DEPARTMENT OF THE INTERIOR
FRANKLIN K. LANE, Secretary

UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, Director

**BULLETIN 660—A**

# NOTES ON THE GEOLOGY AND IRON ORES OF THE CUYUNA DISTRICT MINNESOTA

BY

E. C. HARDER AND A. W. JOHNSTON

Prepared in cooperation with the Minnesota Geological Survey

Contributions to economic geology, 1917, Part I
(Pages 1-26)

Published June 7, 1917



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# NOTES ON THE GEOLOGY AND IRON ORES OF THE CUYUNA DISTRICT, MINNESOTA.

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



## INTRODUCTION.

Geologic work was done in the Cuyuna iron-ore district during 1914, 1915, and 1916 by the United States Geological Survey in conjunction with the Minnesota Geological Survey. The geologic information concerning the district has been obtained almost entirely from drilling and mining operations, and these cover but a small proportion of the total area of the district. As the development work is constantly progressing and new information is becoming available, it has been deemed advisable to publish a brief preliminary report of the results so far obtained and to delay the publication of a more complete report pending the accumulation of further data. The preliminary report, of which the present paper is an abstract, is being published by the Minnesota Geological Survey; the more complete report will be published by the United States Geological Survey.

In connection with the work in the Cuyuna district it has been considered advantageous to make a study of the rock outcrops in east-central Minnesota, west, south, and east of the district. It was thought probable that the structure and geologic relations of these rocks might throw some additional light on the structure and correlation of the rocks of the Cuyuna range and on their relation to the general structure and correlation of the rocks of the Lake Superior region. Consequently many of the outcrops in Cass, Todd, Morrison, Mille Lacs, Kanabec, Aitkin, Pine, and Carlton counties have been mapped in detail and will be fully described in the final report. Brief descriptions of them are given also in the preliminary report. Much interesting information that has a bearing on the geology of the Cuyuna range has been gained in this work.

## GENERAL FEATURES OF THE CUYUNA DISTRICT.

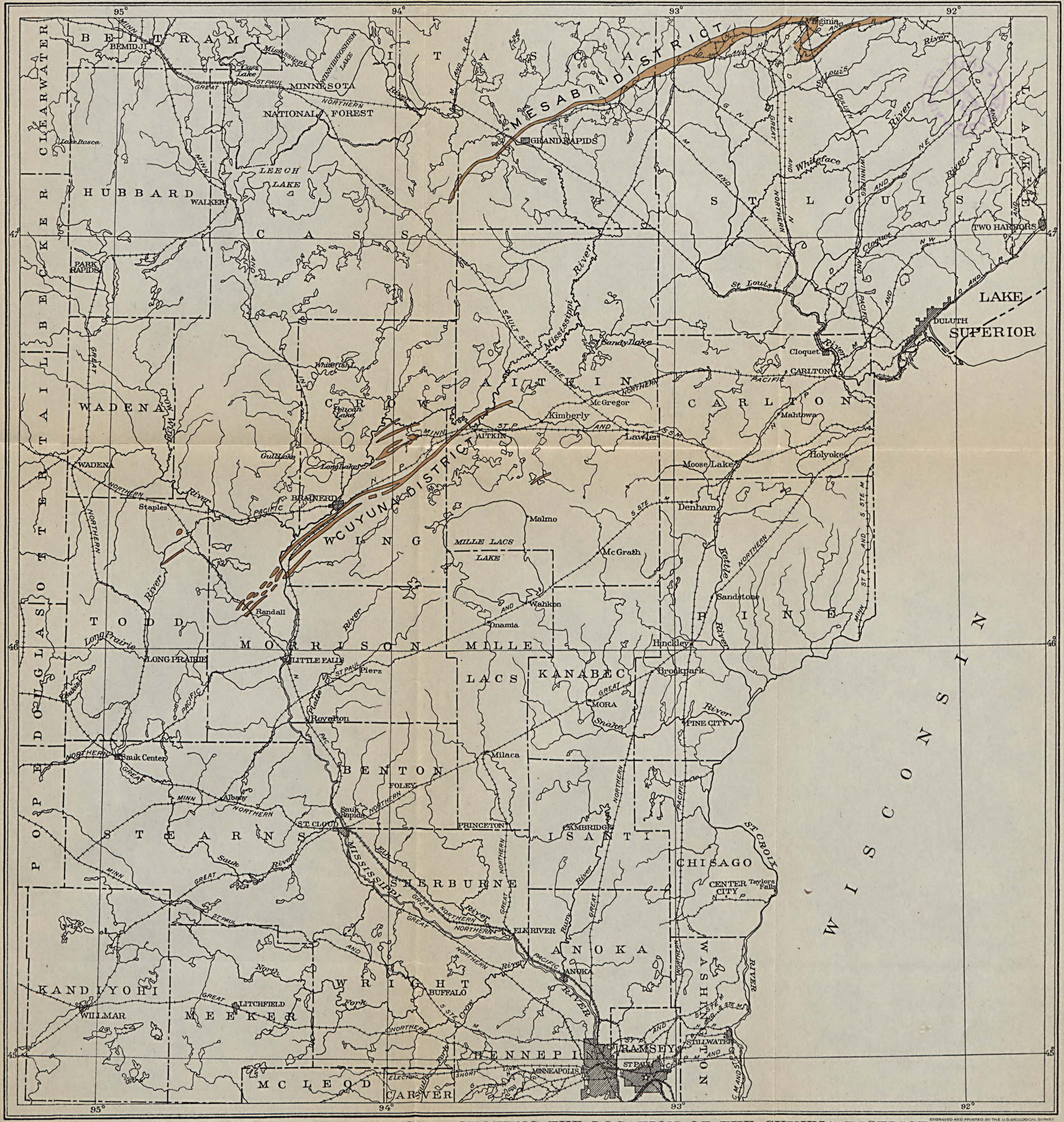
The Cuyuna iron-ore district is near the geographic center of Minnesota, about 90 miles west of Duluth and 55 miles southwest of the western part of the Mesabi district. It extends in a general northeasterly direction, approximately parallel to the Mesabi district, and has a length of about 65 miles. In width it ranges from less than a mile to about 10 miles. Most of the district is in Crow Wing County, but parts of it lie to the northeast in Aitkin County and to the southwest in Morrison County. (See Pl. I.)

The Northern Pacific Railway branch line running from Duluth westward to Staples, to connect with the main line from the Twin Cities to the Pacific coast, passes practically through the entire length of the district, and the main line passes over the southwestern part, near Randall, between Little Falls and Staples. The Cuyuna range branch of the Minneapolis, St. Paul & Sault Ste. Marie Railway connects the eastern and central parts of the district with Duluth and Superior.

The principal part of the Cuyuna iron-bearing belt lies southeast of Mississippi River, to which it is approximately parallel. In the southwestern part of the district, however, the river turns southward and crosses the iron-bearing belt, which continues southwestward beyond it. In the northeastern part of the district, near Aitkin, the iron-bearing belt crosses over to the north side of the river, but it recrosses to the south side within a short distance and continues northeastward to Rice River.

The Cuyuna district, in contrast with some of the other Lake Superior iron-ore districts, does not show any marked topographic relief. It is mainly a region of low, irregular morainic hills interspersed with lakes and extensive swamps and marshes. Outwash plains occupy parts of the district and extend southward from it. Much of the district is under cultivation, especially in the southern part, but in many places the soil is sandy and is covered with a thick second growth of jack pine, poplar, aspen, and locally Norway pine. Much of the rich land also is still uncultivated and supports forests of hardwood. The marshes and swamps contain spruce and tamarack.

The productive part of the Cuyuna district is commonly divided into two ranges—the north range, including the part lying north of the Northern Pacific Railway, and the south range, including the belt lying south of the railway. The north range has a length of about 10 miles and a maximum width of 5 miles. This relatively small area includes most of the productive mines of the district, numbering about 18. The south range is narrow, but it covers a much greater area than the north range and its extensions continue for many miles to the northeast into Aitkin County and to the southwest into Morrison County. One mine on the south range is a steady producer, and four or five others have produced ore intermittently or are in the development stage. The north range is separated from the south range by a belt from 2 to 3 miles wide, underlain mainly by




MAP OF EAST-CENTRAL MINNESOTA SHOWING THE LOCATION OF THE CUYUNA DISTRICT AND A PART OF THE MESABI DISTRICT

Scale $\frac{1}{1,000,000}$

10 0 10 20 30 Miles

1917

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schist and slate. No iron-bearing rocks of economic importance have been found in this belt, although drilling has been done in it at a number of localities.

The principal towns in the Cuyuna district, named in order from northeast to southwest, are Aitkin, Cuyuna, Deerwood, Crosby, Ironton, Manganese, Iron Mountain, Riverton, Woodrow, Brainerd, and Barrows. All these towns except Aitkin, Deerwood, and Brainerd have been built since the discovery of iron ore in the district. Brainerd, the largest town in the district, was established more than 50 years ago and was at one time the center of the great Minnesota lumber industry. It is now surrounded by a farming community and has a population of about 8,000. Aitkin, the next largest town, has a population of about 2,000. Both Aitkin and Brainerd are on Mississippi River.

The discovery of iron ore in the Cuyuna district was entirely due to the existence of abnormal magnetic attractions in the region. The occurrence of magnetic variations in this district had been known for many years and certain well-defined areas in which they existed had been located, but the iron-bearing formation was not definitely discovered until 1904. In that year iron-bearing rocks with some associated ore were encountered in drilling operations south of Deerwood, and in 1905 ore was also found north of Deerwood, near Rabbit Lake. After these discoveries exploration and drilling were carried on with great vigor throughout the region in which magnetic variations were known to occur, but it was some years before ore in commercial quantity was found. The first ore was shipped from the district in May, 1911, from the Kennedy mine, near Rabbit Lake, at the east end of the north range.

The finding of iron ore in the Cuyuna district soon started speculation concerning a possible connecting belt of iron-bearing rock between this district and the west end of the Mesabi district. Considerable exploration work has been done in the region north and northwest of Aitkin and southwest of Grand Rapids, with the view of finding such a connecting belt. Iron-bearing rocks have been found at a number of places and locally concentrations of ore occur, but these occurrences have not yet been definitely shown to be connected either with the Mesabi district or with the Cuyuna district.

## GENERAL GEOLOGY OF MINNESOTA.

The pre-Cambrian complex of the Lake Superior region, consisting of metamorphosed sedimentary and igneous rocks of various kinds, extends westward and southwestward from Lake Superior across Minnesota and forms the basement rock throughout the State. In some places, as in the northeastern part of the State and locally in the southwestern part, the metamorphosed pre-Cambrian rocks are overlain only by a comparatively thin mantle of glacial till; elsewhere they are overlain by flat-lying sediments which in turn are covered by glacial till. Thus in the southeastern part of the State there are beds of Paleozoic and older sediments which are of considerable thickness and extent, and throughout most of the western part of the State there are thin but widespread beds of slightly consolidated Cretaceous rocks.

The sedimentary rocks directly overlying the pre-Cambrian complex in the southeastern part of Minnesota consist of a thick series of red sandstone and shale with associated volcanic clastic rocks,[1] known as the red clastic series and supposed to belong to the red sandstone series of the Keweenawan. They are separated by an unconformity from the underlying older metamorphosed rocks and are similar in lithology and stratigraphic position to upper Keweenawan rocks that are abundantly exposed along the south shore of Lake Superior.[2] Their approximate maximum thickness in southern Minnesota is about 2,250 feet. Fossils have not been found in them.

The Paleozoic rocks, which apparently overlie the red clastic series conformably, range in age from Cambrian to Devonian and consist of interlayered sandstone, limestone, and shale. They are comparatively thin, the entire series, where all the formations are present, having an approximate maximum thickness of less than 2,000 feet.[3]

The Cretaceous rocks that lie on the pre-Cambrian complex throughout most of the western part of the State belong to the Benton and Dakota formations. They consist chiefly of slightly consolidated shale and sandstone, and reach a total maximum thickness of about 500 feet. Locally in the southwestern part of the State they are absent and pre-Cambrian rocks form the bedrock. Outliers of Cretaceous rocks have been found at many places in the eastern part of the State also. Those that occur in the neighborhood of the iron-bearing areas are usually highly ferruginous and in places consist of conglomeratic iron ore.

The pre-Cambrian metamorphosed and intrusive rocks which underlie the sedimentary beds and glacial deposits throughout the State consist of granite and gneiss with which are associated basic igneous rocks of various types and extensive bodies of metamorphosed sediments, such as quartzite, slate, limestone, and many varieties of schist.

In northern Minnesota metamorphosed sediments occur with associated intrusive and extrusive rocks in several unconformable

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[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.

[2] Thwaites, E. T., Sandstones of the Wisconsin coast of Lake Superior: Wisconsin Geol. and Nat. Hist. Survey Bull. 25, 1912.

Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, pp. 380 et seq., 1911.

[3] Hall, C. W., Meinzer, O. E., and Fuller, M. L., op. cit., pp. 37–49.

series, ranging in age from Archean to upper Huronian. The Archean rocks are mainly greenstones and green schists classified as Keewatin, into which are intruded masses of granite, syenite, and porphyry classified as Laurentian. The greenstones and green schists are probably in the main altered basic volcanic rocks, both massive and fragmental. Some of them, however, may be of plutonic origin. They have been metamorphosed to such an extent that at present they consist largely of secondary minerals such as chlorite and amphibole, associated with altered feldspar. Where deformation has accompanied metamorphism schistosity is abundantly developed in them. Much of the rock, however, remains in the massive form. Locally, as in the Vermilion iron-ore district, lenses of iron-bearing rock occur in the greenstone; in the Lake of the Woods region and elsewhere slate and graywacke and locally thin beds of limestone are interlayered with schistose and banded greenstone.

Intrusive granite and syenite of the Laurentian are widely distributed through northern Minnesota, occurring as batholiths, bosses, and dikes in the greenstones and related rocks. Much of the granite and syenite has suffered metamorphism and deformation, so that gneissoid structure is developed in it. Over large areas in this part of the State gneisses are the dominant rocks.

The Huronian rocks of northern Minnesota are of two kinds[1]—an earlier intensely metamorphosed series of slate, graywacke, and conglomerate, usually called lower-middle Huronian, and an upper series, the upper Huronian (Animikie group), consisting of quartzite, iron-bearing rock and slate, which locally, as in the Mesabi district, has suffered but little deformation but which elsewhere, as in the Cuyuna district, has been considerably folded. The lower-middle Huronian metamorphosed sediments are as a rule infolded into the older rocks and occur in irregular areas of somewhat local distribution. The upper Huronian, on the other hand, covers a large part of northeastern and east-central Minnesota and is usually rather regular in its occurrence.

Extensive masses of granite of lower-middle Huronian age are intruded into the lower-middle Huronian metamorphosed sediments as well as into the older Archean rocks. This granite forms the Giants Range, north of the Mesabi iron-ore district. It is difficult to separate from the older Laurentian granite, being distinguishable only by its intrusive relation to lower-middle Huronian rocks.

Besides the Huronian and Archean rocks there are in northeastern and eastern Minnesota several large areas of Keweenawan igneous and sedimentary rocks. Keweenawan rocks consisting of intrusive gabbro and diabase associated with volcanic rocks and some sediments extend along the north shore of Lake Superior from Duluth northeastward

[1] Van Hise, C. R., and Leith, C. K., op. cit., pp. 118-220.

into Canada. These rocks are younger than the pre-Cambrian metamorphosed rocks and overlie them unconformably. The volcanic rocks are mainly diabase amygdaloids, but felsite and quartz porphyrite occur also. The gabbro forms a large laccolith intruded at or near the base of the lavas, and the smaller sills and sheets of diabase are found intrusive into the volcanic rocks at several horizons. The gabbro, diabase, and volcanic rocks are intruded by small dikes and masses of acidic "red rock." Another body of Keweenawan rocks, mainly igneous, occurs along the upper course of St. Croix River. It is composed of flows of diabase and diabase amygdaloid with some local interbedded conglomerate. At several localities in eastern and central Minnesota, as at the east end of the Mesabi range, granitic intrusives of probable lower Keweenawan age cut Archean and Huronian rocks.

Sedimentary rocks of supposed Keweenawan age occur in an area extending southwestward from the west end of Lake Superior. Presumably they continue southward into the red clastic series already mentioned. They consist of pink and red sandstone and arkose and are probably for the most part later than the igneous rocks, though their exact relation to those rocks is not yet known.

In the southern part of the State the Archean is represented mainly by granite and gneiss, which are abundantly exposed along Minnesota River. The Huronian is represented principally by the Sioux quartzite, which underlies large areas in southwestern Minnesota, but certain crystalline schists that have been encountered locally in well drilling are also believed to belong to the Huronian.[1]

With the exception of a small strip of territory in the southeastern part of the State that belongs to the Driftless Area, practically all of Minnesota was at one time covered by continental glaciers. The glaciation resulted in the formation of a mantle of unconsolidated material of varying thickness which except for isolated rock outcrops overlies the bedrock throughout most of the State. The mantle of glacial material commonly consists of gravel, clay, and sand, but in the northwest corner of the State there are extensive lake beds, deposited in glacial Lake Agassiz. The thickness of the glacial drift is variable both on account of the present surface topography and on account of the irregularity of the bedrock surface. The maximum thickness is probably between 500 and 600 feet.

## GEOLOGY OF THE CUYUNA DISTRICT.

### CLASSIFICATION OF THE ROCKS.

The bedrock in the Cuyuna district and adjacent region is largely concealed by a mantle of glacial drift that varies in thickness from 15 feet to about 400 feet. No rock exposures are known in Crow

[1] Hall, C. W., Meinzer, O. E., and Fuller, M. L., op. cit., p. 49.

Wing County, in which most of the Cuyuna district is situated. In parts of the district that lie outside of Crow Wing County, however, there are a few outcrops of bedrock. Thus near the northeast end of the district, in the center of Aitkin County, small outcrops of quartzite, diabase, and diorite occur in the vicinity of Dam Lake and Long Lake, and near the southwest end of the district, in the western part of Morrison County, green chloritic schist crops out in several small areas in the vicinity of Randall.

In the region lying west, south, and east of the Cuyuna district the glacial drift is less continuous and outcrops of bedrock are more common. To the west granite crops out in Cass County northeast of Staples and in Todd County northeast of Browerville, and outcrops of gabbro occur in Todd County near Philbrook. South of the Cuyuna district granite crops out in the region east and northeast of Little Falls, in Morrison County, and south and east of Mille Lacs Lake, in Mille Lacs and Kanabec counties, and slate, garnetiferous and staurolitic mica schist, and associated basic igneous rocks occur along Mississippi River at Little Falls and farther south. Extensive outcrops of granite are also found in the St. Cloud region, in Stearns, Benton, and Sherburne counties.

East and southeast of the Cuyuna district acidic gneiss is exposed in the vicinity of McGrath and Denham, in Aitkin and Pine counties, and extensive outcrops of metamorphosed sediments, such as slate, graywacke, and various schists, and locally quartzite and crystalline limestone occur near Denham, Moose Lake, Carlton, and Cloquet, in Pine and Carlton counties. Semibasic igneous rocks, mainly diorite, some of which have suffered considerable metamorphism, are found near Denham and west of Moose Lake.

North of the Cuyuna district is a great low-lying region that is utterly devoid of rock outcrops, the nearest bedrock exposures in this direction being those of the Mesabi district.

The rocks of the Cuyuna district and adjacent region, as revealed by drilling and mining operations, belong principally to the older metamorphosed pre-Cambrian series, although isolated patches of Cretaceous sediments and Keweenawan volcanic and intrusive rocks occur here and there. The edge of the area of Paleozoic and Keweenawan sediments which occupies the southeastern and eastern parts of the State lies about 45 miles southeast of the center of the district, and the main Cretaceous area of western Minnesota begins about 50 or 60 miles to the west.

The rocks that have been found up to the present time in the district can all be grouped under three classes—(1) sedimentary and igneous metamorphosed rocks interlayered with each other in beds and lenses and usually having steep dips 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 rocks of the other two classes.

The age of the various rocks is not definitely known. Because of their metamorphosed and folded state, those of the first class have usually been designated Huronian, and on account of their general relation to the rocks of the Mesabi district and the occurrence of iron-bearing rock in them, it has generally been supposed that they are of the same age as the iron-bearing rocks of the Mesabi district—that is, upper Huronian.[1]

In accordance with this view all the slates, schists, and other metamorphosed rocks in east-central Minnesota have been grouped under the term Virginia slate, which was originally applied to the slate overlying the iron-bearing Biwabik formation in the Mesabi district. This correlation seems reasonable, to judge from the present knowledge of the structure, but as detailed knowledge of the region increases it may be found to be erroneous. It is possible that the metamorphosed rocks of the Cuyuna district and the surrounding region belong at either a higher or a lower horizon than the upper Huronian rocks of the Mesabi district, or it may be that they comprise rocks of several different geologic epochs. It is undoubtedly true that in most areas of pre-Cambrian rocks in the northern United States and Canada, where detailed work has been possible, the occurrence and distribution of the rocks have been shown to be very much more complex than they are at present supposed to be in east-central Minnesota.

Several attempts have recently been made to revise the generally accepted correlation of the pre-Cambrian rocks of the Lake Superior region established by Van Hise and Leith and their coworkers. Although excellent detailed work has undoubtedly been done in the last few years and much valuable information has been obtained, some of which is entirely new, it seems to the writers that it is premature to change radically a correlation based on years of careful field work. The attempted revision of the correlation is largely based on the finding by Allen and Barrett[2] of a series of metamorphosed sediments unconformably overlying the upper Huronian rocks in the eastern part of the Gogebic district in northern Michigan. This series Allen and Barrett propose to classify as upper Huronian, and the existing upper Huronian is to be placed in the middle Huronian.

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[1] Van Hise, C. R., and Leith, C. K., op. cit., pp. 211 et seq.

[2] Allen, R. C., and Barrett, L. P., A revision of the sequence and structure of the pre-Keweenawan formations of the eastern Gogebic iron range of Michigan: Jour. Geology, vol. 23, pp. 689–705, 1915. Allen, R. C., A revision of the correlation of the Huronian group of Michigan and the Lake Superior region: Idem, pp. 705–724.

Using this revised classification of the rocks of the Penokee-Gogebic district as a basis, Allen has reclassified the rocks in most of the other Lake Superior iron-ore districts in a similar manner, with the result that practically all the productive iron-bearing rocks of the Lake Superior region, except those of the Vermilion district, are placed in the middle Huronian. In the Mesabi district the Pokegama quartzite, the iron-bearing Biwabik formation, and the Virginia slate have all been reclassified by Allen as middle Huronian; in the Cuyuna district also the older metamorphosed rocks have been placed in the middle Huronian; and the lower-middle Huronian rocks of the Mesabi and Vermilion districts have been designated lower Huronian.

There is no additional evidence in Minnesota for this revision in the correlation of the rocks of the Lake Superior region, the entire reclassification being based on the finding of the so-called Copps formation stratigraphically above the upper Huronian in the eastern part of the Gogebic district, supported by certain minor evidence afforded by the lithology and distribution of the rocks in some of the other iron ranges of northern Michigan. The writers believe that so important a change in correlation over a wide area as Allen and Barrett suggest should perhaps have a sounder basis.

Detailed work of exceptional value on the lithology and correlation of the iron-bearing Biwabik formation in the Mesabi district has been done during the last few years by Wolff.[1] He has found at certain horizons slaty and conglomeratic zones, some of which have a remarkably wide distribution, running from one end of the district to the other. In general it appears from his work that the iron-bearing formation shows a definite stratigraphic succession that is fairly uniform throughout the district. Besides working on the iron-bearing rocks, Wolff has also made observations on the contact of the Biwabik formation and the overlying Virginia slate. He finds that a limestone layer several feet thick occurs along this contact wherever it has been observed and that at a few localities conglomeratic material is found in the upper part of this limestone layer. Taking the latter fact in conjunction with the phenomenon of the variation in thickness of the Biwabik formation from place to place, as well as the radical change in the character of the sedimentation from iron-bearing sediments to argillaceous clastic sediments, Wolff suggests that there may have been an erosion interval between the deposition of the Biwabik formation and that of the overlying Virginia slate. He hints that such a time break may be of some significance in a revision of the correlation of the rocks of the Lake Superior district but wisely refrains from drawing any sweeping conclusions.

[1] Wolff, J. F., Recent geologic developments on the Mesabi iron range, Minn.: Am. Inst. Min. Eng. Bull., December, 1916, pp. 1763–1787.

These investigations serve to indicate that by no means the last word has been said in regard to the geology and classification of the rocks of the Lake Superior region. As detailed work continues to be done in the less well-known districts and the stock of information increases, doubtless changes will be made in the correlation of different formations. For the present, however, it seems best to adhere to the generally accepted classification of Van Hise and Leith.

The old metamorphosed rocks of the Cuyuna district, grouped under the term Virginia slate, are principally schists of various kinds associated with beds and lenses of the Deerwood iron-bearing member. Locally quartzite has been found also, and at one or two places limestone is reported to occur. The schists are principally quartzose and argillaceous sericitic schists, probably of sedimentary origin. With these is associated green chloritic schist that appears to be of igneous origin, although the original texture has almost entirely disappeared. Metamorphosed igneous rocks, in which 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 the second class mentioned above, the igneous rocks that are intrusive into the metamorphosed rocks and have themselves not 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 rock and in many places causing further metamorphism along the contacts. All rocks of this class so far found in the district are basic or semibasic, such as diabase and diorite, and are usually medium fine grained or porphyritic. Many of them are massive and fresh and have preserved their igneous texture perfectly, but others are considerably altered. In general they are somewhat difficult to distinguish from the nonschistose phases of the metamorphosed igneous rocks associated with the older schists and iron-bearing formation.

Outside of the district, acidic rocks, such as granite and syenite, as well as basic rocks, are intrusive into the older metamorphic rocks. Some of the acidic intrusives occurring south and southeast of the Cuyuna district, near Little Falls and in the Mille Lacs Lake region, are associated with schists into which they appear to be intruded. These schists are supposed to be of the same age as those of the Cuyuna district and are intruded also by basic and semibasic rocks like those in the Cuyuna district. The acidic igneous rock in this region has therefore all been classed as Keweenawan by Van Hise and Leith, although much of it is not associated with schist and presents coarse gneissoid phases that are much more characteristic of the Archean granite than of the Keweenawan acidic rocks. Much of this granite and gneiss which is not definitely known to be intruded into schist may be older than Keweenawan and may belong to the Laurentian or lower-middle Huronian intrusions, but the separation is difficult to make.

The rocks of the third class occur only locally and in minor quantity. They are of two types—(1) horizontal flows of igneous rocks,[1] 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, which have been correlated with similar patches of sediments of Cretaceous age in the western part of the Mesabi district. 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, but no outcrops of them have been found in the central part of the State. Cretaceous rocks probably to be assigned to the second type crop out along Mississippi River south of Little Falls and elsewhere in central Minnesota. Most of these rocks are clayey or slightly calcareous, but a few are conglomeratic and ferruginous and resemble the rocks found in drilling operations locally in the Cuyuna district.

## STRUCTURE OF THE ROCKS.

The rocks of the Lake Superior region have been subjected to folding at several periods in their history. So far as known, however, the forces causing the deformation in the different periods have been applied in approximately the same direction—that is, from the northwest and southeast—so that the results, as apparent in the rock structure, are superimposed upon one another. 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.

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 been successively more severely deformed, the upper Huronian having many minor folds within the main synclinorium and the lower middle Huronian and Archean being in places so intensely deformed that it is almost impossible to decipher their relation to the general structure of the region. The general strike of the rock bedding, cleavage, and schistosity throughout the Lake Superior region varies between east and northeast. It is this similarity of

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

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 northeastward-trending anticlines and synclines.[1] The dip of the limbs of the folds is usually vertical or very steep, and may be either to the southeast or the northwest, though the southeasterly dip predominates. In many places 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 southeasterly dips in the district in both the north and the 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 southwest end of the north range the pitch of the folds is in general to the northeast, but along the central part of the north range it is to the southwest. In many places the pitch is so low that the crests of the anticlines are practically horizontal for miles, as is the case locally in the south range. Because of this low pitch of the folds the rock layers appear on the erosion surface as approximately parallel northeastward-trending bands. In some places, 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 the insufficient drilling and underground development it has not yet been possible to work out the details of the structure. Drag folds and other secondary structural features 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 features, 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 the rocks in east-central Minnesota indicate that the Cuyuna district is situated near the axis of the southwestern extension of the Lake Superior synclinorium. The close folding which exists in the district would thus be naturally accounted for, as well as the very gentle folding and relatively slight metamorphism of the rocks along the Mesabi range, which are supposed to be on the north limb of the synclinorium. The south limb is as yet unknown. The extensive masses of granitic rock in the Little Falls, St. Cloud, and Mille Lacs Lake regions may be south

[1] Van Hise, C. R., and Leith, C. K., op. cit., pp. 620 et seq. Zapffe, Carl, The Cuyuna iron-ore district of Minnesota: Am. Assoc. Adv. Sci. Proc., December meeting 1910. See also Brainerd Tribune Suppl., July 1, 1910.

of the synclinorium or, as believed by Zapffe,[1] they may be intrusions within it. It is known that some of these granites intrude metamorphosed sediments, but the age of the sediments is not definitely established and they may be older than upper Huronian. If the granite is lower-middle Huronian or Laurentian 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 the Mille Lacs Lake region toward Kettle River. On the other hand, if the granite is of later age than the metamorphosed sediments of the Cuyuna district the south limb of the synclinorium may be far to the southeast.

## LITHOLOGY OF THE ROCKS.

### OLDER METAMORPHOSED ROCKS.

#### GENERAL CHARACTER.

The principal constituents of 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 also occurs in many places, and limestone has been encountered here and there. These rocks are irregularly interlayered with one another. They all have a general northeasterly strike and as a rule dip steeply to the southeast or less commonly to the northwest. On the horizontal surface the different rock layers appear as discontinuous bands of varying width, all more or less 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 horizon markers of any considerable extent are the layers of iron-bearing rock. These, however, are unsatisfactory, for a number of distinct bands of iron-bearing rock run through different parts of the district and it is not yet known whether they are the surface expression of a single layer that 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, a single band of iron-bearing rock may show distinct and even abrupt changes in the nature of its constituent materials, both along and across the strike. Thus certain bands may show

[1] Zapffe, Carl, op. cit.

highly manganiferous ore along one side and ferruginous chert or hematite with only a trace of manganese along the other side. Other bands may consist in one locality almost entirely of red or brown hematite and hematitic or limonitic chert and in another locality 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 perhaps the different bands of iron-bearing rock in 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 belief is based on the fact that the ore and iron-bearing rock in the two ranges present rather distinct lithologic differences. The ore of the south range is usually black or yellow and is associated largely with slaty argillaceous rock, much of which is magnetitic. Ferruginous chert does not occur as abundantly as on the north range, and manganese oxide is present in small amounts only in a few places. The ores of the north range, on the other hand, are usually brown, red, or blue and are abundantly associated with ferruginous chert and only locally with magnetitic slate. In places they contain much manganese oxide, 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 iron-bearing rock of the north range is associated with 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 iron-bearing rocks of the north range and south range are sufficient to justify their assignment to separate horizons.

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 characteristic of these associated rocks, occurs in lenses which, although of considerable width, are rarely very long. Such lenses occur at several horizons, commonly being interlayered within the iron-bearing formation itself.

Carbonaceous slate is frequently used as a local horizon marker, as it has often been found to occur along the boundary of the 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 only in 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 bound to be largely speculative.

### IRON-BEARING FORMATION AND IRON ORE.

The iron-bearing formation of the Cuyuna district presents a variety of lithologic types. Among the more common rocks composing it are hematitic and limonitic chert and slate, cherty and slaty iron carbonate, siliceous magnetitic slate, amphibole-magnetite rock, jaspilite, dark-blue, 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 very abundant in the north range, where they compose the principal part of the iron-bearing formation. They usually consist of interlaminated white, pink, or gray chert and hematite or limonite, the chert and iron oxide occurring in alternate layers. The hematite and limonite may be fairly pure or very siliceous. In many places the iron oxide present is rather of the nature of 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 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.

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 of the iron-bearing formation is a more or less regularly banded ferruginous chert believed by Van Hise and Leith [1]

[1] Van Hise, C. R., and Leith, C. K., op. cit., pp. 499–561.

to have been derived by alteration from an original cherty iron-carbonate rock. In the Mesabi district, however, the ferruginous chert is largely of the type known as taconite, a rather massive-bedded cherty rock irregularly speckled with iron oxide which is supposed to have resulted from the oxidation of the ferrous silicate rock greenalite. No taconite or greenalite has been found in the Cuyuna district. It is therefore generally supposed that here, as in most of the other Lake Superior iron-ore districts, the original rock from which the present hematitic and limonitic chert and iron ore have in large part been formed is a banded cherty iron carbonate rock.

An alternative to the belief of the older geologists that most of the iron-bearing rock of the Lake Superior region was originally deposited as ferrous carbonate or silicate is the view that much of the iron was deposited in the ferric form originally. This view supposes the iron to have been deposited largely as hydrated ferric oxide with colloidal silica and locally with clay. In places, perhaps, thin beds of more or less pure ferric oxide were formed. After the deposition the presence of carbonaceous matter here and there probably caused a partial deoxidation of the ferric oxide and resulted in the formation of local masses of ferrous rock such as iron carbonate or iron silicate. Upon metamorphism these materials were consolidated and in part dehydrated, forming ferruginous chert and slate with local lenses of ore and some bodies of ferrous rock. After the metamorphism had taken place the rocks were subjected to weathering and erosion, which resulted in the formation of additional iron ore by the leaching of silica from the ferruginous chert, as well as in the oxidation of much of the ferrous rock originally present. The main difference between this view and the older one is in the amount of iron originally deposited as ferric oxide, the older view being that very little iron was deposited in the ferric form, the deposition of practically the entire formation occurring under reducing conditions. Thus, according to the older view, the present ferruginous chert, ferruginous slate, and ore have resulted almost entirely from the weathering and leaching by meteoric waters of original rocks containing ferrous carbonate or ferrous silicate.

The evidence afforded by the Cuyuna district on this question is largely in favor of the older view. In the exploratory drill work cherty iron carbonate and associated rocks were encountered below a surface capping of ferruginous chert and iron ore in many parts of the district, and in some of the more recent mining operations such rocks have been encountered in the lower levels in direct continuity along the bedding with the ore, ferruginous chert, and ferruginous slate of the upper levels. In general the gradation from ore at the surface through lean ferruginous chert into ferrous rock below is perhaps more typically illustrated in parts of the

Cuyuna district than in any of the other Lake Superior iron-ore districts.

The cherty iron carbonate of the Cuyuna district, however, differs from the typical cherty iron carbonate rock of the other districts. A number of different varieties occur, some cherty, some slaty, and others highly magnetitic. Most of them contain varying amounts of chert, siderite, and amphibole. With these may be associated argillaceous material, and some varieties contain an abundance of magnetite which is either disseminated through or interlaminated with the other constituents. The cherty iron carbonate generally shows distinct banding and in places fine lamination, the latter being especially characteristic of the slaty varieties, but certain massive argillaceous varieties occur also.

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 reddish, brownish, or yellowish, and present a thinly laminated appearance. Red hematitic slate is by far the most abundant. It is dark red, soft, and in general finely and regularly laminated. Siliceous slates that 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 formation 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 iron-ore districts, especially the Mesabi.

The ferruginous slates differ from the hematitic schist described on page 23 in that they are of sedimentary origin, having been deposited with the ferruginous cherts and 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 formation.

Cherty and slaty or, more properly, argillaceous iron carbonate rocks, as already mentioned, are believed to be the original rocks from which the iron-bearing formation of the Cuyuna range in its various phases is largely derived. Such rocks have been reported from many parts of the district, having been found in the deep drilling. They are of several different types, with gradational phases between. They vary in composition and texture and range from light to dark green or gray in color. Usually they consist of chert or argillaceous material interlayered or intermixed 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 iron carbonate rocks is largely due to interlayering of different constituents. The laminae of chert and siderite are usually light gray or greenish; those of argillaceous material and amphibole are darker and with increasing magnetite become almost black. Some varieties of the iron carbonate rock are light gray and consist almost entirely of chert and siderite, which may be intermixed or may be more or less segregated into layers, producing banding. Grains of magnetite occur along lamination planes, making the banding more marked. Other kinds of iron carbonate rock contain considerable amphibole and show interbanding of light-gray and somewhat darker green layers. Still others 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 rocks are usually very fine grained and show no marked banding. All these varieties of iron carbonate rock occur interbedded and grade into one another.

The siliceous magnetitic slate and amphibole-magnetite rock are portions of the original iron-bearing formation that have suffered metamorphic alteration and recrystallization. They are banded or laminated rocks, usually very dark colored with a tinge of green, and consist mainly of amphibole with magnetite and some chert or quartz. The fine-grained, finely laminated kinds are known as magnetitic slate and probably contain considerable argillaceous material; the coarser grained and coarsely layered kinds are known as amphibole-magnetite rock. Like ferruginous slate, magnetitic slate rarely, if ever, shows slaty cleavage and might, perhaps, be more properly designated magnetitic argillite. The banding 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; other bands, as those of amphibole, may be medium coarse grained. The segregation of minerals in the amphibole-magnetite rocks and magnetitic slates is nowhere perfect. Small amounts of magnetite are usually disseminated through the quartz and amphibole layers, and quartz and amphibole are intermixed with magnetite along the borders of magnetite bands.

There is considerable diversity in the composition of these rocks. In some places they consist largely of magnetite and amphibole, in others they 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. Such irregularities, however, are much less marked than they are in the ferruginous cherts.

The amphibole-magnetite rocks and magnetitic slate of the Cuyuna district differ from the typical amphibole-magnetite rock of other Lake Superior iron-ore districts, such as the Mesabi, Gogebic, and Marquette, in that they are finer grained, more perfectly laminated, and in general contain less quartz and more ferromagnesian minerals. The typical amphibole-magnetite rock of the Cuyuna district consists of alternating fine bands of magnetite and amphibole. That occurring in the eastern part of the Mesabi district, on the other hand, consists of irregular layers of fine-grained magnetite and coarse-grained quartz and amphibole. In the Cuyuna district quartzose and cherty varieties of the amphibole-magnetite rock and magnetitic slate are also common and are characteristic, more especially, of the less highly magnetitic rock.

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 in the southern part of the main 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 bright-red rock is formed. This is the more common variety, the crystalline, specular form that results from pronounced recrystallization being of local occurrence. In places in the Cuyuna district there is a very hard 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 hard, dense form of the ferruginous chert.

The iron ores of the Cuyuna district are inclosed in other iron-bearing rocks. The ore bodies are as a rule roughly tabular in shape, with the longer axes parallel to the bedding of the inclosing rocks. As the beds of rock generally dip steeply, the ore bodies are shown at the surface as bands that extend for considerable distances along the strike of the beds. They range in width to several hundred feet and are usually very long, some of the known ore bodies being more than a mile in length. Some of them are comparatively shallow, extending perhaps to a depth of 200 or 300 feet, where they give way to ferruginous chert, amphibole-magnetite rock, or unaltered iron-bearing rock. Others extend to greater depths, either continuing indirectly 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 are still very incomplete. The deepest mining operations at present extend to a depth of about

280 feet below the bedrock surface, 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 reaching a depth greater than 700 feet. Ore has been encountered in some of the deeper holes, however, and it is believed that certain ore bodies may reach a considerable depth.

The ore bodies are usually inclosed between walls of ferruginous chert or ferruginous slate. Where chert is the wall rock the contact is usually much more irregular than where slate forms the wall rock. Numerous beds and irregular horses of ferruginous slate and chert occur 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 be interlayered with the ore, more or less parallel to the bedding. Other rocks associated with the ore bodies are amphibole-magnetite rock, magnetitic slate, cherty and slaty iron carbonate rocks, and black carbonaceous slate. These are very common along the south range, where they form the wall rocks of the ore bodies in many places. In the north range the amphibole-magnetite rock and iron carbonate rock more commonly occur underneath ore bodies, representing the deeper, unaltered portions of the iron-bearing formation.

Most of the iron ore occurring in the ore bodies of the Cuyuna district is medium soft, but hard ore is also abundant 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, and siliceous and argillaceous manganiferous iron ore is of common occurrence. Locally wash ore is associated with the other ores. On 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, Ironton, and Pennington mines in the north range. Much of this ore is of Bessemer quality, picked samples from the Croft mine analyzing as high as 67 to 68 per cent metallic iron and as low as 0.01 to 0.03 per cent phosphorus. Ore of this grade is of course exceptional, but 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. The common ore in the north range is a medium-soft to hard brown to reddish or bluish-brown hydrated hematite and limonite. Much of this ore is siliceous and grades with increasing silica into ferruginous chert and wash ore. Much of it also is somewhat argillaceous. Ore of this type is shown in the Kennedy, Thompson, Armour, Pennington, and Rowe mines. It is usually found in somewhat irregular, lenticular bodies inclosed in or associated with hematitic and limonitic chert and slate. In places 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 inclosing rock. Where the wall rock is mainly hematitic slate, as in certain deposits in the southwestern and central parts of the north range, the ore is soft, dark red or bluish red, and usually somewhat argillaceous. On the other hand, ore that is inclosed in ferruginous chert is medium hard, somewhat siliceous, and generally much fractured, so that it breaks up into small blocks. Ore of this class usually ranges in content of metallic iron from 58 or 60 per cent downward, its grade depending on the amount of silica or alumina present. The phosphorus ranges from 0.1 to 0.4 or 0.5 per cent.

Another variety of ore found in the north range is finely laminated brownish-yellow limonite such as occurs in the Mahnomen open pit. Ore of this type, though usually relatively low in silica, is more hydrated than the other ores of the north range. The yellow ocherous limonite ore also is common along the south range, where its occurrence is similar to that of the black limonite ore. Usually it is soft and friable. Though in a few places argillaceous, as a rule it is fairly pure and carries as much as 56 or 57 per cent of metallic iron, which is nearly the theoretical limit for limonite.

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 particles of iron oxide behind. The metallic iron content of the ore may be increased in this manner by 8 to 12 per cent.

The soft black limonite ore is common on the south range but is rarely found on the north range. It is generally associated with amphibole-magnetite rock and magnetitic slate, just as the typical ores of the north range are associated with ferruginous chert and slate. As a rule it is slightly magnetic, owing to the presence of disseminated particles of magnetite. This magnetite, which occurs also in other south-range ores, is presumably similar in origin to the magnetite in the associated amphibole-magnetite rock and magnetitic slate. It is probably residual from original magnetite-bearing rock which has in large part been altered to ore.

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 only a fraction of 1 per cent of manganese. The distribution of the ores of different grades 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, and the latter are themselves irregularly interbedded with other portions of the iron-bearing formation or with schist. A number of manganese minerals occur in these deposits, chief among which are manganite, pyrolusite, psilomelane, and wad. Any of these minerals may compose the nodules or bodies of manganese ore, and in places two or more of them are associated in a single body.

The manganiferous iron ore is usually black or dark brown, and much of it has a yellowish or reddish tinge. The content of manganese commonly ranges from 1 or 2 to 30 or 35 per cent. The ore usually occurs in large bodies, the manganese content of which varies greatly from place to place. Generally 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 being fairly constant. As the iron and manganese decrease silica and alumina increase, and the material becomes manganiferous iron-bearing rock. Manganiferous iron ore may be soft or hard. Some forms are dense and massive; others are friable. It is difficult to tell which of the manganese minerals is associated with the hematite or limonite in the manganiferous iron ore. Probably all the manganese oxides are present in different phases of the ore, but manganite appears to predominate in the hard ore and wad and pyrolusite in the soft ore.

The manganiferous iron-bearing rock in which manganese ore and manganiferous iron ore occur in small and large bodies is argillaceous or siliceous. Some varieties of it are very low in manganese, being simply ferruginous chert, ferruginous slate, or their decomposed equivalents; other varieties are irregularly impregnated with small quantities of manganese oxide throughout. In the rocks of both these groups the richer bodies of manganese and manganiferous iron ore are scattered irregularly.

The general distribution of manganiferous material in the iron-bearing belts of the Cuyuna district is also somewhat irregular. As a rule the more northerly belts are richer in manganese. In the south range exploration work thus far has shown the presence of very little manganiferous material. Some beds of the ore-bearing formation, as those on which the Armour No. 1, Armour No. 2, and Thompson mines are situated, have manganiferous iron-bearing rock on the footwall; other beds, such as that on which the Mahnomen open pit is situated, contain manganiferous material along the hanging wall. In still other localities manganiferous iron-bearing rock and ore may be interbedded with nonmanganiferous iron-bearing rock. Thus there are all variations in the occurrence of the manganiferous material.

The green and gray chloritic schist and the dark-red hematitic schist do not belong to the iron-bearing formation proper but are rather rocks that have become associated with it. They usually occur as small lenses within the layers of the iron-bearing formation or they may bound such layers on each side. The dark-red hematitic schist usually occurs along the borders of such lenses, where they are in contact with iron-bearing rock or iron ore and have become impregnated with hematite for varying distances from the contact; 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.

It is believed that the chloritic schist represents original masses of basic igneous rock that were intruded as sills into the iron-bearing formation 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. Subsequent metamorphism and deformation affected igneous rocks and sediments alike.

### SCHIST, SLATE, QUARTZITE, AND 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 rock 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 varieties of schist and slate are found in the Cuyuna district, among which are white, light-greenish, or light-brownish quartzose sericitic schist or slate; gray, finely micaceous schist or phyllite; dark-green or gray chloritic schist, commonly micaceous and locally quartzose, as already described; dark-red hematite schist or slate, which may be derived from any of the varieties above mentioned by impregnation with hematite; and 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, and black carbonaceous slate is conspicuous locally in the northeastern part of the south range.

Although most of the slate and schist of the Cuyuna district are undoubtedly of sedimentary origin, there are certain kinds, as the green chloritic schist, which in their occurrence and relation to the associated rocks strongly suggest an igneous origin. Much of the chloritic schist occurs in comparatively short, thick lenses which are interlayered with other rocks without any apparent order or regularity, although they practically always run parallel to the bedding of the inclosing rocks. The chloritic schist rarely shows lamination or other sedimentary characteristics, and its contact with the associated rocks is sharp. 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 for much of it.

Most of the light-colored quartzose sericitic schist or slate is very siliceous, and some 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.

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 typical fine-grained vitreous quartzite have been encountered in drilling operations along a belt more than a mile in length, 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 quartzite has also been found by drilling in a number of localities, especially in the neighborhood of Cedar Lake. At Dam Lake, about 10 or 12 miles east of the Cedar Lake region, quartzite crops out, and there may be some connection 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 semibasic character and now consist mainly of chlorite. Some still show the original igneous textures; others have been rendered schistose and grade into chloritic schist. Gradations have been found between the schistose and nonschistose varieties.

These rocks are believed to be of approximately the same age as the associated metamorphosed sediments, namely, upper Huronian. The less schistose varieties are usually medium to fine grained. In comparatively fresh samples they are difficult to distinguish from the later igneous intrusive rocks, which are believed to be of Keweenawan age. Of the many bodies of igneous rock found in the district very few 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 inclosing 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 ascertainable.

### 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 basic or semibasic and are of the type usually classed as greenstones, including diorite, diabase, gabbro, and perhaps more basic 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 variety has been encountered. Many of these intrusive rocks have been altered so that at present they consist mainly of chlorite and decomposed feldspar.

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.[1] Some are known to be in the form of dikes; others are irregular.

The metamorphic effect of the intrusion along their contact with the older rocks is in most places clearly noticeable. Where the igneous rocks have been intruded into the original iron-bearing formation they have usually produced a recrystallization of the chert into quartz and of lime, magnesia, and other constituents into 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 these varieties of rock 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 effective wherever they occurred, but from present indications they do not appear to have been sufficiently widespread to account for much of the metamorphism.

[1] Zapffe, Carl, The Cuyuna iron-ore district of Minnesota: Brainerd Tribune Suppl., July 1, 1911.

## LATER VOLCANIC AND SEDIMENTARY ROCKS.

Volcanic rocks that lie on the eroded surface of the older rocks are reported by Van Hise and Leith[1] to occur at several localities a short distance south and southwest of Brainerd and also about 6 miles east of Brainerd. They are said to be acidic and to have amygdaloidal texture. The beds are as much as 25 feet in thickness and seem to occupy depressions in the underlying rock surface.[2] 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 formation, 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.[2] Outside of the district the Cretaceous beds consist mainly of sandy and calcareous clay.

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[1] Van Hise, C. R., and Leith, C. K., op. cit., p. 215.
[2] Zapffe, Carl, op. cit.