volcanic rocks are believed to be of Keweenawan age.

Isolated patches of sediments lying in horizontal beds on the eroded surface of the iron-bearing rocks, schist, and associated rocks have been encountered in drilling and mining operations at a number of localities in the Cuyuna district. These rocks are believed to be of Cretaceous age because of their similarity to isolated patches of Cretaceous rocks in the Mesabi district. Cretaceous rock that bears a similar relation to the underlying metamorphosed rocks, also crops out at several points southwest of the district. In the Cuyuna district proper this rock is a ferruginous conglomerate, consisting of small pebbles of iron-bearing and other rocks in a slaty matrix.[113] Outside of the district the Cretaceous beds consist mainly of sandy and calcareous clay.

OCCURRENCE OF THE IRON-BEARING ROCKS AND IRON ORE

DISTRIBUTION OF IRON-BEARING ROCKS AND ORE

As has been stated, seven or eight main belts of iron-bearing rocks trend approximately northeast-southwest through the district. Some of these are less than a mile long, as, for example, certain belts in the north

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[111] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: *U. S. Geol. Survey Mon.* 52, p. 215, 1911.

[112] Zapffe, Carl, *op. cit.*

[113] *Ibid.*

range and in Morrison County at the southwest end of the south range, while others as the main south range belt extend almost continuously for many miles.

The most northerly known iron-bearing rocks in east central Minnesota occur in the region of Lake Emily in T. 138N., R. 26W., about 35 miles southwest of the west end of the Mesabi district. The extent of these iron-bearing rocks is as yet only imperfectly known. Farther south bands of low grade iron-bearing rocks are found in T. 136N., R. 26W., and T. 136N., R. 25W., a short distance north of Mississippi River, these being the northeasterly extensions of the northern iron-bearing belts in the north range. Besides these, a few occurrences of iron-bearing rocks are known in the region northwest of Aitkin in T. 137N., R. 25W.

The iron-bearing belts which have so far been found to contain ore bodies of commercial importance are practically confined to the area south and east of Mississippi River in Crow Wing County. However, some ore bodies have been found along the iron-bearing belts in Morrison County west of Mississippi River, although as yet no attempts have been made to develop them. The northerly iron-bearing belts south of Mississippi River are included in the north range and the southerly belts in the south range.

The most northerly north range iron-bearing belt is only indefinitely known. Traces of it occur in section 25, T. 47N., R. 30W., and thence northeastward in sections 20 and 22, T. 47N., R. 29W., beyond which it crosses Mississippi River, as has been noted. No important ore bodies have been found along it.

The next belt of iron-bearing rocks to the south is of considerable importance, containing the manganiferous iron-ore bodies of the Ferro and Algoma mines in sections 32 and 33, T. 47N., R. 29W., and other important ore bodies in sections 28, 22, 27, and 23, T. 47N., R. 29W., the latter in the vicinity of Island Lake. Certain breaks occur in the continuity of the belt, but in general it has been fairly well determined by extensive exploration. The iron-bearing rocks appear to be more or less manganiferous throughout.

South of this belt of manganiferous iron-bearing rock and ore, there are a number of scattered occurrences of iron- and manganese-bearing rocks in the region north and west of Menomin Lake and southwest of Rabbit Lake, such as those in sections 34 and 35, T. 47N., R. 29W. The relation between the separate areas is not yet known. They extend southwestward as far as section 12, T. 46N., R. 30W. To the northeast of them, south of Rabbit Lake, is the important iron-bearing belt containing the Kennedy ore bodies. The Kennedy belt is known from the southern part of section 25, T. 47N., R. 29W., as far east as the eastern part of

Rabbit Lake where it either dies out or turns to the south and doubles back on itself.

A short distance south of the eastern end of the Kennedy iron-bearing belt, is the northeastern end of another belt of iron-bearing rocks which lies to the south. It is uncertain whether these two belts are actually connected. Possibly they form the limbs of a syncline. The southern belt runs southwestward through the northwestern part of section 32 and the centers of section 31, T. 47N., R. 28W., and section 1, T. 46N., R. 29W., into the broad belt of iron- and manganese-bearing formation lying north and northwest of Ironton and Crosby in sections 2, 11, and 10, T. 46N., R. 29W., which contain the Mahnomen and Mangan No. 2 ore bodies along the northern margin and the Thompson north ore body and the Armour No. 1 and Pennington ore bodies along the southern margin. West of the Mahnomen and Pennington mines the belt divides into two parts separated by a strip of slate and schist. The northern part has been explored for only a short distance southwestward into section 9, while the southern part extends southwestward through the Feigh property in section 10, and along the north side of Blackhoof Lake in the southern part of section 9 where it contains the Hillcrest and other ore bodies. Thence it continues through the northwestern corner of section 16 and the northern part of section 17 into section 18, T. 46N., R. 29W., where the Rowe mine is located. Here it makes a synclinal turn northward and doubles back on itself for a short distance. The extent of the backward turn is not yet known.

This iron- and manganese-bearing belt is one of the most important in the district. It is known continuously over a length of more than 8 miles, and along it are some of the most important ore deposits in the district. Unlike the belts to the north, this belt contains many important iron-ore deposits, but manganiferous iron ores are found in it at various places also. On the north it is separated along the central portion, from the Cuyuna-Mille Lacs–Sultana manganiferous iron-bearing area by a thin band of slate or schist, while on the south another thin band of schist separates it from the important Croft-Armour No. 2 iron-bearing belt.

The Cuyuna–Mille Lacs–Sultana manganiferous iron-bearing area is in section 3, south and southeast of Menomin Lake. It is manganiferous throughout and contains important bodies of manganiferous iron ore. It is known to be quite wide where the Sultana and Cuyuna–Mille Lacs mines occur, but its longitudinal extent northeast and southwest is only imperfectly known. Areas of iron-bearing formation, however, occur north and south of June Lake in the northern part of section 9, and these may have some connection with the Cuyuna–Mille Lacs–Sultana area. Other ore bodies occurring in the Cuyuna–Mille Lacs–Sultana ore-bearing area are those of the Mangan No. 1 and the Hopkins mines, the latter containing both iron ore and manganiferous iron ore.

The Croft-Armour No. 2 belt has been well explored to the northeast as far as section 1, T. 46N., R. 29W., where the Croft mine occurs. From this point it runs southwestward through the Meacham, Thompson, Armour No. 2, and Ironton properties in section 11, T. 46N., R. 29W., and continues a short distance into the eastern part of section 10, where it pinches out. The belt is fairly narrow throughout its length, but contains important iron ore bodies. North of the Ironton-Armour No. 2 ore body and the Thompson south ore body which occupy its central portion in section 11, is a band of green schist which separates it from the ore body of the Pennington and Armour No. 1 mines.

The Croft-Armour No. 2 belt consists very largely of iron-bearing formation and associated iron ore, though locally, as in the eastern part of the Armour No. 2 property and the northern part of the Thompson south ore body manganiferous iron-bearing formation and ore occur in it. The proportion of ore to iron-bearing rock in the belt is high, the ore bodies consisting largely of a somewhat siliceous, hydrated, brown to red hematite, but in places containing large masses of red, medium soft, high-grade hematite, some of which is of Bessemer quality. The ore-bearing belt is bounded on the south mainly by green chloritic schist and red hematitic schist.

South of the Croft-Armour No. 2 and the Pennington-Rowe iron-bearing belts, are local occurrences of manganiferous and non-manganiferous iron-bearing formation and ore, such as those in sections 19, 17, 12, and 1, T. 46N., R. 29W. These are the southernmost areas of iron-bearing formation in the north range.

The south range belts of iron-bearing rocks, although narrow, are far more extensive longitudinally than the iron-bearing belts of the north range. The most northeasterly occurrences of south range iron-bearing rock are in the Rice River region northeast of Aitkin. From this point southwestward as far as Deerwood a number of areas of iron-bearing rock are known. They are approximately along the same strike, but there are large unexplored areas between them.

From Deerwood the south range belt of iron-bearing rocks has been traced for about 24 miles more or less continuously southwestward to a point a short distance southwest of Barrows. Mines and exploratory shafts occur along it at intervals where ore bodies have been found, the Adams mine being located in section 30, T. 46N., R. 28W., the Hobart Iron Co. (of Pickands, Mather and Company) shaft in section 8, T. 45N., R. 29W., the Wilcox mine, near Woodrow, in section 13, T. 45N., R. 30W., the Adbar Development Company shaft in section 22, T. 45N., R. 30W., the Brainerd-Cuyuna mine, near Brainerd, in section 36, T. 45N.,

R. 31W., the Barrows mine, near Barrows, in section 10, T. 44N., R. 31W., and the Rowley shaft, also near Barrows, in section 16, T. 44N., R. 31W. Besides the more or less developed ore bodies on which mines and exploratory shafts are located, there are numerous other ore bodies of importance at various points along the belt, as shown by drilling.

Throughout most of its extent, the main south range belt of iron-bearing rocks occurs as a single band. There are, however, small stretches containing two or three parallel bands. In places these are due to a break in a band where the ends are pushed past each other as in a drag fold or thrust fault; elsewhere the repetition has probably resulted from extensive folding. There are also numerous places along the belt where iron-bearing rock has not yet been found, and barren stretches occur which apparently break the continuity of the iron-bearing belt. Future exploration may result in the discovery of iron-bearing formation in such areas.

South and southeast of Brainerd and south of Barrows, a second belt of iron-bearing rock trends parallel to and lies about 1½ miles south of the main south range belt. Ore bodies have been found along it here and there, but it is not yet thoroughly explored.

The Morrison County belts of iron-bearing rock are the continuations of the south range belts west of Mississippi River. Most of them are short. They lie approximately parallel to each other and cover an extensive area in which ore bodies have been found at a number of places.

Isolated bands of iron-bearing rock have been found at several localities south of the south range in Crow Wing County. Among the most important of these is one which contains a considerable amount of iron ore mixed with ferruginous chert, in sections 8 and 9, T. 45N., R. 28W., about halfway between Clearwater Lake and Bay Lake. Another isolated band has been found near Clear Lake in the southern part of T. 46N., R. 25W., and the northern part of T. 45N., R. 25W., in Aitkin County.

The areas between the different belts of iron-bearing rock have been only very imperfectly explored. Practically wherever drilling has been done, however, some variety of schist or slate has been encountered, such as chloritic, amphibolitic, sericitic, quartzose, and graphitic or carbonaceous schist, or slate. Green and gray micaceous and chloritic schist appear to be by far the most abundant. Locally quartzite has been encountered, but usually it is in small amounts, occurring apparently in local lenses. Elsewhere considerable areas of subsilicic igneous rocks have been found.

It is not impossible that as exploration work progresses other areas of iron-bearing rock and ore may be encountered between the belts now known. Drilling has up to the present been confined largely to areas showing abnormal magnetic attraction. Nevertheless iron-bearing rock and ore have been found in several places where no marked abnormal magnetic attraction existed. It seems possible that as the drilling work is extended over larger areas, iron-bearing rock may be found where it is hitherto unsuspected.

The iron-ore bodies are found at intervals along the belts of iron-bearing rock. In some belts they are very abundant, while in other belts they are almost absent. Even along single belts of iron-bearing rock they are more or less grouped in certain parts with stretches of barren iron-bearing rock between. Thus along the Armour No. 2-Thompson belts, ore is almost continuous, while in the Armour No. 1-Pennington belt important ore bodies are grouped together in some parts, and elsewhere they are almost wanting. Other belts, as the main south range belt, have ore bodies scattered along them at irregular intervals with barren areas consisting of ferruginous chert, ferruginous slate, amphibole-magnetite rock, or magnetitic slate between.

OCCURRENCE AND CHARACTER OF ORE

As already stated, the iron-bearing beds are composed of a number of different kinds of rocks. The different varieties vary in abundance in different parts of the district, as well as in different parts of the same belt. The most abundant and most generally distributed of the iron-bearing rocks is the ferruginous chert, and it is with this rock that the iron ore is commonly associated. Ferruginous slate also is abundant, but is not as commonly associated with iron ore. Along the manganiferous iron-bearing belts, however, manganiferous iron ore bodies are frequently found in ferruginous slate as disseminated masses and irregular impregnations. The mining development in the district is not as yet sufficiently advanced to give more than a general idea of the occurrence of the other phases of the iron-bearing rock such as the cherty or argillaceous iron carbonate rock and amphibole-magnetite rock. Iron carbonate rock is usually found at a greater or less depth below other iron-bearing rocks, while amphibole-magnetite rock occurs where metamorphism of the original iron-bearing rock has taken place. Amphibole-magnetite rock is frequently associated with ore, and there is good evidence that certain types of iron ore are closely related with it in origin.

The ferruginous chert occurring in the Cuyuna district is very similar to that found in most of the other Lake Superior iron-ore districts except the Mesabi. In all the Michigan and Wisconsin districts the common rock composing the iron-bearing formation is a more or less regularly banded ferruginous chert, believed by Van Hise and Leith[114] to have been derived by alteration from an original cherty iron carbonate rock. In the Mesabi district the ferruginous chert is largely of the type

[114] Van Hise, C. R., and Leith, C. K., *op. cit.*, pp. 499-560.

known as taconite, a rather massive, bedded cherty rock irregularly speckled with iron oxide which is believed to have resulted from the oxidation of the ferrous silicate rock, greenalite rock. No taconite has been found in the Cuyuna district, nor has any greenalite been encountered. It is, therefore, believed that here as in most of the other districts, the original rock from which the present hematitic and limonitic chert and iron ore have in large part been derived is a banded cherty ferrous carbonate rock.

It is not the object in this paper to present a discussion on the origin of the iron-bearing rocks and ores. This is reserved for the final report for which more detailed information is being gathered. In view of a recent tendency, however, to question the hypothesis of geologists expressed in earlier reports that most of the iron-bearing formations of the Lake Superior region were deposited originally as ferrous carbonate or silicate, and to supplant it by the hypothesis that the iron was deposited in the ferric form originally, it may be interesting to mention some occurrences in the Cuyuna district which have a bearing on this subject.

Leaving out of consideration the source of the iron, it may be briefly stated that the older hypothesis supposes the iron to have been deposited from the original solutions largely under reducing conditions as ferrous carbonate or ferrous silicate in association with colloidal silica or with argillaceous material. Locally and at certain stages in the deposition, ferric oxide also was probably precipitated, either in a relatively pure form or along with colloidal silica or argillaceous material. However, the ferric oxide deposition is believed to be of relatively minor importance. Eventually these sediments were raised into the belt of weathering and were transformed by surface agencies into their present condition. The ferrous carbonate and ferrous silicate rocks were oxidized to ferruginous chert and ferruginous slate, and the ferruginous chert by the leaching of silica was altered to iron ore. Dynamic metamorphism previous to oxidation in some localities resulted in the alteration of the ferrous carbonate or ferrous silicate to amphibole-magnetite rock, and the latter also was locally in part altered to ore by weathering processes where the previous metamorphism was not very intense.

The other hypothesis differs from this in that the iron is supposed to have been deposited largely as ferric hydroxide, locally in a comparatively pure form, but more generally along with impurities such as colloidal silica or clay. In places the presence of carbonaceous matter or other deoxidizing agents probably resulted in a partial deoxidation of the ferric hydroxide and the formation of local masses of ferrous sediments. Upon metamorphism, these materials were consolidated and in part dehydrated, forming the present ferruginous chert and slate with local original lenses of ore and bodies of ferrous carbonate or ferrous silicate. Later weathering and erosion processes resulted in the formation of additional iron ore by the leaching of silica from the ferruginous chert, and also in the oxidation of some of the ferrous carbonate and ferrous silicate originally present.

The main difference between the two hypotheses is that according to the older one most of the iron-bearing rock was at one time largely in the ferrous state, while according to the later one small masses of ferrous sediments were only locally formed due to the presence in places of deoxidizing agents.

The evidence afforded by the Cuyuna district on this question is largely in favor of the older view. In the exploratory drill work, ferrous carbonate was encountered below a surface capping of ferruginous chert and iron ore, in many parts of the district, while more recently in some of the mining operations ferrous carbonate with associated amphibole-magnetite rock and magnetitic slate has been encountered in the lower levels directly continuous along the bedding with the ore and ferruginous chert of the upper levels. In general, the gradation from ore at the surface through lean ferruginous chert into ferrous rocks below is perhaps more typically illustrated in parts of the Cuyuna district than in any of the other Lake Superior iron-ore districts.

The ferrous carbonate rock of this district, however, differs from the typical cherty iron carbonate rock which has been described from other districts. A number of different phases occur, some cherty, some argillaceous, and others containing amphibole and magnetite. Apparently various gradations occur between ferrous carbonate rock and amphibole-magnetite rock. Their general character and lithology have already been described. Their occurrence is usually irregular. While occasionally magnetitic slate and amphibole-magnetite rock are found practically at bed rock surface, more generally they, as well as the ferrous carbonate rock, are found at some depth. In places, ferrous carbonate rock is also found as masses within the oxidized iron-bearing rocks.

The drilling has not yet been deep enough or thorough enough to give any indication of the average depth at which ferrous rocks are encountered below the oxidized iron-bearing formation phases. At the Kennedy mine, ferrous carbonate rock is abundant on the 262 foot level, while in some other parts of the district drilling has shown ferruginous chert continuing to a depth of 800 feet or more. The depth of oxidation is dependent both on the original nature of the material and on various structural conditions such as fracturing, folding, and faulting.

The average depth to which the Cuyuna ore bodies may be expected to extend is also a doubtful question. It is possible that locally beds of ferruginous chert or ore occur which were originally deposited as such, and these may extend to great depths without much change in their character. On the other hand, where the ferruginous chert was undoubtedly formed by the oxidation of original ferrous sediments and the ore has resulted from the leaching of silica from lean iron-bearing rock, the deposits do not extend to great depths, except perhaps in a few instances where exceptionally favorable structures occur for secondary concentration.

The Cuyuna iron-ore bodies are as a rule roughly tabular in shape, the longer axes being parallel to the bedding of the enclosing rocks. As the beds usually dip steeply, the ore bodies are shown at the surface as bands that extend for considerable distances along the strike of the beds. They vary in width up to several hundred feet, and some of the known ore bodies are more than a mile long. Their behavior with depth varies. Some are comparatively shallow, extending perhaps to a depth of 100 or 200 feet below bed rock surface, where they give way to ferruginous chert, amphibole-magnetite rock, or unaltered iron-bearing rock. Others extend to greater depths, either continuing directly downward along the bedding, or running diagonally downward parallel to the strike in the form of shoots. The data regarding the depths reached by the ore bodies is still very incomplete. The deepest mining operations at present extend to a depth of about 280 feet below the base of the glacial drift, and to this depth ore is known to continue uninterruptedly. The exploratory drill work in the district has for the most part been shallow, few holes occurring which reach a depth greater than 700 feet. Ore, however, has been encountered in some of the deeper holes, and it is suspected that some ore bodies may reach a considerable depth.

The ore bodies are usually enclosed between walls of ferruginous chert, ferruginous slate, or other iron-bearing rocks. Where ferruginous chert forms the wall rock, the contact is usually very irregular. Beds and irregular horses of ferruginous slate and chert are of frequent occurrence in the ore bodies. Green chloritic schist and dark red hematitic schist are also common associates of the iron ore. They may form the wall rock of the ore bodies, or they may occur interlayered with the ore, more or less parallel to the bedding. Other rocks associated with the ore bodies are amphibole-magnetite rock, magnetitic slate, ferrous carbonate rock, green and gray sericitic and siliceous slates, and black carbonaceous slate. These are especially common along the south range, where they form the wall rocks in many places. In the north range, the ferrous rocks in places occur underneath ore bodies representing the unaltered portions of the iron-bearing formation.

Most of the iron ore occurring in the ore bodies of the Cuyuna district is soft, but hard ore is also abundant both in the north and south ranges, and is more or less irregularly 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 Lake Superior iron-ore districts. It shows all stages of hydration from pure reddish blue hematite to ocherous, yellow limonite, and both argillaceous and siliceous phases are common. On the north range the ores vary from dark reddish blue, high-grade hematite, to reddish and yellowish brown siliceous or argillaceous hematite and limonite, while siliceous and argillaceous black, red, and brown manganiferous iron ore is common. Locally wash ore is associated with the other ores. In the south range, the typical ores are reddish brown hydrous hematite, dark brown to black limonite, and yellow, ocherous limonite.

The richest ore that has been found in the district is a medium soft, reddish blue hematite which occurs at the Croft mine and locally in the Armour No. 1, Armour No. 2, Ironton, and Pennington mines in the north range. Much of this ore, especially that at the Croft mine, is of Bessemer quality, samples from the latter deposit analyzing as high as 67 to 68 per cent metallic iron and as low as .01 to .03 per cent phosphorus. While ore of this grade is, of course, exceptional, a large part of the Croft ore body consists of ore of Bessemer quality and will be mined as such. In the other mines no attempt is made to mine the Bessemer ore separately. In the Armour No. 2 and Ironton mines, much of this type of ore is finely crystalline.

The most common ore in the north range is a soft to medium hard, brown to reddish or bluish brown, hydrated hematite and limonite. This ore is locally highly siliceous, and grades with increasing silica into ferruginous chert and wash ore. Much of it also is somewhat argillaceous. Ore of this type is found at the Kennedy, Thompson, Armour No. 1, Armour No. 2, Pennington, and Rowe mines. It usually occurs in somewhat irregular, lenticular bodies of different sizes which are enclosed in or associated with hematitic and limonitic chert and slate. Often ferruginous chert is interbedded with the ore, or occurs in the ore bodies as irregular masses. The character of the ore varies somewhat with the nature of the enclosing rock. Where the wall rock is mainly hematitic slate, as is the case in some of the deposits in the north range, the ore is soft, dark red or bluish red, and usually somewhat argillaceous. On the other hand, where ore is enclosed in ferruginous chert it is medium hard, somewhat siliceous, and generally much fractured, so that it breaks into small blocks. Such ore usually ranges in grade from 58 or 60 per cent metallic iron downward, depending upon the amount of silica or alumina present. The phosphorus ranges from .05 per cent up, and is frequently as high as .4 or .5 per cent. It is generally above .1 per cent.

Another variety of ore found in the north range is the finely laminated, brownish yellow limonite of the Mahnomen open pit. This ore, while usually relatively low in silica, is more hydrated than the other north range ores. The yellow ocherous limonite ore also is common in the south range, where its occurrence is similar to that of the black limonite ore. Usually it is soft and friable. While occasionally argillaceous, as a rule it is quite pure, and ranges up to 56 or 57 per cent in metallic iron, which is nearly the theoretical limit for limonite. Combined moisture in the yellow ocherous ore may run as high as 14 or 15 per cent.

The so-called wash ore of the Cuyuna district has attracted considerable attention, and two washing plants have been erected to treat it. This ore is simply disintegrated ferruginous chert in which the chert is in the form of extremely fine sand, and can readily be washed out, leaving the iron oxide particles behind. The metallic iron content of the ore may be increased in this manner from 8 to 12 per cent.

The soft black limonite ore is common on the south range, but is rare on the north range. It is generally associated with amphibole-magnetite rock and magnetitic slate. As a rule it contains considerable carbonate and is slightly magnetic, owing to disseminated particles of magnetite which occur in it as well as in other south range ores. This magnetite is probably residual from original magnetite-bearing rock which has been altered to ore by the leaching of soluble constituents.

Manganese ore and manganiferous iron ore are common in the north range, especially in the northern part. All gradations occur, from an almost pure manganese ore with only a few per cent of iron, to iron ore with less than one per cent of manganese. The distribution of the different grades of ore is very irregular. Nodules and small bodies of high-grade manganese ore usually occur scattered through low-grade manganiferous iron ore or manganiferous iron-bearing rock. They are too small to be mined separately but are mixed with the manganiferous iron ore. A number of manganese minerals occur in these deposits, chief among which are manganite, pyrolusite, and wad. Any of these minerals may compose the nodules or bodies of manganese ore. Often two or more of them are associated in the same body.

The manganiferous iron ore is usually black, dark red, or dark brown. It occurs in irregular large or small bodies in ferruginous chert or ferruginous slate which may or may not be manganiferous. In places, the manganese-bearing portions of the iron-bearing rocks follow distinct zones more or less parallel to the bedding. The manganese content of the ore bodies varies greatly from place to place. The percentage of manganese commonly ranges from 1 or 2 per cent to 30 or 35 per cent.

Usually a decrease in the percentage of metallic manganese is accompanied by an increase in the percentage of iron, the combined percentage of iron and manganese generally being fairly constant. As the combined percentage of iron and manganese decreases, silica and alumina increase and the material becomes manganiferous iron-bearing formation. Manganiferous iron ore may be soft or hard. Some forms are dense and massive, while others are friable. It is uncertain which of the manganese minerals is associated with the hematite or limonite in the manganiferous iron ore. Possibly all the various manganese oxides are present in different phases of the ore, but it is probable that manganite predominates in the hard ore and pyrolusite and wad in the soft ore.

Iron-bearing rocks in which manganese ore and manganiferous iron ore occur in small and large bodies, are argillaceous or siliceous. Phases of it are very low in manganese, being simply ferruginous chert or ferruginous slate, while other phases are irregularly impregnated with small quantities of manganese oxide throughout, being a manganiferous iron-bearing rock. The bodies of manganese and manganiferous iron ore are found scattered irregularly through these manganese-bearing zones and differ in richness in different parts. As already mentioned the manganiferous iron-bearing rock commonly occupies more or less definite stratigraphic zones of varying width and length in the iron-bearing formation.

The distribution of the manganiferous iron-bearing rocks in the Cuyuna district is somewhat irregular, although in general the more northerly iron-bearing belts are richer in manganese. The south range thus far has not shown the presence of much manganiferous material. Some iron-bearing belts as those on which the Armour No. 1, Armour No. 2, and Thompson mines are situated, have manganiferous iron-bearing rock on the foot wall while other belts such as that on which the Mahnomen open pit is located contain manganiferous material in the hanging wall. In still other localities manganiferous iron-bearing rock and ore may be interbedded with iron-bearing beds. Thus there are all variations in the occurrence of the manganiferous material.

GEOLOGY OF THE PRINCIPAL MINES

NORTH RANGE MINES[115]

FERRO MINE

The Ferro mine of the Onahman Iron Company, is situated in the SE¼ of NE¼, section 32, T. 47N., R. 29W., the shaft being in the foot-wall of the ore body which cuts in a northeast-southwest direction

[115] A few field notes made by H. G. Ferguson of the United States Geological Survey in July, 1917, have been inserted in the following descriptions, where indicated.

across the southeast corner of the 40-acre tract, dipping steeply to the southeast. The property also includes several adjoining 40-acre tracts.

The ore body in which the Ferro mine is located is near the southwestern end of a belt of manganiferous iron ore and manganiferous iron-bearing formation which extends from the southern part of section 32, T. 47N., R. 29W., northeastward through sections 33, 28, 27, 22, and 23 to about the center of section 24, T. 47N., R. 29W. In general the iron-bearing belt is of varying width, and is bounded on both sides by schist or slate, the nature of which varies at different places along the belt. The iron-bearing rock itself, where affected by surface weathering, consists mainly of ferruginous chert or manganiferous ferruginous chert with which is associated ferruginous slate, manganiferous iron ore and iron ore. With depth, much laminated dark green siliceous rock is encountered which contains ferrous silicates and carbonate mixed with chert.

The Ferro mine has a timber shaft 157 feet deep. The main hauling level is at 149 feet, and the working level from which ore is at present being mined is about 75 feet deep (summer, 1917). The workings are all in iron-bearing rock and ore, no schist having as yet been encountered. The bottom of the shaft is in laminated, greenish black iron-bearing formation which probably consists of a mixture of ferrous carbonate and silicates and chert, the so-called foot-wall of the ore body. A cross-cut to the southwest passes from this rock through the ore body and into dense black ferruginous chert, which forms the hanging wall. The glacial drift overlying the ore body is from 55 to 60 feet thick.

The dip of the bedding of the iron-bearing rocks is from about 65° southeast to vertical, and this is also the range in dip of the ore body. The latter occupies a certain zone in the iron-bearing beds, and apparently represents a replacement of the original rock along this zone by oxides of manganese and iron, chiefly manganese. This is well shown by the fact that the ore occurs along joints and minor cracks, and penetrates from these for varying distances into the mass of the rock. Many little rectangular blocks of ore are found which, on being broken, present an interior of decomposed or partially replaced rock. The nature of the original rock is not known. The character of the rock bounding the ore body leads one to suppose that it probably consisted largely of chert, ferrous carbonate, and ferrous silicate with perhaps considerable manganese carbonate and silicate. The decomposed residue, which at present acts as a sort of matrix in which the ore is embedded and in which it forms replacements, is a dark red, siliceous material rich in iron and usually soft and porous. Associated with the ore are certain layers of epidote rock, the relations of which are not yet known.

The grade of the ore is variable. Masses of rich, finely crystalline pyrolusite occur locally, while elsewhere mixed manganese and iron oxides are found. The matrix of dark red material in which the ore occurs can not be separated from it in mining, so that the ore as shipped ranges between 20 and 30 per cent in metallic manganese and about the same in iron. It is one of the best grades of manganiferous iron ore shipped from the Cuyuna district at the present time.

The following is the average cargo analysis of ore shipped from the Ferro mine during the season 1916.[116]

Average Cargo Analysis of Ore Dried at 212° F. from the Ferro Mine

	Fe	P	SiO_2	Mn	Al_2O_3
Per cent	29.29	.075	17.56	22.29	1.47

JOAN NO. 3[117]

This is a new shaft mine, operated by the Joan Mining Company, situated in the NE¼ of SE¼ of section 32, T. 47N., R. 29W., about 500 feet west-southwest of the Ferro mine, and apparently on the same ore body. Ore is at a depth of 95 feet. The strike is southwest and the dip is steep toward the north and vertical in places. Ferruginous slate, carrying a little carbonate, occurs on the south wall, and changes to limonitic material with bands of chert near the ore. The limonitic ore (partly replaced by manganese) is said to have a higher phosphorus content than the more completely replaced black ore.

ALGOMA MINE

The Algoma mine of the Algoma Mining Company, is about one half mile northeast of the Ferro mine in the NE¼ of NW¼ of section 33, T. 47N., R. 29W. It is located on the same general iron-bearing belt as the latter, although there is apparently a slight break in it between the two properties.

The main hoisting shaft is a lath shaft, which penetrates about 60 feet of surface and about 100 feet of bed rock, while the timber shaft is about the same depth. The principal hauling level is 110 feet deep, and the main present working level is at about 80 feet (summer, 1917). There are several sublevels. As in the Ferro mine, all the workings are in iron-bearing rock and ore, no schist or slate having been encountered. The shaft is in the foot-wall rock, northwest of the ore body.

The ore at the Algoma mine does not occur in a compact body, as that at the Ferro mine, but is found along four or five zones in the iron-bearing formation, running parallel to the bedding of the latter. The zones are separated by ferruginous chert which in some places is hard and siliceous, and elsewhere medium soft and decomposed. Along certain layers it is highly manganiferous, while elsewhere it contains only

[116] Lake Superior Iron Ore Association, Analysis of Lake Superior iron ores, season 1916, p. 9, 1917.

[117] Ferguson, H. G.

a trace of manganese. The ore zones vary in width from a few feet to 20 feet or more. Some of them are continuous for a considerable distance along the strike.

The material varies in character in the different ore zones, as well as in different parts of the same zone. One zone consists mainly of ocherous, brown iron ore, speckled and blotched with impregnations of manganese ore. Others consist of uniformly black manganiferous iron ore, at some places soft and at others hard and siliceous. At one point a zone of manganiferous iron ore passes into high-grade iron ore along the strike. Thus there is considerable variation in the character as well as in the composition of the ore, and in order to maintain a uniform product, the ore from the different zones is mixed in mining.

The general strike of the ore-bearing beds is perhaps a little more nearly north and south than at the Ferro mine. The dip is steeply southeast. Northeast of the Algoma mine the iron-bearing belt continues across the SE¼ of section 28, where considerable drilling has been done, and where the MacKenzie mine is now being opened up. At this point the belt is wide and consists mainly of ferruginous chert, much of which is manganiferous and locally contains ore. To the northwest of it, green and gray schist have been encountered in drilling, and it seems probable that these rocks also bound the iron-bearing belt to the northwest in the Algoma and Ferro mines. Northeast of section 28, the belt has been explored along the line between sections 27 and 22, and also in section 23, south of Island Lake. At both of these localities it consists mainly of manganiferous iron ore and manganiferous iron-bearing rock. South of Island Lake, the belt is narrow and is highly manganiferous. It is bounded on the north by gray schist and on the south by gray schist and graphitic slate.

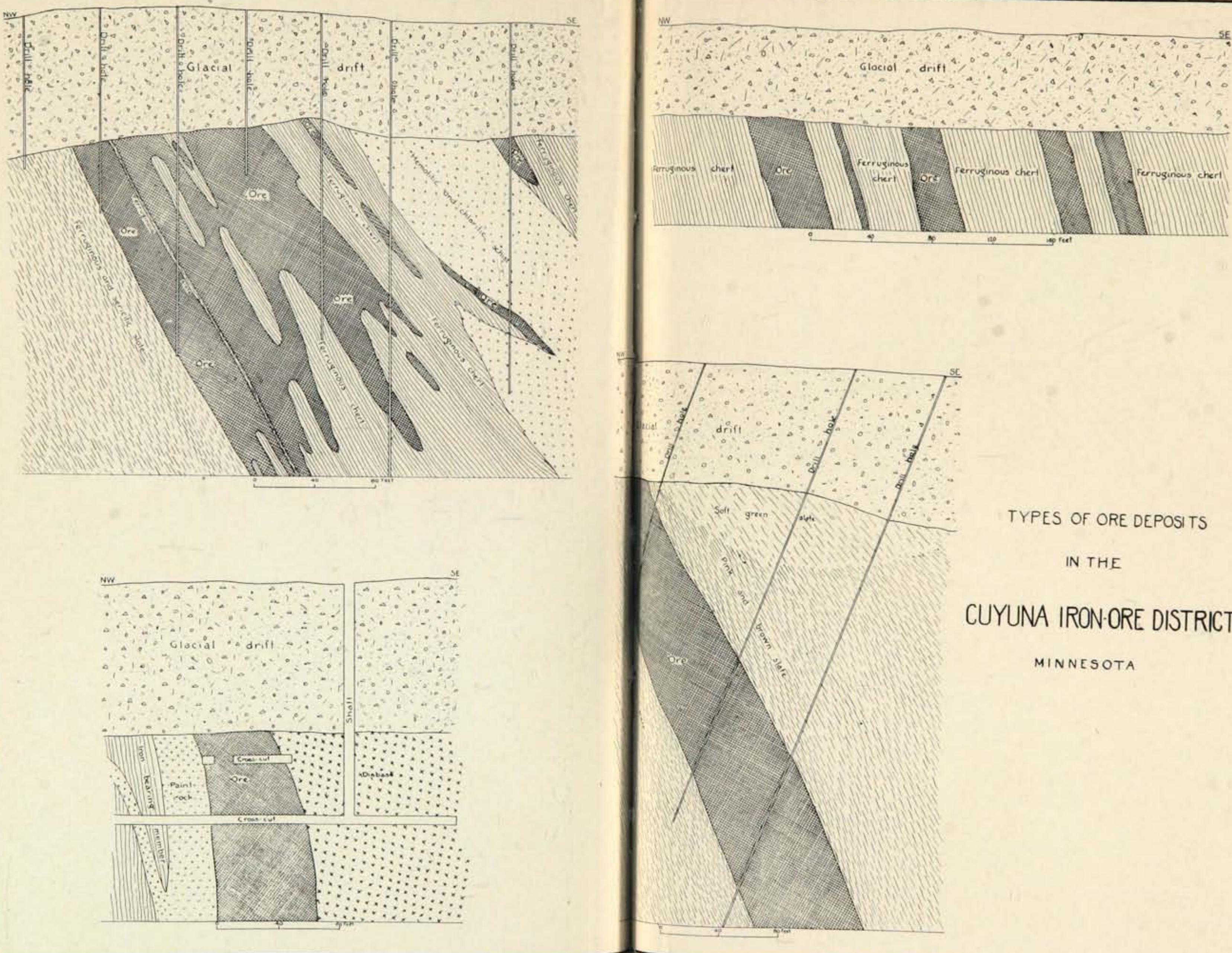
The Algoma-Ferro iron-bearing belt, although varying in character in different parts, is distinctly manganiferous throughout its known extent. It varies greatly in width. At some places it is very narrow; in others it is 1,000 feet or more wide. It has a fairly uniform steep dip to the southeast or south. Its extent to the northeast and southwest beyond the present known limits is not yet thoroughly explored. Small areas of iron-bearing formation, however, are known at several localities beyond both ends.

The following is the average cargo analysis of ore shipped from the Algoma (Hoch) mine during the season of 1916.[119]

Average Cargo Analysis of Ore Dried at 212° F. from the Algoma Mine

	Fe	P	SiO_2	Mn	Al_2O_3
Per cent.....................	32.26	.090	16.47	19.50	2.43

119 Lake Superior Iron Ore Association, *op. cit.*, p. 9.



TYPES OF ORE DEPOSITS

IN THE

CUYUNA IRON-ORE DISTRICT

MINNESOTA

ROWE MINE

The Rowe mine, operated by the Pittsburgh Steel Ore Company, is located in the N½ of SE¼ of section 18, T. 46N., R. 29W., on Little Rabbit Lake near Riverton, at the western end of the north range. The mine consists of a large open pit about 2,500 feet long, east and west, and about 700 feet wide from crest to crest at the widest part. The depth of the pit at the present time varies from about 100 feet on the north side near the center, to about 20 feet on the south side, the difference being due both to surface topography and to irregularity of excavation (summer, 1917). The overburden, consisting mainly of sand and clay, varies in thickness from 15 feet at the west end of the pit to 74 feet on the north side. The difference in elevation of the ore surface underneath the overburden of glacial till is about 30 feet, thus showing considerable irregularity of the pre-glacial surface over this comparatively small area. The greatest depth of the bottom of the pit below the bed rock surface is about 60 feet, and is near the center of the pit. During the summer of 1917 a concrete hoisting shaft was sunk south of the west end of the pit.

Iron-bearing rock and ore are exposed in the pit over a length of about 1,900 feet and over a maximum width of 450 feet. The general strike of the iron-bearing belt is about N.63°E., but, owing to a sharp synclinal fold at the west end of the pit, the details of the structure within the pit are very complex, as may be seen from the strike and dip readings, shown on Plate XX. The general dip is southeasterly but locally the rocks dip steeply to the north.

The iron-bearing belt has been traced by drilling toward the Rowe mine from the northeast through the north half of section 17. Where it enters section 18 at the east end of the Rowe pit, the iron-bearing belt is about 200 feet wide. Its width gradually increases to the southwest, and near the middle of the pit it has a width of 300 feet. This point marks the beginning of the synclinal turn to the north which occupies the entire west end of the pit. The synclinal fold is composed of a number of minor folds which in turn are composed of smaller folds and crenulations. (Plate XVIII B). Around the end of the turn the outlines of the iron-bearing belt are very irregular, and its width varies between 300 and 600 feet; but beyond the turn on the north limb of the syncline the belt again becomes regular, and decreases in width to between 200 and 300 feet. The turn of the syncline is very sharp, the north limb running back in a northeasterly direction practically parallel to the south limb. Both limbs have a general steep dip to the southeast. The bottom of the syncline pitches to the east between 45° and 60°.

The iron-bearing belt is bounded on both sides by schist and slate. South of the syncline and extending around the west end, is an extensive area underlain by gray and green chloritic and argillaceous schist and slate. Within the syncline, overlying the iron-bearing formation, are light gray siliceous sericitic slate and red ferruginous slate. The latter commonly occurs near the contact of the iron-bearing formation, but is also found within the gray schist. The contact between the red and gray slate is usually irregular and in most cases the red color is due to local staining. Slate or schist are found in the pit in only a few places, the principal exposures being along the center of the north side. The open pit, therefore, is almost entirely in ore and iron-bearing rock.

The iron-bearing rocks at the Rowe mine consist of three distinct types of materials: (1) medium grade hematite and hydrated hematite ore (direct-shipping ore), (2) wash ore, consisting of hematite and hydrated hematite mixed with more or less disintegrated chert, and (3) hard ferruginous chert. These materials are somewhat irregularly distributed and frequently occur intermixed. In some parts of the pit, however, good ore predominates, and in other parts wash ore and ferruginous chert predominate. The latter especially seems to be concentrated along certain lines as is shown on Plate XX. The largest of these areas of ferruginous chert passes lengthwise through the center of the eastern portion of the pit, while another large area occurs in the southern part of the western half of the pit and trends northeasterly. Smaller masses are intermixed both with the wash ore and the direct-shipping ore.

The direct-shipping ore differs from the wash ore and ferruginous chert in that it contains a smaller quantity of impurities such as chert or clay. It consists of a mixture of brown, red, and blue hematite, most of it more or less hydrated. The direct-shipping ore is the principal material in the pit.

The ferruginous chert consists of intermixed hematite and chert. Usually the chert is dense and hard and is white, gray, or pink in color. It may be interlaminated with the hematite in thin irregular layers, or it may be intermixed with it in specks and blotches. This interlayering of light and dark bands is very characteristic of ferruginous chert. In the leaner ferruginous chert the dark bands, instead of being composed of hematite, consist chiefly of chert which has been stained by iron oxide. Usually in such cases the layering is less regular, however.

The wash ore differs from the ferruginous chert in that the chert layers are disintegrated and consist mainly of very fine sand, in places slightly consolidated. This sand is removed by washing and the iron oxide interlayered with it becomes concentrated, the richness of the concentrate depending on the degree of disintegration which the chert has suffered and on the amount of impurity which the hematite layers contain. The hematite interlayered with the chert in wash ore or ferruginous chert may be brown, red, or blue, depending on the amount of hydration which it has undergone.

On the southern side of the iron ore body is a small mass of manganiferous ore, carrying about 43 per cent iron, 15 per cent manganese, and 11 per cent silica, and is apparently a replacement of ferruginous slate. The quantity of manganiferous ore, however, is so small that it is not shipped separately, but mixed with the non-manganiferous iron ore.[129]

The depth to which the Rowe ore body extends is not known. One drill hole near the center of the pit encountered ore to a depth of 360 feet below the original rock surface, while another one located in the angle of the syncline, passed into ore at a depth of 304 feet and continued in merchantable ore for 110 feet. Many encountered ore at a depth of more than 200 feet below the base of the glacial drift. The lower limit of the ore body is probably irregular, the depth varying in different parts, depending upon the attitude and texture of the rock strata. The ore will probably be found to extend to its greatest depth in the western portion of the pit.

The northern limb of the syncline at the Rowe mine consists mainly of ferruginous chert, and as far as known contains but little ore. It has not been thoroughly explored, however, and good ore bodies may be found along it. A minor fold occurs in this limb in the northeastern part of section 18, and beyond this the iron-bearing belt continues northeasterly through the northwest corner of section 17 into section 8. It may be continuous with some of the northern ore belts in sections 9, 3, and 2, T. 46N., R. 29W., in the central part of the north range. However, this connection has not yet been traced out.

HILLCREST MINE

The Hillcrest mine, operated by the Hill Mines Company, is located in the NE¼ of SE¼ of section 9, T. 46N., R. 29W., just northeast of Blackhoof Lake and about one mile west of Ironton. It is approximately on the line of strike of the iron-bearing belt which forms the southern limb of the syncline at the Rowe mine. Iron-bearing rock has been traced almost continuously between the two mines, but it is not yet possible to state definitely whether the iron-bearing formations at the two mines are at the same stratigraphic horizon. However, the iron-bearing rock and associated ore of the Hillcrest mine are known to continue southwestward through the south half of section 9 and into the northwest quarter of section 16, thus leaving a stretch of only about three fourths of a mile of little known territory between this point and the northeast extension of the iron-bearing belt from the Rowe mine.

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[129] Ferguson, H. G.

Hydraulic stripping operations at the Hillcrest mine were in progress during the summer and autumn of 1915, and during a large part of the winter until stopped by excessive cold. During the summer of 1916 the final stripping was being done with steam shovels. The overburden is 65 to 70 feet thick. The upper part is sand and the lower part is clay containing locally boulders of considerable size.

The iron-bearing rocks and associated ore are known mainly as a result of drilling. The drilling indicates that the iron-bearing belt has a maximum width of 400 feet and is mainly ore over most of its width. The strike of the iron-bearing belt is approximately N.70°E. and the dip is to the south at a fairly steep angle. Locally the beds are vertical. Gray slate and schist bound the iron-bearing belt on the north and south. Near the contact with the iron-bearing rock there is red ferruginous slate or paint rock.

Recently there has been opened at the Hillcrest mine a small lenticular mass of manganiferous iron ore within the iron-ore body. It is bounded on both sides by iron ore with fairly sharp dividing lines. The lens is about 200 feet long by 20 wide, but is somewhat irregular in outline. It represents an impregnation of a part of the ore body by manganese oxide.

Below are given average analyses of ore dried at 212° F. from the Hillcrest mine.[121]

Average Cargo Analyses of Ore Dried at 212° F. from the Hillcrest Mine

	Fe %	P %	SiO_2 %	Mn %	Al_2O_3 %	CaO %	MgO %	S %	Loss by ignition %
Hillcrest.....	58.000	.238	5.500	.230	2.680	.290	.030	.001	6.420
Hillcrest manganiferous	43.811	.230	6.110	9.880	.....	....	....	....	.....

PENNINGTON MINE

The iron-bearing belt of the Hillcrest mine is directly continuous northeastward with the iron-bearing formation of the Pennington and Armour No. 1 mines. The ore bodies, however, are not connected.

The Pennington mine, operated by the Pennington Mining Company of Tod-Stambaugh Company, is an open pit mine situated in the SW¼ of NE¼ of section 10, T. 46N., R. 29W. It is about half a mile from the Hillcrest mine, and the intervening area, which is known as the Feigh property, contains iron-bearing rock throughout its length; with it is associated a considerable quantity of ore. The Pennington pit is about 1,200 feet long, east and west, and has a maximum width of 680 feet from crest to crest. On the east it is directly continuous with the Armour No. 1 open pit which has a length of 750 feet

[121] Lake Superior Iron Ore Association, *op. cit.*, p. 9, 1917.

and a width of 550 feet from crest to crest. The depth of the pit formed by these two mines is about 110 feet near the center and about 70 feet at the west end. The overburden of clay and sand above the ore and rock surface averages between 70 and 85 feet thick. The old erosion surface of the ore and iron-bearing rock shows a difference in elevation of about 15 feet in different parts of the pit. Locally ore has been excavated to a depth of 35 to 40 feet beneath the original surface (summer, 1917). The width of ore and rock exposed along the bottom of the pit between the slopes of sand and clay varies from about 400 feet near the center to about 100 feet at the west end. Along the length of the combined pit, ore and iron-bearing rock are exposed for about 1,500 feet.

The iron-bearing rock as exposed in the Pennington portion of the pit is very largely ore, some of it of very high grade. Along the north side, however, at the base of the sand slope, there are a few places where hard ferruginous chert is exposed. In the south half of the pit there is a lens of hematitic and chloritic schist varying in width from 50 feet to 120 feet. (Plate XXI.) It is bounded on the north by ore. On the south it is bounded at some places by ore and at others by ferruginous chert. Locally, especially along its north side, the schist lens consists of dark red, soft, hematitic schist or paint rock, but for the most part it is made up of dark green or grayish green fine-grained chloritic schist containing both chlorite and sericite. In general appearance and structure as well as in its relation to the enclosing sedimentary rocks, the chloritic schist suggests a squeezed and altered subsilicic igneous rock. This is true not only of the chloritic schist in the Pennington and Armour No. 1 mines, but elsewhere in the Cuyuna district, practically wherever it occurs. Analyses and microscopic examinations of this rock will probably aid in determining its true character.

The best ore in the Pennington mine is a soft, dark red to reddish blue hematite. It is usually porous and breaks into a mixture of sand and small fragments when handled with the steam shovel. In general it is thinly laminated, and in many places shows crumpling. With increasing silica this ore grades into ordinary laminated ferruginous chert. The ferruginous chert as it occurs in the Pennington mine consists of thin layers of white, pink, or gray chert interlaminated with similar layers of more or less pure hematite, or hydrated hematite or with layers of chert stained dark red or blue by hematite. Thus there are all gradations from chert with certain layers stained by iron oxide to ore with only a very small amount of chert. The different layers or laminae vary in thickness from mere seams to an inch or more. Usually the layers themselves show fine lamination parallel to the bedding. Some ferruginous chert, while showing distinct lamination, does not have continuous layers of different colored materials. The coloration may be irregular, following certain layers for a short distance and then cutting across the lamination, in general giving the rock a blotched appearance. This is especially common in the low-grade ferruginous chert which consists mainly of silica partly stained by iron oxide. Where the rock consists of distinct layers of chert and iron oxide, the layering is usually quite regular and very thin laminae may be followed for several feet. This is well shown locally along the north wall of the pit. In some of the ferruginous chert, the chert layers are partly disintegrated and the rock is soft and readily broken. Elsewhere, however, the rock is dense and extremely hard.

The following average cargo analysis of ore from the Pennington mine is given by the Lake Superior Ore Association.[122]

Average Cargo Analysis of Ore Dried at 212° F. Shipped from the Pennington Mine during the Season of 1916

	Fe %	P %	SiO_2 %	Mn %	Al_2O_3 %	CaO %	MgO %	S %	Loss by ignition %
Per cent.....	58.09	.192	8.26	.31	3.13	.30	.05	.021	4.55

In places in the Pennington portion of the pit, drag folding is conspicuously shown. (Plate XXI.) Three or four well-developed drag folds occur, whose axes trend obliquely across the pit in a direction slightly more north of east than the general strike of the bedding. These drag folds pitch 15° to 30° southwest, and their axial planes dip southeast, indicating that the iron-bearing rock of the Pennington-Armour No. 1 pit is on the south limb of an anticline. This structure is distinctly at variance with the structure as shown at the Rowe mine, where presumably the same iron-bearing layer forms the south limb of a syncline. This discrepancy may indicate that there is a break in the iron-bearing belt between the Hillcrest and Rowe mines.

ARMOUR NO. 1 MINE

The Armour No. 1 mine, operated by the Inland Steel Company, is adjacent to the Pennington mine on the northeast and occurs on the extension of the Pennington ore body. It was operated during 1912 and 1913 as an underground mine, but was idle during 1914. In the spring and summer of 1915 the overburden was stripped and at present the Pennington and Armour mines are both in one big open pit, the Armour No. 1 mine operations being at the east end and the Pennington mine operations at the west end. The first ore was shipped from Armour No. 1 open pit during the fall of 1915.

The Armour No. 1 shaft, a circular concrete shaft, is located south of the ore body in the southern part of the SE¼ of NE¼ of section 10,

[122] Lake Superior Iron Ore Association, *op. cit.*, p. 11.

T. 46N., R. 29W. It is 340 feet deep and drifts were run northward to the ore body at the 200 foot and 300 foot levels. The shaft penetrates 65 feet of overburden, and below this it is mainly in green and gray chloritic schist similar to that occurring in places in the present open pit. Locally the schistosity of this rock is not very prominent and the rock is quite massive. About 200 feet north of the shaft on the bed rock surface is the contact between the chloritic schist and the southernmost layer of iron-bearing rock. Iron-bearing rock with associated iron ore and manganiferous iron ore and lenses of green schist and paint rock occupy the northern part of the Armour No. 1 40-acre tract. (Plate XXI.) The Pennington-Armour No. 1 ore body proper is about 500 feet north of the shaft on the bed rock surface.

The general strike of the rock beds is approximately N.70°E., with local variations, and the dip is steeply to the south. The ore body has the same general strike as the rocks. It is cut into two parts longitudinally by a lens of green schist and paint rock that varies up to 100 feet in thickness. This lens pinches out to the west at the boundary of the Pennington property, and to the east it splits into several thin layers separated by ore layers, and gradually pinches out as it approaches the Armour No. 2 property. Unaltered green schist forms the center of the lens, and the paint rock is found along the contact with the ore. The part of the ore body south of the schist lens is bounded on the south by another belt of paint rock and green chloritic schist, which is apparently continuous with the schist lens on the Pennington property. The part of the ore body lying north of the northern schist lens grades northward into manganiferous iron-bearing rock, some of which carries 14 per cent or more of manganese. The ore body including the lens of paint rock and green schist varies up to more than 200 feet in width and extends northeastward across the entire 40-acre tract from the Pennington property line to the Armour No. 2 property line.

The ore is of good grade, ranging on the average between 55 per cent and 62 per cent in metallic iron. It is of non-Bessemer quality, however, ranging in general between 0.15 and 0.3 per cent phosphorus. Its appearance and texture are very similar to the ore on the Pennington property, and seem to be more or less uniform throughout the ore body. The following average cargo analysis of ore from the Armour No. 1 mine is given by the Lake Superior Iron Ore Association.[123]

Average Cargo Analysis of Ore Dried at 212° F. Shipped from the Armour No. 1 Mine during the Season 1916

	Fe	P	SiO_2	Mn	Al_2O_3
Per cent	58.27	.187	7.39	.29	2.47

[123] Lake Superior Iron Ore Association, *op. cit.*, p. 8.

IRONTON MINE

The Ironton mine of the Cuyuna-Duluth Iron Company is located just north of the village of Ironton, in the NW¼ of SW¼ of section 11, T. 46N., R. 29W. It consists of a lath shaft which passes through 65 feet of glacial till into underlying green chloritic schist to a total depth of 300 feet. At the 200 and 280 foot levels, drifts run northwestward from it to the ore body, the distance being about 200 feet on the 200 foot level. (Plate XXI.) The ore body is the southwesterly extension of the main Armour No. 2 ore body. It is more or less parallel to the Pennington-Armour No. 1 ore body and is about 1,000 to 1,200 feet southeast of it. Between the two ore belts are green chloritic schist, and paint rock with some lenses of lean iron-bearing rock.

The ore of the Ironton mine is for the most part soft and granular hematite, dark red to reddish blue. It is of high grade and is similar to much of the ore in the western part of the Armour No. 2 mine.

The following average cargo analysis of ore from the Ironton mine is given by the Lake Superior Iron Ore Association.[124]

Average Cargo Analysis of Ore Dried at 212° F. Shipped from Ironton Mine During the Season 1916

	Fe	P	SiO_2	Mn	Al_2O_3
Per cent	59.70	.172	5.75	.81	4.44

ARMOUR NO. 2 MINE

The Armour No. 2 mine of the Inland Steel Company, is located in the SW¼ of NW¼ of section 11, T. 46N., R. 29W. It consists of a circular concrete shaft 298 feet deep and a considerable amount of underground workings. The shaft penetrated 63 feet of glacial overburden, below which it encountered green chloritic schist. The main hauling level is at a depth of 168 feet. At this level, cross-cuts run north-northwestward and south-southeastward from the shaft. (Plate XXI.) The first of these connects with the extension of the 200 foot level of the Armour No. 1 mine in the Pennington-Armour No. 1 ore body, and the second connects with the main Armour No. 2 ore body which continues northeastward from the Ironton mine through the Armour No. 2 40-acre tract. Sublevels are found 127 feet and 107 feet below the surface, and a new exploration drift runs south-southeastward from the shaft at the 258 foot level.

The general strike of the main Armour No. 2 ore body is about N. 55°E. The Pennington-Armour No. 1 ore body strikes N.70°E., thus indicating a convergence of the two ore bodies to the northeast. The main ore belt has a maximum width of more than 400 feet, and, as the

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124 Lake Superior Iron Ore Association, *op. cit.*, p. 9.

dip is at a fairly high angle to the southeast, this gives considerable thickness to the ore body. There is, however, some lean ferruginous chert mixed with the ore, as is the case in nearly all the ore bodies in the Cuyuna district.

The ore body is of considerable longitudinal extent, for the indications are that it continues northeastward through the adjoining 40-acre tract which also forms part of the Armour No. 2 property, and through the Thompson, Meacham, and Croft properties, a total length of more than one and three fourths miles. However, not enough drilling has been done as yet definitely to prove the continuity of the ore.

There is a curious distribution of different kinds of ore in the ore body on the Armour No. 2 property. The southwestern part of the body, to a point a short distance northeast of the main cross-cut, consists of dark red and reddish blue hematite, usually soft and granular and but slightly hydrated. This ore is high in metallic iron, ranging up to 66 and 67 per cent, and is comparatively low in phosphorus, much of it varying between .02 and .07 per cent. Probably a considerable amount of ore of Bessemer grade could be mined by careful selection. The northeastern part of the ore body consists of an entirely different type of ore. It is largely a medium-hard, brown ore consisting of limonite and hydrated hematite. This ore continues northeastward into the eastern Armour No. 2 40-acre tract, where it locally becomes highly manganiferous, although it contains less manganese than the foot-wall of the Armour No. 1 ore body. The manganiferous iron ore appears to occur as local lenses interlayered with ore and ferruginous chert which is practically free from manganese.

Southeast of the main Armour No. 2 ore body, and forming the hanging wall throughout most of its extent, are beds of hard and rather lean ferruginous chert. Locally, however, in the southwestern half of the ore body, some of the drifts have encountered red, ferruginous slate in the hanging wall directly in contact with the ore. It is probable that drifts driven southward through the ferruginous chert will penetrate it and encounter red hematitic and green chloritic schist south of it similar to that which occurs in the hanging wall of the ore body at the Ironton and Thompson mines.

The foot-wall of the main Armour No. 2 ore body is formed by a layer of paint rock or hematitic schist, which, however, is only 10 or 15 feet thick, and grades into compact green chloritic schist. (Plate XXI.) The latter probably continues northward to the Armour No. 1 ore body, containing locally, however, a few lenses of iron-bearing formation. The main cross-cut running north-northwestward from the shaft to the extension of the Armour No. 1 ore body is entirely in chloritic schist.

The presence of local layers or lenses of iron-bearing formation, however, such as occur also in the Armour No. 1 property, has been shown by drilling.

The extension of the Pennington-Armour No. 1 ore body in the Armour No. 2 property is comparatively thin and appears to become thinner to the northeast. Compared to the main ore body, it is of no great importance. Its hanging wall consists of green chloritic schist, while the foot-wall is formed by iron-bearing formation which is locally manganiferous like that in the Armour No. 1 property. The ore is similar to that in the Armour No. 1 and Pennington mines.

Three grades of ore are shipped from the Armour No. 2 mine.[126]

Average Cargo Analyses of Ore Dried at 212° F. Shipped from the Armour No. 2 Mine during the Season 1916

	Fe	P	SiO_2	Mn	Al_2O_3
Red (per cent)	58.20	.104	9.05	.19	3.60
Brown (per cent)	54.80	.281	6.94	1.05	3.92
Manganese (per cent)	49.30	.215	8.90	5.28	3.43

THOMPSON MINE

The Thompson mine of the Inland Steel Company consists of both open pit and underground workings. The latter, however, were not used, except for drainage purposes, between 1913 and 1916, after which date steam shovel operations gave place to milling. The shaft is located in the southern part of the NW¼ of NE¼ of section 11, T. 46N., R. 29W., and the open pit is just south of it on the line between this 40-acre tract and the one immediately to the south.

The shaft, which is 305 feet deep, has cross-cuts north and south at the 150 and 250 foot levels. There is also a sublevel at 100 feet not connected with the shaft. The north cross-cuts encounter an important, but as yet little developed, ore lens located in the northern part of the 40-acre tract in which the shaft is located, and in the southern part of the 40-acre tract adjoining it on the north. This lens is on the line of strike of the Pennington-Armour No. 1 ore body, but drilling has shown that it is a separate lens although it occurs at approximately the same horizon. The south cross-cuts connect with an ore body immediately south of the shaft which is the northeastward extension of the main Armour No. 2 ore body, as has already been mentioned. (Plate XXII.)

The Thompson open pit, which is on the south ore body, has a length of about 1,600 feet and a maximum width from crest to crest near the middle of 450 feet. The overburden, consisting of sand above and of gray and red clay and sand below, varies in thickness from 50 feet to

[126] Lake Superior Iron Ore Association, *op. cit.*, p. 8.

80 feet depending upon the topography. The ore surface is comparatively level, although it rises somewhat toward the west. Ore and ferruginous chert are exposed along the bottom of the pit practically throughout its entire length. The width of the bottom of the pit is approximately 100 feet. The bottom in the west end of the pit in the fall of 1915, was about 50 feet below the original ore surface, and in the fall of 1916 about 90 feet below. The strike of the beds is very regular throughout the length of the pit and is about N.65°E. The dip is to the southeast and varies between 50° and 75°, averaging about 65°.

The foot-wall of the ore body which forms the north wall of the lower part of the pit, consists of light gray to dark gray or red siliceous and ferruginous argillite (or slate). It is very thin-bedded and, due to the abundance of silica, has only locally developed slaty cleavage. In places it is stained dark red by hematite. Ferruginous layers are interbedded with siliceous and argillaceous layers. Just below the main ore body a thin lens of ore is interbedded with the foot-wall argillite.

The ore of the main ore body occupies most of the bottom of the pit. In places it consists of almost pure dark brown limonite, while elsewhere it is mixed with sandy disintegrated ferruginous chert or with hard, dense, ferruginous chert. A thin layer of red, ferruginous argillite occurs interbedded with ore in the western part of the pit. The ore as a rule is richest near the foot-wall and for 50 or 60 feet away from it. Toward the hanging wall it becomes more siliceous. Locally along the foot-wall between the ore and the argillite are irregular lenses of manganiferous ore.

The south wall of the pit consists in the western part of hard, massive, ferruginous chert, and in the eastern part of soft, dark red hematitic schist, which is doubtless decomposed and iron-stained chloritic schist, and forms the hanging wall of the iron-bearing formation.

Most of the ore is shipped directly, as it is loaded by steam shovels in the pit, but the hard ferruginous chert occurring with it irregularly along certain horizons is not used. The soft, more or less disintegrated, ferruginous chert is concentrated in a small washing plant equipped with log washers. The following average cargo analysis of ore from the Thompson mine is given by the Lake Superior Iron Ore Association.[126]

Average Cargo Analysis of Ore Dried at 212° F. Shipped from the Thompson Mine during the Season 1916

	Fe	P	SiO_2	Mn	Al_2O_3
Per cent......................	52.34	.250	8.30	2.38	3.44

[126] Lake Superior Iron Ore Association, *op. cit.*, p. 11.

The north ore lens of the Thompson mine, as indicated by the drilling, is considerably larger than the south lens. It has a length of about 2,000 feet and a maximum width of 600 feet. Much of it is manganiferous, and it contains considerable iron-bearing rock mixed with the ore. Like the south ore lens, it dips steeply to the southeast. Between the north and south lenses is a great thickness of slate and green chloritic schist with bands of iron-bearing formation.

MEACHAM MINE

The Meacham mine, operated by Rogers-Brown Ore Company, is situated just east of the Thompson open pit on the continuation of the upper or southern Thompson ore body. The property is an 80-acre tract including the NE¼ of NE¼ of section 11, and the NW¼ of NW¼ of section 12, T. 46N., R. 29W.

The shaft, which is located in the NE¼ of NE¼ of section 11, is a circular concrete shaft having a total depth of 254 feet, of which the upper 70 feet are in glacial drift. The main hoisting level is at 154 feet, while the principal working levels at present are at 85, 105, and 115 feet. The shaft is in the foot-wall of the ore body which, like the Thompson ore body, dips steeply to the southeast. The association of ore and wall rocks is similar in the two mines.

The following average cargo analyses of ore from the Meacham mine are given by the Lake Superior Iron Ore Association.[127]

Average Cargo Analyses of Ore Dried at 212° F. Shipped from the Meacham Mine during the Season 1916

	Fe %	P %	SiO_2 %	Mn %	Al_2O_3 %	CaO %	MgO %	S %	Loss by ignition %
Meacham Bessemer..	59.90	.045	3.50	.40	.....	....	....	....	.....
Meacham Non-Bessemer..	55.00	.3347	5.889	.535	3.216	.536	.272	.0139	10.547
Meacham Manganese	46.58	.308	6.52	4.42	4.22	2.08	.55	....	12.02

CROFT MINE

The Croft mine, operated by John A. Savage and Company, is situated one half mile northeast of the Meacham mine on the same iron-bearing belt as the Armour No. 2, Thompson, and Meacham mines. The property comprises the SE¼ of SW¼ and the SE½ of SW¼ of SW¼ of section 1, T. 46N., R. 29W. The western portion of it adjoins the eastern Meacham 40-acre tract on the north.

[127] Lake Superior Iron Ore Association, Analyses of Lake Superior iron ores, season 1916, pp. 10 and 11, 1917.

A circular concrete shaft located a short distance northwest of the iron-bearing belt, was sunk through 110 feet of surface drift to the ledge. From its bottom a rectangular steel shaft passes through rock forming the foot-wall of the ore body to a total depth of 250 feet. The main cross-cut, on the 222-foot level, connects the shaft with the various drifts and cross-cuts in the ore body. The main working level is at 160 feet.

Two bands of iron-bearing rock cross the Croft property in an approximately northeast-southwest direction. They are separated by a wedge of green chloritic schist and associated red hematitic schist, which widens to the northeast and comes to a point in the southwestern part of the property. On the northwest and southeast, the iron-bearing belts are bounded by green and red schists. Those to the southeast are chloritic and those to the northwest are locally quartzose, and are probably sedimentary in origin as indicated by their banded and laminated character. The dip of the iron-bearing beds averages about 60° southeast.

The upper iron-bearing bed, i.e., the one to the southeast, consists mainly of ferruginous chert and slate associated with low grade ore, some of which is manganiferous, and with lenses of green and red schist. It has a maximum width of 350 feet on the erosion surface. The mine is located on the lower iron-bearing bed. This bed has an average width of 180 to 200 feet on the erosion surface, but is rather irregular. A part of the layer consists of ferruginous chert associated with some ferruginous slate, and another part of it consists of rich, dark reddish blue hematite which occurs as a layer of varying width running practically through the entire length of the property. Most of the ore, according to drill records, is of Bessemer quality and is the richest ore that has been found in the Cuyuna district. The following average analysis of ore from the Croft mine is given by the Lake Superior Iron Ore Association.[128]

Average Cargo Analysis of Ore, Dried at 212° F., Shipped from the Croft Mine during the Season 1916

	Fe	P	SiO_2	Mn	Al_2O_3	CaO	MgO	S	Loss by ignition
Per cent.....	59.718	.0435	10.250	.110	1.630	.290	.030	.0010	2.600

The depth to which the Croft ore body extends has not yet been shown by drilling. Throughout most of the property it dips southeast more or less parallel to the bedding of the associated rocks and retains a fairly regular thickness with depth. The indications that the ore may extend to a considerable depth are probably as favorable here as they are in any other deposit in the district.

[128] Lake Superior Iron Ore Association, *op. cit.*, p. 8.

CUYUNA-MILLE LACS MINE

The Cuyuna–Mille Lacs mine of the Cuyuna–Mille Lacs Iron Company, is located in the SE¼ of SW¼ of section 3, T. 46N., R. 29W., southeast of Menomin Lake, but the property includes also the NW¼ and SW¼ of SW¼ of section 3. The main hoisting shaft, a lath shaft, was sunk through about 50 feet of glacial till and 175 feet of ore and rock to a depth of 225 feet. The timber shaft is 205 feet deep and the main hauling level is at the bottom of it. Both shafts are sunk directly to the Cuyuna–Mille Lacs north ore body. The principal mining operations are now on the 85, 125, 145, 165, and 205 foot levels. At the present time (summer 1917) a second hoisting shaft is being sunk in the SW¼ of SW¼ of section 3. This will connect directly with the south ore body.

The Cuyuna–Mille Lacs north ore body occurs along the crest of an anticline which strikes approximately northeast-southwest. The north limb of the anticline near the ore body has a steep dip northwest, but away from the ore body the beds are overturned, and have a steep dip to the southeast. The south limb of the anticline dips southeast. The dip is fairly low near the ore body, but is higher toward the southeast. The ore body appears to occupy a somewhat indefinite stratigraphic horizon, but its position along the crest of the anticline and its continuation downward along the axial plane suggests that in part, at least, the ore body is a replacement of a fractured zone. Ferruginous chert bounds the ore body on the northwest and southeast. The most characteristic wall rock is an evenly laminated, medium hard, ferruginous chert, which cleaves readily along lamination planes, breaking in thin slabs. This rock is found on both sides of the ore body, but is more characteristically developed on the south side. Some phases of it are rather argillaceous, approaching ferruginous slate in character. At some points along the south side of the ore body, there is a layer of hard, jaspery, ferruginous chert. It is bounded on the north side by low-grade, soft, manganiferous iron ore, and on the south side by the laminated, argillaceous ferruginous chert already mentioned. Up to the present time this jasper layer has not been encountered on the north limb of the anticline. It is probably a local lens.

The structure of the Cuyuna–Mille Lacs anticline with its north limb dipping steeply northward or overturned, and its south limb dipping steeply southward, suggests that it may be a drag fold on the south limb of a more extensive major anticline. South of the ore body for some distance, southeasterly dips of varying steepness prevail, the rocks being mainly iron-bearing formation or manganiferous iron-bearing formation. In the southern part of the SE¼ of SW¼ of section 3, however, a southwestward pitching syncline occurs which is apparently continuous to the northeast with the synclinal trough in the northern part of the Sultana property. The rock strata, however, composing the syncline differ from those found in the Sultana syncline in being more cherty, though slaty layers occur here and there. Several extensive ore lenses are found in the syncline and adjacent to it. They are known collectively as the south ore body.

South of the Cuyuna–Mille Lacs property, in the northern part of section 10 is the Mahnomen open pit. Steep southeasterly dips prevail in the ore at this place, and no secondary structures which might aid in determining the relation of this ore belt to the major structure have so far been found. Lithologically, however, certain manganiferous iron ore layers found in the southern part of the Mahnomen pit are very similar to the manganiferous iron ore of the Sultana and Armour No. 1 mines, and they may represent the same stratigraphic horizon. As already mentioned, the drag folds found along the Pennington-Armour No. 1 ore belt south of the Mahnomen ore belt, indicate that the beds here are on the south limb of a major anticline. Not enough data are as yet available to determine the structural relations of these various beds. It seems probable, however, that a series of folds exists between Menomin Lake and the Pennington pit and results in a repetition of layers. Between which of the ore beds there are anticlines and between which there are synclines can not yet be stated definitely.

The iron-bearing belt in which the Cuyuna–Mille Lacs ore body occurs has been traced continuously only from the southern part of section 4, T. 46N., R. 29W., northeastward through section 3. Little is, therefore, known of its longitudinal extent.

The Cuyuna–Mille Lacs north ore body is compact in form, but the south ore body consists of several separate masses. Both vary considerably in the character of the material from place to place. Locally bodies of rich black manganese ore occur, but the general run of material is a medium soft to hard black or brownish manganiferous iron ore which varies in manganese content from place to place. The rich manganese ore as a rule is finely crystalline pyrolusite; some is fairly hard and compact and some is soft and friable. Dense, hard, black psilomelane is also of frequent occurrence. The manganiferous iron ore usually has a blocky structure and is dense and amorphous. Specks of crystalline material, however, frequently occur scattered through it.

Four grades of ore are mined by the Cuyuna–Mille Lacs Iron Company; the average cargo analyses are as follows:[129]

[129] Lake Superior Iron Ore Association, *op. cit.*, p. 9, 1917.

Average Cargo Analyses of Ore Dried at 212° F. Shipped from Cuyuna-Mille Lacs Mine, for the Season 1916

	Fe %	P %	SiO_2 %	Mn %	Al_2O_3 %	CaO %	MgO %
Crow Wing "A".....	37.71	.091	11.46	21.22	.95	.82	.47
Crow Wing "B".....	39.02	.096	13.20	17.06	.42	.84	.67
Crow Wing "C".....	37.39	.79	19.50	12.91	.220	.670	.63
Crow Wing "D".....	40.02	.051	22.00	8.96	.182	.68	.60

The Cuyuna-Mille Lacs mine has been by far the largest shipper of manganiferous iron ore in the Cuyuna district. When the mine was first opened, considerable high-grade ore was produced, but more recently the reserves have been increased by reason of the fact that lower grade ore in large quantities is being shipped.[130] The Cuyuna-Mille Lacs ore contains a considerably lower percentage of phosphorus than the general run of iron ore of the Cuyuna district.

MANGAN NO. 1 MINE

The Mangan No. 1 mine of the Mangan Iron and Steel Company is situated in the NE¼ of SW¼ of section 3, T. 46N., R. 29W., just northeast of the Cuyuna-Mille Lacs mine, being on the northeastern extension of the same ore body. The shaft, a round timber shaft, was sunk to a depth of 122 feet, of which 60 feet are in surface drift and 62 feet in slate and slaty iron carbonate rock. The ore body is south of the shaft. Some ore was mined in the summer and autumn of 1916 and mining continued during 1917.

SULTANA MINE

The Sultana mine, situated east of the Cuyuna-Mille Lacs mine in the SW¼ of SE¼ of section 3, T. 46N., R. 29W., is operated by the Sultana Mines Company. It is in the southern part of the same belt of iron-bearing formation on which are located the Cuyuna-Mille Lacs and Mangan No. 1 mines and the Hopkins shaft. As already mentioned this belt of iron-bearing formation consists typically of a finely laminated, somewhat argillaceous ferruginous chert in the vicinity of the Cuyuna-Mille Lacs ore body. To the southeast across the strike this grades into a denser, more siliceous, ferruginous chert with lamination planes less marked. The portion of the belt along the northeastward extension of which the Sultana mine is located is still farther southeast and consists predominantly of ferruginous slate with local layers of hard, siliceous, ferruginous chert or of more or less decomposed ferruginous chert.

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130 Zapffe, Carl, Matters of interest to operators regarding the Cuyuna district: *Proc. Lake Superior Min. Inst.*, vol. 20, p. 197, 1915.

The ore body at the Sultana mine is located in the trough of a northeast-southwest trending syncline[131] with a gently southeastward dipping north limb and a steeply northwestward dipping south limb. It appears to occupy a position farther south relative to the general trend of the iron-bearing belt than the Cuyuna–Mille Lacs anticline, but is more or less parallel to it. This relation seems to indicate that the Cuyuna–Mille Lacs–Sultana iron-bearing belt contains a series of more or less parallel folds whose axial planes dip uniformly to the southeast. The degree of folding varies in different parts, but in general it has been intense, so that isoclinal folds have resulted and the general dip of the beds also is to the southeast. Locally, however, near the axes of the folds northwesterly dips occur.

With the exception of a few small bands of schist, the Sultana 40-acre tract is underlain by iron-bearing rock and associated ore. The bands of schist have a northeast-southwest trend, parallel to the strike of the iron-bearing beds. One band occurs near the southeast corner of the property, north of the eastern end of the Mahnomen open pit, and the other is in the northeastern part. In the northern part of the property, where the ore body occurs, the iron-bearing rock consists mainly of laminated ferruginous slate of which there are two distinct varieties. One of them is the common dark red, medium hard, hematitic slate (or hematitic argillite) and the other a brownish or yellowish, soft, plastic, limonitic clay which becomes medium hard and compact on drying.

As far as can be seen in the present underground workings, the soft, limonitic clay occurs along the northern line of the 40-acre tract and continues some distance southward. It is everywhere finely laminated, due to interlayered light and dark colored laminae. The general strike of the bedding is somewhat north of east. The dip in parts is low to the southeast and in other parts steeply to the northwest. The dark red hematitic slate has been encountered only in a few places. It lies south of the soft limonitic clay and dips steeply to the north or northwest. Ore occurs in both varieties of ferruginous slate, but most of it is in the limonitic phase of the slate.

The main hoisting shaft was sunk directly in the portion of the ore body found in the limonitic clay about 200 feet south of the north line of the property. It is 91 feet deep, and at the bottom of it is the main hauling level. Other levels occur at depths of 65 feet and 75 feet. Cross-cuts run from the shaft northward through the ore body and southward into the dark red hematitic slate. A drift running westward

[131] Much of the information concerning the Sultana mine was kindly furnished the writers by Mr. H. H. Bradt, Mines Efficiency Co., Duluth, Minn., and Mr. E. Newton, School of Mines Experiment Station, Minneapolis, Minn.

from the main shaft to an exploration shaft in the northwest corner of the property passes through much manganiferous ferruginous slate and chert. Ferruginous chert also occurs locally interlayered with the limonitic clay.

The manganiferous iron ore at the Sultana mine consists of: (1) irregular nodules, lumps, and masses of different sizes scattered through the yellow and brown limonitic clay, and (2) veins and nodules in the dark red hematitic slate (or hematitic argillite). The ore in the limonitic clay is usually dense, amorphous, and hard, although considerably broken up. Its distribution in the clay is most irregular, appearing to be in the form of local replacements.[132] The limonitic clay matrix carries only a very small percentage of manganese except locally, where masses of it appear to have been partly replaced by manganese oxide, but not so completely as to convert it into ore. The origin of the limonitic clay is not clear. It may have been derived from the dark red hematitic slate by hydration and leaching, or the limonitic clay and hematitic slate may both be decomposed phases of ferruginous argillaceous rock which differed somewhat in character and were interbedded with each other. The ore in the hematitic slate is usually very hard and characteristically occurs along joints and fissures. Locally elongated nodules of manganiferous iron ore are found along joints where solutions following the joints have had an opportunity to penetrate the wall rocks on either side. Elsewhere thin veins of nearly pure manganese oxide occur along fissures. Such veins are bounded on both sides by bands of low-grade, reddish black, manganiferous iron ore representing a partial replacement of wall rock, and these low grade bands in turn are bordered with sharp contacts by unaltered hematitic slate.

The following is an average cargo analysis of ore from the Sultana mine:[133]

Average Cargo Analysis of Ore, Dried at 212° F., Shipped from the Sultana Mine during the Season 1916

	Fe	P	SiO_2	Mn	Al_2O_3	CaO	MgO	S	Loss by ignition
Per cent.....	39.302	.170	8.536	13.426	3.50	.75	.50	.015	10.00

HOPKINS MINE

The Hopkins property includes the N½ of SE¼ of section 3, T. 46N., R. 29W., the shaft being located in the NW¼ of SE¼ of section 3, just

[132] The ore body at the Sultana mine is a very interesting one as regards structure and origin. A detailed examination of the mine was made by Mr. Harlan H. Bradt, of Duluth, and Mr. Edmund Newton, of Minneapolis, who suggested to the writers the probability that the manganiferous iron ore of the Sultana mine originated by the replacement of an original iron-bearing rock or manganiferous iron-bearing rock by manganese oxide. Subsequently one of the writers (Harder) made an examination of this and other Cuyuna Range manganiferous iron-ore deposits and found that the replacement hypothesis was probably applicable to all of them without exception.

[133] Lake Superior Iron Ore Association, *op. cit.*, p. 11.

north of the Sultana mine. The shaft has a depth of 145 feet, about 50 feet being in glacial drift and the rest mainly in a hard, jaspery, ferruginous chert and jaspilite. No ore has been shipped from the mine, the shaft having not yet (summer, 1917) reached the ore body.

The Hopkins mine is located along the same general stratigraphic horizon on which the Cuyuna–Mille Lacs and Mangan No. 1 mines are located, and the jaspilite and hard ferruginous chert which occur in the shaft resemble similar rocks found in the Cuyuna–Mille Lacs mine. Some layers are dark, reddish black, and massive and some are finely laminated and black, dark red, or brown. Laminae of amphibole or hematite, and locally also of carbonate minerals, occur interlayered with the laminae of dark colored chert. Many jasper layers have a well-developed oolitic texture. The rock in general is hard and siliceous.

The shaft was sunk for the purpose of opening up a body of rich hematite ore, but operations were discontinued before the ore was reached. The southern part of the Hopkins property contains the northeastward continuation of the Sultana iron-ore belt.

JOAN MINE[184]

This is a new mine, operated by the Joan Mining Company, located in the SW¼ of NE¼ of section 3, T. 46N., R. 29W., from which shipment of manganiferous ore has just begun. The ore consists of a replacement by manganese oxides of cherty ferruginous material. The outlines of the ore body are irregular, and development work has not yet been carried far enough to determine the extent of the ore. It appears to be a band about 12 feet wide following a generally northerly direction.

MAHNOMEN MINE

The Mahnomen open-pit mine of the Mahnomen Mining Company is in the northern part of section 10, T. 46N., R. 29W. Most of the pit is in the NE¼ of NW¼ and the NW¼ of NE¼ of the section, but the eastern end of it projects for a short distance into the 40-acre tract of the Sultana Mines Company, as well as into the 40-acre tract of the Mangan Iron and Steel Company which comprises the NE¼ of NE¼ of section 10. The location is about half-way between the Pennington open pit and the Sultana mine.

The Mahnomen ore body occurs along the northern edge of a broad belt of iron-bearing rock which extends in a southwest-northeast direction through the northern part of sections 10 and 11, the southeastern part of section 3, and the southern part of section 12, T. 46N., R. 29W. To the southwest it can be traced with interruptions through section 9,

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[184] Ferguson, H. G.

T. 46N., R. 29W., into section 8, while to the northeast it continues through the northern part of section 1, T. 46N., R. 29W., and through section 31, T. 47N., R. 28W., toward the southeastern part of Rabbit Lake. The details of the structure of this iron-bearing belt, and its relation to the Pennington-Armour No. 1 belt on the south and the Cuyuna–Mille Lacs–Sultana belt on the north, have not been determined. The belts appear to merge into each other, although locally they are separated by schist bands. Development work is constantly progressing, and it will doubtless soon be possible to determine some definite relation between them.

The Mahnomen open pit contains both iron ore and manganiferous iron ore. The iron ore is mainly of the yellow and brown ocherous variety, of porous texture and finely laminated structure, which is not very common on the north range, but is abundant on the south range. Layers of soft red ore, however, are interlayered with the yellow ocherous ore. Little or none of the hard cherty ore common in the Thompson and Armour mines occurs in the Mahnomen open pit. The lamination of the ore is parallel to the general strike of the iron-bearing belt, being somewhat north of east. It dips steeply south for the most part, but locally is vertical, and in many places crumpling has resulted in northerly dips.

The iron ore of the Mahnomen mine is found along the north side of the pit. To the south, across the strike of the beds, it grades into dark red ferruginous slate, locally impregnated with manganiferous iron ore, which in general occupies a band running lengthwise through the center of the pit. The south side of the pit is in manganiferous iron ore associated with yellow clay and some red ferruginous slate. The ore generally occurs as veins and as large and small nodular or irregular masses imbedded in soft yellowish and brownish clayey and slaty material. Some ore is also found in the ferruginous slate layers interbedded with the yellowish and brownish clay, but is less abundant and less rich. The ferruginous slate layers are not numerous along the south wall of the pit, but increase in abundance northward on approaching the red slaty horizon separating the manganiferous iron ore from the iron ore. Here and there are thin layers of gray or variegated, finely laminated, plastic clay very similar to material occurring in the Sultana mine. As has been mentioned, the entire manganiferous bed is strikingly like that of the Sultana mine and may represent the same stratigraphic horizon.

The following grades of ore are offered by the Mahnomen Mining Company, according to the year-book of the Lake Superior Iron Ore Association.[135]

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[135] Lake Superior Iron Ore Association, *op. cit.*, p. 10.

Average Cargo Analyses of Ore Dried at 212° F. Offered by Mahnomen Mining Company for the Season 1917

	Fe	P	SiO	Mn	Al_2O_3	CaO	MgO	S	Loss by ignition
	%	%	%	%	%	%	%	%	%
Mahnomen......	57.50	.19	6.10	.80	2.67	.98	.42	.054	7.84
Mahnomen No. 1	40.00	.15	10.00	14.00	3.80	.22	.31	.015	7.84
Mahnomen No. 3	46.00	.20	7.55	8.00	3.80	.22	.31	.015	9.84
Mahnomen No. 4	51.00	.19	6.10	4.50	3.70	.75	1.24	.029	9.90

MANGAN NO. 2 MINE

The Mangan No. 2 mine of the Mangan Iron and Steel Company is located in the NE¼ of NE¼ of section 10, T. 46N., R. 29W., just north of the Armour No. 1 40-acre tract and east of the Mahnomen open pit. The southern portion of the property contains the northeastward continuation of the Pennington-Armour No. 1 ore belt, while the northern portion contains the continuation of the Mahnomen ore belt. With the exception of a few schist bands, the entire 40-acre tract is underlain by iron-bearing rock and associated ore. Both iron ore and manganiferous iron ore are present on the property.

The shaft is a round timber shaft. It was sunk during the summer and fall of 1916 to a depth of 100 feet, of which the upper 52 feet are in glacial drift.

KENNEDY MINE

The shafts and principal underground workings of the Kennedy mine, operated by Rogers-Brown Ore Company, are located on the Orelands property, lot 5, section 30, T. 47N., R. 28W. The older underground workings, however, extend also into the SE¼ of SE¼ of section 30, known as the Brown property, and into lot 6 and the SW¼ of SW¼ of section 29, T. 47N., R. 28W., known respectively as the Harrison and Ehric properties.

The mine has a number of shafts, only two of which, however, are in use. The hoisting shaft, which is a wooden drop shaft, is located near the southeastern corner of lot 5, while the timber shaft is near the center of lot 5. The main hauling level is at 262 feet, being at the bottom of the main shaft, but the 150-foot level also connects with the main shaft. Besides these there are numerous sublevels.

The mine is south of Rabbit Lake, at the northeastern end of a belt of iron-bearing rock which is known to extend southwestward a short distance beyond the southwestern end of Rabbit Lake, while to the northeast it runs under the lake. Traces of iron-bearing rock are found farther southwest along the same strike north and northwest of Menomin Lake, but their relation to the Kennedy belt is uncertain. The iron-bearing rock at the Kennedy mine, as indicated by the underground operations, occupies a belt about 1,400 feet wide including ore, ferruginous chert, hematitic schist, and green chloritic schist, all of which occur in irregular bands having a general strike of N.45°E. This broad belt of iron-bearing rock and schist is bounded both on the northwest and southeast by areas of slate and schist, which near the contact of the iron-bearing rock is generally altered to paint rock. This alteration is characteristic also of the chloritic schist included within the iron-bearing beds. The various bands are the expression on a horizontal plane of steeply inclined beds and lenses of different rocks irregularly interlayered. The general dip of the rock layers varies in different parts from 55° to 70° S.E. The hematitic schist and green chloritic schist within the iron-bearing beds are usually in the form of discontinuous lenses more or less parallel to the bedding of the iron-bearing rock. The hematitic schist usually occupies the borders of such lenses and extends for distances varying from a few feet to 50 feet or more into the interior, the unaltered centers being green chloritic schist. Some lenses are all of hematitic schist.

Judging from secondary structures in different parts of the mine, it appears that the entire body of iron-bearing rock is a straight succession. The beds appear to be on the south limb of an anticline, the older rocks occurring along the northwest side of the belt. The iron-bearing rock consists mainly of ferruginous chert with local irregular bodies of iron ore. In places the ferruginous chert is hard and massive, while elsewhere it is partly disintegrated forming wash ore. With depth, the ferruginous chert grades into cherty and argillaceous ferrous carbonate and silicate rocks such as cherty and slaty iron carbonate, amphibole-magnetite rock, and magnetitic slate. These unoxidized phases are especially abundant in the deeper workings of the western and northwestern parts of the mine. Thus above the 210 foot level there is hardly a trace of ferrous rocks, the entire iron-bearing rock being oxidized, while on the 262-foot level the unoxidized phases are abundant. Ferruginous chert, however, is still abundant on the 262-foot level, especially directly underneath the ore bodies where downward circulation has probably been facilitated by the greater porosity of the material. The metamorphosed magnetitic phases of the original iron-bearing rock are more common in the western portion of the workings, the unaltered carbonate phases occurring in the central and northern parts. In the unoxidized parts of the iron-bearing formation in the lower levels, green chloritic schist occurs as it does in the upper levels, but its alteration to red hematitic schist is much less marked. Usually the green schist is in direct contact with the ferrous rocks, and locally it is somewhat difficult to distinguish underground between the argillaceous ferrous rocks and the green schist. In many parts of the mine the schist contains small disseminated crystals of carbonate, probably calcite. In the green chloritic schist these crystals are fresh and transparent, but in the red hematitic schist they are decomposed and form scattered white spots.

There is thus a general gradation in the Kennedy mine from ore, wash ore, ferruginous chert, and hematitic schist in the upper levels, to cherty and argillaceous iron carbonate, amphibole-magnetite rock, magnetitic slate, and green chloritic schist in the lower levels. The occurrence of the different rocks is necessarily somewhat irregular, green chloritic schist being fairly common in the upper levels and ferruginous chert being abundant in the lower levels; nevertheless the general change is very significant.

There are four main ore bodies at the Kennedy mine, which, although irregular, are roughly in the form of lenses parallel to the general trend of the rock layers. They are located in general along a line transverse to the bedding of the rock and have been designated, from northwest to southeast, the (1) north lens, (2) midway lens, (3) intermediate lens, and (4) south lens. The longer axis of each body is parallel to the bedding of the enclosing rocks. Little scattered lenses of ore are found between the main lenses and along their borders. The main shaft is located between the intermediate and south lenses. At the present time only the lenses north of the shaft are producing ore, but in the past considerable ore has been mined from the south lens.

The ore from the different lenses varies somewhat as regards texture and composition. The characteristic ore of the north lens is distinctly laminated, dark reddish to bluish hematite associated with more or less brownish, siliceous, hydrated hematite and limonite. The latter becomes more abundant in the lower levels. The laminated ore is mostly amorphous, but certain layers contain much crystalline hematite. The lamination is caused by the interlayering of ore of different colors, or by the interlayering of siliceous laminae or crystalline laminae with the common amorphous ore. The ore usually breaks along lamination planes, often yielding large slabs.

The principal ore of the midway lens is a soft, yellow to brown, ocherous limonite. Locally masses and fragments of hard, brown limonite occur in it. Bedding is very indistinct and in places wanting.

The intermediate and south lenses consist largely of ordinary hard, amorphous, dark brown limonite or hydrated hematite. Bedding is fairly distinct, but instead of the straight lamination shown by the north lens ore, the bedding planes are irregular and the ore is considerably fractured and crumpled. Much of the ore is of good grade, but much of it is siliceous, grading into ferruginous chert. There seems to be little regularity in the occurrence of the richer or leaner portions.

They are irregularly intermixed. Even the boundary between the ore body and the enclosing ferruginous chert is indefinite. Where the ore lies against hematitic schist, however, as southeast of the intermediate lens, the boundary is sharp.

The differences in the character of the ore lead one to suspect that there were distinct differences in the character of the original iron-bearing formation from which the various types of ore were derived.

The following is an average cargo analysis for ore from the Kennedy mine:[136]

Average Cargo Analysis of Ore, Dried at 212° F., Shipped from the Kennedy Mine during the Season 1916

	Fe	P	SiO_2	Mn	Al_2O_3	CaO	MgO	S	Loss by ignition
Per cent.....	55.09	.241	11.867	.222	1.736	.302	.229	.034	6.09

SOUTH RANGE MINES

ADAMS MINE

The Adams mine is the easternmost mine on the south range, being situated in the SW¼ of NW¼ of section 30, T. 46N., R. 28W. It was operated by Cuyler Adams during 1914, but has since been idle.

The shaft is of concrete and has a depth of 207 feet, the upper 136.5 feet being in glacial drift and the remainder in a dark green, coarsely crystalline diabase. The pump station is at the bottom of the shaft and is excavated in the diabase. From the pump station the main level drift passes first southeastward and then turns and runs in a general southwesterly direction along the ore body. For a short distance, the main drift is in diabase beyond which it penetrates in succession a layer of amphibole magnetite rock and magnetitic slate, a layer of green schist and then another layer of magnetitic slate and amphibole-magnetite rock of considerable thickness, before it encounters the ore body. The layers have a general strike a little north of east and dip steeply south. The magnetitic slate and green schist layers through which the drift passes therefore form the foot-wall of the ore body. Immediately in contact with the ore, the magnetitic slate is oxidized and is soft and clayey, but in general it is hard, dense, and finely laminated. The green schist is soft chloritic schist, usually finely crystalline but showing distinct cleavage.

The diabase through which the shaft passes is dark green in color and consists of a ground-mass of fine-grained, dark green chlorite in which are abundant, long, narrow laths of pink feldspar. These feldspar phenocrysts range in length up to four fifths of an inch, but are rarely

136 Lake Superior Iron Ore Association, *op. cit.*, p. 10.

wider than one twentieth of an inch. They are scattered irregularly through the rock, giving it a coarse, ophitic texture. Near the bed rock surface the diabase is light brownish green and thoroughly decomposed. On nearing the contact of the magnetitic slate along the main drift, the diabase loses its porphyritic texture and becomes very fine-grained. However, it retains a fine ophitic texture. This clearly indicates that the rock is intrusive.

The band of iron-bearing rock next to the diabase is a dark-colored, locally almost black, laminated amphibole-magnetite rock. It is hard and dense and in places contains layers several inches thick consisting entirely of dark gray chert. With this are interlaminated thinner layers of black argillaceous rock rich in iron. Locally the chert layers contain abundant brownish fibrous amphibole.

The chloritic schist is distinctly green in color, some being light and some dark. It appears to be of very uniform composition, consisting almost entirely of chlorite. The schistosity varies in different parts. In some places the rock has fine cleavage lines and elsewhere it is more massive. It is fine-grained throughout.

The bed of iron-bearing rock between the chloritic schist and the ore body is of considerable thickness and consists of a mixture of magnetitic slate and amphibole-magnetite rock, the former being more abundant. In general the rocks are more finely laminated and less siliceous than the iron-bearing rock between the diabase and the chloritic schist. The typical magnetitic slate consists of interlaminated light-green, finely crystalline amphibole and black, siliceous or argillaceous, fine-grained magnetite. In some laminae amphibole and magnetite are intermixed and then form greenish black layers. The laminae vary in thickness, usually being very fine, but in places ranging up to half an inch thick. The rock cleaves readily along lamination planes. The proportion of chert or quartz present is small in the magnetitic slate, and with increasing siliceous material and coarser layering the slate grades into amphibole-magnetite rock. Thin pyrite veins occur in both the magnetitic slate and amphibole-magnetite rock.

The ore of the Adams mine varies greatly in character and appearance. Some of it is finely laminated and medium soft, while some is hard. In color it usually ranges from dark brown or red to black, the more hydrated ore being dark brown. Some of the finely laminated varieties, although of good grade, show a greenish or grayish tint, as if they contained much clay. The ore in general is of good grade.

HOBART EXPLORATION SHAFT

The exploration shaft of the Hobart Iron Company of Pickands, Mather and Company, is situated in the SW¼ of SE¼ of section 8, T.

45N., R. 29W. It is about two miles east of Woodrow and is on the same general iron-bearing belt on which the Wilcox mine at Woodrow is located. Several minor breaks, however, occur in the belt between the two localities.

The shaft has a depth of 120 feet, of which the upper 76 feet are in glacial drift. Its bottom is in magnetitic iron-bearing rock while a cross-cut 205 feet long running southward from it at the 114-foot level passes through 165 feet of mixed magnetitic iron-bearing rock and ore into green slate. The beds are very steep, having an average dip of about 80°SE. The green slate forms the hanging wall of the iron-bearing bed. The foot-wall is not shown in the workings.

The iron-bearing bed contains a number of different kinds of rock. The shaft is mainly in finely laminated, black, magnetitic slate and lean magnetic ore. Much of this material, especially near the surface, is oxidized to a brown or brownish red, siliceous limonite. Near the bottom of the shaft, in the cross-cut, is a rather massive, fine-grained, dark green chlorite rock. Some of this is dense, but some of it contains small rhombic cavities from which crystals of carbonate have evidently been leached. Southward from the chlorite rock, the cross-cut passes through different kinds of black or dark green cherty and slaty iron-bearing rocks, some bands of which average over 50 per cent in metallic iron. In some of the beds, distinct layers of dark-colored chert appear, while other beds contain much green argillaceous rock. In general, however, the material is black, finely laminated, hard, lean ore. Much of it is slightly magnetic, but much has been completely oxidized and hydrated to a dense, brownish black, siliceous limonite. A drift runs eastward from the cross-cut in this lean ore for a distance of 80 feet.

The hanging wall slate is in part argillaceous and in part chloritic. Both phases show distinct cleavage, the chloritic variety being slightly less schistose. Both are dark green.

Above the iron-bearing bed, lying on its eroded edges and overlain by glacial drift, are a few feet of dark red fragmental rock. This rock, which is penetrated by the shaft, consists largely of small pebbles or concretions of impure ferruginous and argillaceous material cemented together by siliceous iron oxide. It is believed to be analogous to the ferruginous Cretaceous rock occurring locally in the Mesabi district.

WILCOX MINE

The Wilcox mine, operated by the Paterson Construction Company, is located in the SE¼ of NW¼ of section 13, T. 45N., R. 30W., just south of the village of Woodrow, and about 6 miles north of east from Brainerd. The property embraces also several of the adjoining 40-acre tracts.

The iron-bearing belt on which the mine is situated runs across the northern half of section 13 approximately N.60°E., and dips about 65° south. It consists mainly of ore, but a little ferruginous chert and paint rock are associated with the ore, especially along the borders of the belt.

The iron-bearing rock is bounded both on the north and south by light green and gray slate. The hanging wall slate near the contact of the iron-bearing rock is decomposed, clayey, and of a bluish green color. In some places quartz veins occur in it and at others it is mixed with brown iron-stained clay. Quartz and clay are also found in the ore along the contact.

The portion of the ore bed occurring along the hanging wall usually consists of ocherous yellow limonite, soft but distinctly bedded. This grades into yellowish and brownish black, medium hard limonite, which forms the main ore body.

The foot-wall of the iron-bearing rock is a light-colored, greenish or grayish slate with marked schistosity but with little or no evidence of bedding. Near the ore body the slate becomes dark red, due to impregnation with hematite, and is known as paint rock. It is medium hard and shows cleavage similar to the green and gray slate. Locally traces of bedding are found in it, and at such points the cleavage and bedding appear to be parallel. The contact between the paint rock and ore is usually sharp.

Both the ore and wall rocks contain a soft but compact, fine-textured, decomposed rock, also termed paint rock, which has the appearance of being intrusive. It occurs in masses which, although in general parallel to the strike of the enclosing rocks, are dike-like in character. The rock itself is light green where associated with green or gray slate, and dark red where associated with dark red slate or ore. When wet it is soft and clayey, but on drying it hardens. It does not show any cleavage and has sharp contacts with the enclosing rocks.

The Wilcox shaft is situated north of the iron-bearing belt in the slate which forms the foot-wall of the ore body. It has a depth of 230 feet, of which the upper 95 feet are in glacial drift and the rest in green and gray slate. The main hauling level is at 200 feet, and the principal auxiliary level is at 125 feet. Most of the ore now mined is being taken from the 112-foot level.

The ore, as already mentioned, is in part a yellow or brown, porous, ocherous ore and in part a brownish black, medium hard ore. Both types are limonitic. The following average cargo analysis of the ore is given by the Lake Superior Iron Ore Association.[137]

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[137] Lake Superior Iron Ore Association, *op. cit.*, p. 11.

Average Cargo Analysis of Ore Dried at 212° F., Expected from the Wilcox Mine for the Season 1917

	Fe	P	SiO_2	Mn	Al_2O_3	CaO	MgO	S	Loss by ignition
Per cent.....	57.40	.25	6.00	.50	2.90	.45	.25	.03	8.70

BRAINERD-CUYUNA MINE

The Brainerd-Cuyuna mine, of the Brainerd-Cuyuna Mining Company, is situated in the southern part of the city of Brainerd in the NE¼ of SW¼ of section 36, T. 45N., R. 31W. The property includes also several of the adjoining 40-acre tracts. The shaft, which is situated northwest of the iron-bearing belt in the foot-wall slate, has a depth of 164 feet, of which the upper 90 feet are in glacial drift. A cross-cut runs southeastward from it through slate into the north ore body at the 154-foot level. At the bottom of the shaft, the slate is light green and gray, but near the ore body it is dark red due to impregnation by hematite. Southeast of the north ore body is the south ore body, separated from it by a thin bed of barren rock.

The ore from the Brainerd-Cuyuna mine is yellowish and brownish limonite typical of the south range. It occurs in two lens-like bodies, the north lens and the south lens. The north lens consists mainly of soft yellow ocherous ore, while the south lens ore is darker and somewhat manganiferous.

The iron-bearing belt has a general trend of about N.50°E. in the vicinity of Brainerd, running from the southeastern part of section 30, T. 45N., R. 30W., through the northwestern corner of section 31 into the northeastern part of section 36, T. 45N., R. 31W., from where it continues southwestward through most of section 36. The bed has a fairly steep southeasterly dip.

BARROWS MINE

The Barrows mine, from which ore was produced during 1913 and 1914 by the Virginia Ore Mining Company, of M. A. Hanna and Company, is situated in the NW¼ of SE¼ of section 10, T. 44N., R. 31W. It is the westernmost of the south range mines that has been operated.

The main hoisting shaft has a total depth of 160 feet, of which the upper 110 feet are in glacial drift and the rest in dark green, massive, finely crystalline diabase which forms the hanging wall of the ore body. The main hauling level was at 160 feet and the upper working level at 120 feet when the mine was in operation.

The ore body has a general strike of about N.40°E., while the dip varies from 65° southeast to vertical. At a few places northwesterly dips are found. The main cross-cut on the 160-foot level runs northwestward from the shaft, cutting through the hanging wall diabase and the ore body into the foot-wall rock which consists of a mixture of iron-bearing rock and ocherous clay. The contact between the ore and hanging wall diabase is very regular in strike but varies in dip between 65° and 85° southeast. The ore body has a width of about 60 feet where the main cross-cut passes through it. The contact between the ore and the foot-wall rock dips about 65° south.

The diabase is a massive, dark green, medium fine-grained rock with distinct ophitic texture. Most of it is hard and appears to be fresh, but some of it, especially that near the contact of the ore is soft and altered. The altered phase still retains the original texture to a large extent, but its color is brownish green and it appears to consist mainly of clay and ocherous hydrated iron oxide with perhaps some chlorite. Even some of the fresh looking rock has suffered considerable alteration to chlorite.

The ore as a rule is finely laminated and varies in color from yellow to dark brown or black. Yellow laminae are interlayered with dark brown laminae, the latter predominating, while in places thin argillaceous reddish or greenish layers occur. Much of the ore is ocherous and has a porous texture, but much of it, although soft, is dense and compact. Layers of dark brown or bluish brown hard ore are interbedded with the soft ore. The bedding as a rule dips steeply to the southeast, but locally northwesterly dips are found. The contact between the ore and the diabase is nearly everywhere sharp and distinct, but the contact with the foot-wall rocks is less so.

The foot-wall rock at the Barrows mine is largely of the variety usually termed paint rock by the miners. Paint rock includes many kinds of soft, argillaceous, iron-stained rocks some of which are massive and some schistose. The paint rock at the Barrows mine is similar to the massive paint rock at the Wilcox mine, and like it appears to be the decomposed phase of a fine-grained igneous rock. As it occurs in the ground it is soft, wet and clayey, but on drying it hardens and becomes dense and compact. It is fine-grained, breaks with even fracture, and varies in color from grayish green, to ocherous yellow, brown, or dark red, depending on the degree of oxidation and hydration. The first change appears to be one of oxidation from the green ferrous form to the dark red ferric form. The latter then becomes hydrated and turns brown and yellow. Most of the rock is even colored throughout, but some shows lamination due to color banding. The foot-wall paint rock occurs as a layer about 30 feet thick where penetrated by the main cross-cut. Beyond it to the northwest are interbedded iron-bearing rock and paint rock. The layering of the iron-bearing beds usually dips steeply to the southeast, but the contacts between iron-bearing rock and paint rock are more irregular.

The original nature of the paint rock is difficult to determine. Its general appearance is that of a decomposed igneous rock, yet it is not unlike a decomposed, dense, homogeneous slate. Its general parallelism in layering with the iron-bearing rock suggests that the two rocks were laid down at approximately the same time. However, the minor irregularities along the contacts indicate that there was not continuous deposition. In general it seems more probable that the paint rock is of igneous origin, representing either contemporaneous volcanic flows or later intrusive sheets.

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(See also VAN HISE, C. R., and LEITH, C. K.)

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