THE GEOLOGY OF THE CUYUNA DISTRICT, MINNESOTA: A PROGRESS REPORT
The Geology of the Cuyuna District, Minnesota

A PROGRESS REPORT

BY

FRANK F. GROUT

AND

J. F. WOLFF, SR.

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FOREWORD

In 1918 Mr. J. F. Wolff, Sr., studied the mines of the Cuyuna district in considerable detail. About 1940 a brief synopsis of Cuyuna geology was presented before a sectional meeting of the American Institute of Mining and Metallurgical Engineers at the University of Minnesota.

In 1941 Mr. Grout started active field work on the Cuyuna largely in connection with the manganese problem. As a result of the field work a project was submitted to the Graduate School of the University of Minnesota proposing certain drilling to clarify the stratigraphy and furnish more precise data on the primary manganese content of the formations. During the interpretation of the results of the drilling Mr. Grout recognized the value of the data obtained by Mr. Wolff in 1918, when the underground mines were still open. He accordingly asked Mr. Wolff to collaborate with him in preparing a bulletin on the geology of the Cuyuna district, using as a basis Wolff's maps, structural cross sections, and a correlation chart showing the relation of the formations on the Cuyuna to those in the Mesabi and Gogebic districts.

Both Mr. Grout and Mr. Wolff have spent a great deal of time in the field and in preparation of the report. Mr. Wolff, now retired from his post as General Mining Engineer and from a later appointment as Engineering Consultant for the Oliver Iron Mining Division of the United States Steel Corporation, has at no time received compensation for this work; Mr. Grout, Geologist of the Minnesota Geological Survey and Emeritus Professor of Geology and Mineralogy at the University of Minnesota, has received none since his retirement in 1948. Theirs has been truly a labor of love.

Mr. Grout has written much of the manuscript, using data from various sources including that furnished by Mr. Wolff. The name of the author appears with the title of each section for which he takes sole responsibility. Chapters and sections without designated author are to be considered as of joint authorship, but this does not necessarily imply complete agreement on the many puzzling problems. The authors do agree on all major geologic facts and correlations.

It is thirty-six years since the only major report on the district was prepared by E. C. Harder and A. W. Johnston. New mine exposures have revealed many new features, and new minerals such as minnesotaite and groutite have been discovered. Nevertheless it should be realized that there are no natural rock exposures in the district and the geology must be interpreted from drill records and mine openings. The structure is extremely complex and it is to be expected that new data and inter-
pretations will accumulate. Such work is now being carried on by the U.S. Geological Survey.

The colored map and cross sections were published by the Continuation Center with the cooperation of Dean J. M. Nolte of the Extension Division of the University of Minnesota.

G. M. Schwartz
ACKNOWLEDGMENTS

The writers are especially grateful to Dr. George M. Schwartz, Director of the Minnesota Geological Survey, for contributions, helpful suggestions, and guidance in all parts of the work.


Early work in the district is acknowledged by references to published papers, notably those by C. K. Leith (who contributed also a private report), E. C. Harder and A. W. Johnston, G. A. Thiel, and Mrs. Margaret Skillman Woyski.

The U.S. Bureau of Mines, office of Division V in Minneapolis, has permitted the writers to study compilations from state and private reports, and to consult their extensive drill records and reports. Carl Wood and his assistants of the metallurgical branch of the Bureau have cooperated with the writers in laboratory studies. Walter Lewis of the Bureau has cooperated in several projects.

The mining and metallurgical data in this Bulletin have been contributed largely by the staff of the University of Minnesota Mines Experiment Station (E. W. Davis, Director, and H. H. Wade, Assistant Director). Assays and chemical data are mostly from the Experiment Station laboratories (W. E. Apuli, associate scientist, and Vernon E. Bye, chemical engineer).

The E. J. Longyear Company (Robert Longyear, President) gave us records and drill cores, and a chance to examine some old samples.

The mining companies and their officials have been very helpful, especially in allowing the writers to copy some records, and to sample formations and drill cores. We are grateful for contributions by the Oliver Iron Mining Company; Pickands Mather & Co., P. S. Gray, former superintendent, and T. F. Rundle at the Sagamore office: the Inland Steel Company, A. T. Anderson, Superintendent; The Congdon Office Corporation, Robert Congdon, President; the former Evergreen Company, Perry Harrison, Superintendent; The M. A. Hanna Co., John S. Owens, Geologist; The Cleveland-Cliffs Iron Co., E. L. Derby, Geologist; Butler Brothers, Earl Mollard and Peter Warhol; Great Northern Iron Ore Properties, C. J. Calvin, Vice President; Northern Pacific Railway Company, Carl Zapfe, Geologist; Snyder Mining Company, O. A. Sundness, General Manager; W. S. Moore Company, W. S. Moore, President, and Jack Everett, Geologist; the Charles W. Potts Estate; Zontelli Brothers; Robert M. Adams, et al.; Clyde Pierce; George H. Crosby at Crosby; J. D. Lamont at Virginia; J. W. Van Evera at Crosby; John A. Savage at
Duluth; J. A. McKillican at Hibbing; and A. K. Knickerbocker, Superintendant of the Northland Mine.

Dr. Theodore C. Blegen, Dean of the Graduate School, administrator of a large fund (granted by the Legislature) for University researches, gave a generous portion of the fund for Cuyuna explorations (see Appendix C). Most of this was used for diamond drilling by Sam Atkins of Duluth. The drilling would never have been started without the funds that Dean Blegen made available and Mr. Atkins’ help in sending drill crews from the more active Mesabi Range.

Professors J. W. Gruner, Fred M. Swain, and Herbert E. Wright, Jr. of the University of Minnesota’s geology department contributed new data on the minerals, fossils, and glacial features. Field assistants in geology, Ernest Lathram, Milton Novak, and Clemens A. Nelson were very helpful. Leonard Weis, David A. White, and E. J. Bolin have each prepared a recent thesis involving Cuyuna materials, and these have been helpful to the writers.

F. F. Grout
J. F. Wolff
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This report emphasizes initially the subdivision of the Cuyuna district into a North and a South Range, the former containing iron-bearing rocks comparable with those of the Mesabi district and its Michigan and Wisconsin equivalents and the latter being the equivalent of the younger Michigan iron-formations.

The manganiferous iron ores produced on the Cuyuna Range, in east-central Minnesota, have been much desired for use in iron furnaces. The geology of the ore formations and their correlations with ore formations in other districts have been subjects of considerable disagreement, largely because the iron formations on the Cuyuna lie under 50 to 300 feet of glacial deposits.

J. F. Wolff, Sr. has a lifelong familiarity with the rocks of the nearby Mesabi Range, and recognizes divisions of the iron formation into four members. He has also had years of work on the Cuyuna area and recognizes the same four members, with analogous subdivisions inside the members, and similar sequences of other formations above and below the iron formation. Other men have not wholly agreed on the sequence because of the scarcity of exposures, and the lack of drill cores and records over much of the area. There are also geologists who question the correlation of Mesabi and Cuyuna series, because the “South Range” iron ores on the Cuyuna lie some thousands of feet up in the slates above the main iron-bearing beds of the North Range; and no such high beds of ore have been found in the slates thousands of feet above the Mesabi ore horizons. Only a few hundred to a thousand or more feet of the thickness of the slates overlying the Mesabi iron formation have been penetrated by drills in the Mesabi district, and these were not high enough to encounter the possible South Cuyuna member.

This report presents the maps and sections prepared by Wolff, and his interpretation of the sequence, and a comparison with other districts. Some drilling planned by Grout to check the underground sequence of beds was generously supported by funds allotted by the Legislature to the University for research. These two studies of detail are here reported, with scattered data from outlying areas, and suggestions of correlations with the more remote iron ore districts south of Lake Superior.

The possible use of the lean manganiferous iron formation of the Cuyuna Range as an emergency resource of manganese, should foreign supplies on which we normally depend be cut off during wartime, is here recommended for further research.
THE GEOLOGY OF THE CUYUNA DISTRICT, MINNESOTA: A PROGRESS REPORT
1. INTRODUCTION

The Cuyuna District lies farthest west of all the producing iron ranges of the Lake Superior Region, about a hundred miles west and a little south of Duluth. Abnormal magnetic attractions were known as early as 1859, and magnetic ore was found by Cuyler Adams in 1904. By 1909 some 2000 exploration holes had been drilled. The first ore shipment was made from the Kennedy Mine in 1911. As recorded in the Mining Directory of Minnesota,* in 1915 there were ten producing mines which shipped 1,128,131 tons of ore.

Frequent use has been made of the annual Mining Directory of Minnesota compiled by H. H. Wade and Mildred Alm. The names of mines may change as control of the properties changes, but the Directory records both the older and newer names. New exposures are constantly being made in the mines as old pits are enlarged and new pits are opened. Most of the mine locations are shown on Plate 2 of this bulletin.

LOCATION OF PROPERTIES AND NEWLY OPENED MINES IN THE CUYUNA

1. The Section 6 Mine is in NW¼ SE¼ Sec. 6, T. 46 N., R. 29 W.
2. The Pontiac property (formerly Clark, and Joan No. 3) is in SE¼ NW¼ and S½ NE¼ Sec. 34, T. 47 N., R. 29 W.
3. The South Alstead pit extends the Alstead Mine nearly to the center of Sec. 9, T. 46 N., R. 29 W.
4. The North Hillcrest was an extension of the Alstead pit in the E½ NE¼ Sec. 9, T. 46 N., R. 29 W.
5. The Louise property is not in Sec. 10 (where the word Louise appears on Plate 2). The shaft is about 850 feet north and 4300 feet west of the SE corner Sec. 3, T. 46 N., R. 29 W.; the property includes S½ SW¼ Sec. 3.
6. The Mallen pit is in the W½ NE¼ Sec. 17, T. 46 N., R. 29 W.
7. The Yawkey reserve is opened near the center of NE¼ Sec. 1, T. 46 N., R. 29 W.
8. The Manuel pit is in NE¼ SE¼ and SE¼ NE¼ Sec. 1, T. 46 N., R. 29 W.
9. The Mangan No. 2 pit in NE¼ NE¼ Sec. 10, T. 46 N., R. 29 W. is now a part of the Mahnomen Mine.

* Publications to which references are made are listed under "References" on pp. 136 ff. General works, listed by number under Section A, will be designated in text by the letter "A" followed by the number (for instance, A-1, A-2); those listed under Section B will be designated by the author's name and the publication date.
Thiel wrote, in 1927, that the gap between the Mesabi and Cuyuna ranges was becoming smaller, but that their ores were so different that more work was needed. Wolff, with many years' experience on the Mesabi iron range, spent a year on the Cuyuna Range and published a study comparing the series of members of the formation in the two areas (Wolff, 1919); this comparison can now be elaborated and shown by maps which are very suggestive. Leith, Lund, and Leith (1935) correlated the Cuyuna formations with Virginia slate, but said it is still possible that the Cuyuna "Deerwood" formation may be equivalent to the Mesabi Biwabik. Schwartz (1942a) called attention to certain facts that suggest the Cuyuna ores may be older than the Algoman granite which is unconformably below the Mesabi formations. If such a difference of opinions could be reconciled, conclusions might be reached that would save time and money in future explorations.

The most detailed publication on the Cuyuna district was Bulletin 15 of the Minnesota Geological Survey, published in cooperation with the U.S. Geological Survey, a report of 178 pages, written by Harder and Johnston in 1918. The active developments of the range in the many years since then have so enlarged the knowledge of the structure and details that it is only natural there should be some changes of interpretation. This is a report of progress. Zapffe (1928) suggested that data be recorded by publication at frequent intervals, because some well-known features might be forgotten or lost by further mining.

REGIONAL GEOLOGY IN RÉSUMÉ

The geology of the region has been described by several geologists (Zapffe, 1925; Leith, Lund, and Leith, 1935). Harder and Johnston (1917, pp. 6-7) say: "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 natural rock exposures are known in Crow 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. . . . and outcrops of gabbro occur in Todd County near Philbrook."

In general, Animikie rocks in which iron ores occur run southwest from the Mesabi Range about 65 miles, and are not more than 25 miles wide. At the southwest end of the district the magnetic belts turn somewhat south but formations are not well explored. The main productive area has been only about 10 miles long and 4 miles wide. The U.S. Geo-
Logical Survey has recently cooperated with the Minnesota Geological Survey in aeromagnetic mapping of large areas including the Cuyuna Range.

Extensive outcrops of Thomson formation occur in Carlton County, east of the Cuyuna Range; these are beyond the quartzite near Dam Lake, beyond the diabase and diorite near Long Lake, and south of Clearwater Lake. Intrusives of some variety are rather extensive northeast and southwest of Mille Lacs; but southwest of them, along the Mississippi River at Little Falls, the Thomson formation reappears in metamorphosed form.

Granites are of two ages (Woyski, 1949), one corresponding to that of the Giants Range, and the other Keweenawan—young enough to have contributed to the metamorphism of both the Cuyuna iron formation and all the slates. There are also basic intrusives, some apparently about the age of the iron-bearing rocks and others Keweenawan, overlying and cutting the iron formation.

Names for the Iron-Bearing Rocks

Different geologists take different attitudes toward the suggested “Deerwood iron-bearing member.” Van Hise and Leith (1911, p. 212) proposed the name for “iron-bearing beds . . . not . . . satisfactorily correlated with the Biwabik . . . from their typical development at and near Deerwood”; these words if strictly interpreted would apply best to the group of relatively narrow bands we call the South Range iron-bearing member of the Virginia formation that cuts the SE corner Sec. 21, T. 46 N., R. 29 W., a part of the Village of Deerwood. Harder and Johnston (1918, pp. 114-16) used “Deerwood” for “iron-bearing rocks of the Cuyuna district” of variable thickness. Zapffe (1933, pp. 74-78) restricted the use of the term “Deerwood” in his papers to a magnetic “member” (or possibly several “members” about 100 feet thick at several horizons) in the Cuyuna member of the Crow Wing formation. It is very confusing, however, to read of a member enclosing another member. Zapffe (1933, p. 76) also believed that an underlying “Emily member” had “numerous scattered lenses” of iron-bearing rocks. Leith, Lund, and Leith (1935, p. 15) changed the name “Deerwood” to “Deerwood iron-formation member of the Virginia formation” but used the term for the iron formation resting on “quartzite much like the Pokegama.” Our work since the publication of these papers has not made it possible to identify such formations and members as are mentioned. No satisfactory use can be made of terms so loosely and variably defined as the “Deerwood.” (See pages 84 and 93.)

Anticipating some conclusions to be drawn in later pages, the writers here suggest that the main productive part of the Cuyuna Range, the North Range—“north of the Northern Pacific Railway” (Zapffe, 1910) — has a series of formations which can be well correlated with the Animi-
kie formations of the Mesabi and other ranges. For the Cuyuna district the familiar names of formations on those ranges serve very well.

Animikic series
3. Virginia formation
2. Biwabik iron formation
1. Pokegama formation

One exception to the correlation of the Cuyuna formations with this sequence on the Mesabi Range is the South Range (Zapffe, 1910)—“south of the Northern Pacific Railway”—where an iron-bearing bed, 100 to possibly 200 feet thick, lies in the thick slates that are otherwise well correlated with the Virginia formation. The writers, like most other writers on the geology of the Cuyuna district, follow local usage to the extent of calling this part of the Cuyuna the “South Range” and designating it as an iron-bearing member of the Virginia formation.

Harder and Johnston (1917, p. 14) did not think the differences between the North Range and South Range sufficient to justify assigning the two to different horizons. The following features, now well established, justify making a distinction, since in all five points the North Range (Biwabik) differs from the South Range member: the South Range member has (1) very little chert—and what there is has thin lamination, (2) no manganiferous ore (Zapffe, 1933, p. 83), or only small amounts, (3) no more than 200 feet of iron-bearing beds, (4) barren slates for thousands of feet above and below the iron-bearing bed, and (5) a structure dominated by one belt, in one major syncline, but with a few faults and some minor drag folds. (For further notes, see Chapter 6.)

RESEARCH PROPOSED

In 1941 the Minnesota legislature made funds available for some important researches at the University of Minnesota, and through the interest of Dean T. C. Blegen a liberal portion of the money was allotted to a study of the Cuyuna iron range. (See Appendix C.) Most of the resulting work was based on exploratory diamond drilling, referred to throughout this report as “University drilling”; preliminary reports of progress in that research were made in 1942 (see Chapter 4, Part I). A brief summary of the manganese resources of the range was printed (Grout, 1943), because war conditions were seriously interfering with manganese imports. The Cuyuna Range has probably the largest reserve of this metal in North America (Lewis, 1951).

The funds provided by the legislature for University drilling were applied to the solution of several major problems of the area, selected as likely to help further explorations and developments in the district.

Specifically, the University drilling was planned in the hope of obtaining satisfactory information as to the number, thickness, and continuity of the green carbonate slate beds on the Cuyuna Range. These commonly carry from 2 to 10 per cent of manganese, and interest was expressed by
government experts in their possible use for concentration of manganese in times of a shortage of foreign supplies. Data from the old files indicate that exploration work almost invariably stopped when the drilling reached such fresh green slates. No record was discovered of old drilling that crossed the fresh slate from top to bottom showing its original thickness. The continuity of the carbonate slate beds, however, had been fairly well established at some places for a mile or more, and they appear to run for many miles. As a result of the University drilling, estimates of the manganese reserves of the country can be made much more accurately. (See Chapter 7.)

The more general problems of succession and correlation were kept in mind, but almost any exploration crossing the beds of fresh rock would give data as to succession. It was likely also that the data on any one division and its place in a series, would be of interest in connection with ore bodies already known. Certain members might prove to be favorable to oxidation and enrichment. Some might carry manganese in a form to yield manganiferous ores, whereas others might yield mostly iron ores.

For drilling, places were selected where mining and previous drilling for ore suggested that the deeper rocks might show a sequence of major divisions of different rocks. Four holes were drilled and the records do contribute to the solution of the problems that were in mind. The material collected in the study proved useful also for researches on the minerals of the formations and the structures of the district.
2. GENERAL SETTING AND NOTES ON ROCKS AND MINERALS

GENERAL SETTING

The general geology and history of the Cuyuna Range were reported in Bulletin 15 of the Minnesota Geological Survey (1918), which also included notes on the early history of exploration and production. The mining statistics of the range, based on official reports to the state offices, are annually compiled and printed in the *Mining Directory of Minnesota*, a bulletin of the University of Minnesota (see page 136, and Appendix B). Exploration finds new reserves and re-estimates set up old reserves about as fast as production removes the good ore. While this balance may not be permanent, there is little sign at present of the exhaustion of the ores of the range.

Harder and Johnston (1918, pp. 94–96) give the following notes:

"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 southwest to south, crosses the ore-bearing belt... 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... 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 through the region... The valley of Mississippi River is narrow and in general is not very deep, although locally as at Brainerd there is a distinct gorge..."

"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."
"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."

To this a few notes may be added. The climate is temperate, but the winters are too cold for open-pit mining. Two state highways, Nos. 100 and 169, pass close to the mines. Brainerd, the largest city in the range, has a population of about 13,000 and is the county seat of Crow Wing County.

The productive area of the range is shown on the maps, Plates 1 and 2; cross sections are on Plates 3 and 4. There are persistent attempts to extend the ore belts to the northeast into Aitkin County and southwest to the Gorman Mine near Randall, and ore has been developed by drilling far out from the productive part of the district and southwest of western Mesabi mines.

GEOLOGIC SECTION OF ROCKS OF EAST-CENTRAL MINNESOTA

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<th><strong>Pleistocene</strong></th>
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<td>Recent alluvium</td>
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<td>Wisconsin till and outwash</td>
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<td>Pre-Wisconsin till and outwash</td>
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<th><strong>Cretaceous</strong></th>
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<td>Sands, clays, and conglomerates, with fossils</td>
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<td>Upper Cambrian sandstone</td>
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<td>Later</td>
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<td>Keweenawan</td>
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<td>Thick sandstone</td>
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<td>Flows, intrusives, gabbros, and granites</td>
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<tr>
<td>Thin sandstone</td>
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<td>Animikie</td>
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<td>Igneous flows, sills and dikes</td>
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<td>Virginia formation, argillite and slate</td>
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<td>Upper slates</td>
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<td>South Range iron-bearing member</td>
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<td>Lower slates</td>
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<td>Biwabik iron formation</td>
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<td>Pokegama formation, quartzite and slate</td>
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<td>Algoman granite</td>
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<td>Thomson formation, with granites and gneisses</td>
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<td>Slates and graywackes</td>
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<td>Local dolomites</td>
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<th><strong>Earlier</strong></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Granites and gneisses</td>
<td></td>
</tr>
<tr>
<td>Greenstones, schists</td>
<td></td>
</tr>
</tbody>
</table>

* These occur in outlying areas (Plate 1), but little has been observed in the productive Cuyuna district (Plate 2). See Harder and Johnston (1918). Plate II.
Recent alluvium is widespread throughout the Cuyuna but is rarely very thick. Some swamps have been largely filled with recent peat, and at a few places there have been deposits of bog iron and bog manganese. The tonnages, however, are probably small.

Glacial deposits covered all the area of Plate 2, and most of that of Plate 1. Glacial ice moved into the area from both the northeast bringing red drift, and from the northwest bringing gray drift. A glacial moraine that lies west of the active range and largely west of the Mississippi River near Brainerd, was deposited by ice from the Lake Superior area. As the ice retreated, the water flowing southwest deposited a variety of materials, and the area is now dominated by gravel ridges, elongated in the general direction of flow. Few of these ridges are higher than 200 feet above the relatively flat swampy areas, and there are sandy deposits between them. One of the higher hills northeast of Crosby supports a forest lookout tower.

A late readvance of the ice from Lake Superior brought into the eastern area shown in Plate 2, near Rabbit Lake (Zumberge, 1952, pp. 72-73), a small quantity of bright red drift, which is notably in contrast with earlier gray material. Beneath these easily noted deposits, there are several different kinds of glacial deposits at different open pits, with several different ages indicated by unconformities. An instructive exposure is easily seen in the northeast wall of the Sagamore Mine.

The glacial features have economic applications, since many of the outwash deposits are loose, porous, and wet, and therefore "bad ground." Shaft-sinking operations and even open pits have met with materials that flowed so freely that equipment was persistently flooded or overwhelmed.

The thickness of glacial deposits in the productive part of the Cuyuna ranges is from 20 feet to more than 200 feet. At Emily, which is ten to fifteen miles north of the area of Plate 2, iron formation has been drilled under glacial deposits 250 to 340 feet thick. Few mines in the district have been worked where the glacial cover was more than 200 feet thick, but some are planned. A few glacial lakes have been drained so that ore could be mined.

The complexity of the geology of the Cuyuna Range under the glacial deposits is evident to the casual visitor. There are no natural outcrops except at a distance of many miles from the active mines. Data are therefore obtainable chiefly from magnetics, drilling, and mine exposures. The rocks are complexly folded, and some are overturned; in such rocks the beds thicken and thin even if they were originally uniform; the folds plunge variously as if developed at great depths, passing each other like the folds in a coat sleeve near a bent elbow. Faults which can be seen in the walls of open pits are without doubt only suggestive of larger faults not yet accurately mapped. Several faults are known to offset formations for hundreds of feet. Any suggestion of continuity of beds or structures between pits must be considered with great caution because experience
has shown that horizontal beds in a pit may change to vertical within
20 feet.

Outlying areas around the productive Cuyuna Range area are described
in more detail in Chapter 5, where some new data, acquired since the
publication of Bulletin 15 (Harder and Johnston, 1918) are presented.
There are many formations and complex structures in the outlying areas
— old slates, schists, and dolomite; Paleozoic sediments; and igneous in-
trusives. Cretaceous deposits from several drill explorations in northern
Aitkin County, have been studied by advanced students of paleontology
at the University of Minnesota.

TERMS USED FOR FORMATIONS AND MEMBERS

The usage of terms in Bulletin 15 of the Minnesota Geological Survey
(1918, pp. 2-4) is followed here for the most part. The Precambrian of
central Minnesota includes some rather uncommon rocks, and these have
been given distinctive names which are widely used. This section explains
the usage in this bulletin for several of the terms.

Cherty and Slaty Members. These terms are almost wholly structural.
A reader unfamiliar with the literature of the Mesabi district might think
these terms indicated that chert was dominant in one member, and clay
minerals, more or less metamorphosed, in the other. This would be a very
inaccurate explanation of the names. A Cherty member commonly does
have dominant cherty beds (unless replaced by ore) but the name is
given to members of the iron formation, usually 75 to 250 feet thick, in
which dominant chert beds are from one inch to 20 inches thick. A Slaty
member, usually 100 to 2000 feet thick, is a succession of beds with thin
laminated structure, with visible laminae usually much thinner than an
inch, and most characteristically less than an eighth of an inch; a few
thick beds in a hundred or more feet of thin-bedded rock do not change
the classification of the whole member. Note that this does not specify
the mineral nature of the Slaty member; it may be cherty, or ferruginous,
or argillaceous; it must have dominantly thin sedimentary bedding, how-
ever, and on the Cuyuna Range a slaty member commonly has a slaty
metamorphic cleavage. The reader should not be confused to find abun-
dant chert at places in a Slaty member. Clay minerals and their meta-
orphic products commonly occur in the Slaty members, but are not
necessarily dominant everywhere.

Examples on the Cuyuna Range may be helpful. The east wall of the
Virginia open pit (Secs. 4 and 5, T. 46 N., R. 29 W.) looks cherty from
a distance, but it is thin-bedded and hence part of a Slaty member.
Wolff (1917), after long experience in the Mesabi and other iron ranges,
recognized four major parts of the Biwabik formation, two “cherty” and
two “slaty.” In this bulletin (Chapter 4, Part I), these four members, in the
same order, are recognized on the Cuyuna Range. (See pp. 49-51, 56 ff.)

The designation iron-bearing series is intended to include a larger per-
centage than usual of normal sediments such as graywacke, sandy slates,
phyllites, and argillites. The “iron-bearing formations” on most Lake Superior ranges include only a few relatively thin beds of mechanical sedimentary origin; one commonly cited is the “intermediate slate” on the Mesabi Range. Such mechanical sediments are much more abundant in the Cuyuna iron-producing area than in the Mesabi, and are here included as parts of the iron-bearing series. Some readers may question whether the whole Cuyuna series is properly called an “iron-bearing formation,” as it is in this report. Future investigations may furnish reasons to change present usage (James, 1954, pp. 239-40).*

Iron-bearing formation, and iron formation are intended to include any iron-bearing beds which have iron enough, and in such condition, that they may locally be enriched or altered to ore.

Cherty iron carbonate, which may be light or dark, is mostly dense, fine-grained chert mixed with siderite or manganosiderite. These cherts are commonly thick-banded (layers are from one-half inch to several inches thick), and many beds are wavy or even concretionary. Laminated cherts (having layers \( \frac{1}{4} \) to \( \frac{1}{4} \) inch) are parts of a slaty division of the iron formation. The cherty rocks may grade, at their borders, into more argillaceous beds — slaty if laminated, with or without secondary cleavage.

Carbonate slates consist largely of fine-grained carbonates of iron and manganese. (These should not be called “carbonaceous,” a term which would indicate black graphitic rocks; several such rocks do occur locally.)

Greenalite rock carries granules of a dark green iron silicate that was named greenalite by Leith (1903, pp. 102-18, 239-59) when he discovered it on the Mesabi Range. The peculiar granules, about the size of sand grains may, by slight metamorphism, break down into quartz and iron oxide without wholly losing their granule texture. Such granules are common in Cherty members on the Cuyuna Range (Thiel, 1927). Gruner (1946, p. 27) finds the green granules commonly a mixture of minerals (see Figs. 22 and 23 below).

Hematite and goethite (limonite) are iron oxides formed by near-surface alteration of the cherty and slaty iron formations. They may still retain the banding, lamination, and granule textures of the original sediments. Ferruginous chert is a general term for common mixtures of any oxides of iron with chert.

Taconite is a term that has been used for granule-textured ferruginous chert and lean ores on the Mesabi Range. So much of the Mesabi ore has this texture, where lean, that the term taconite has gradually come to include all facies of the Mesabi iron formation, even “slaty taconite.” Those who believe the Cuyuna is equivalent to the Mesabi use the term “taconite” chiefly for the cherty rocks on the Cuyuna.

The slates of the Cuyuna district carry clay minerals only locally, but some have chlorites and micaceous flaky minerals. They were derived

* James specifies that iron formation is “typically thin-bedded,” but this ignores the thick-bedded, highly productive members on the Mesabi and Cuyuna ranges.
from the thin-laminated sediments. Below the Virginia formation the iron minerals, cherts, and carbonate are nearly everywhere abundant. It is clear that such cherts and carbonates do not have a typical slate petrography and mineralogy. Brown goethite (limonitic) slates and red (hematitic) slates are “argillaceous” thin-bedded rocks (with or without carbonates) having secondary cleavage. The term “ferruginous slate” includes both red and brown rocks. Carbonate slate is thin-laminated but commonly rich in iron carbonate. In a few rocks (only very few in the Cuyuna district), the secondary slaty cleavage is faint, or parallel to the lamination, so that it may be best to describe these few rocks as argillites. They resemble rocks of the Mesabi Range known as “intermediate slate” and “Virginia slate,” which are very slightly metamorphosed.

The minerals of the Cuyuna slaty rocks are complex and do not include as much “amphibole magnetite” as was early assumed by analogy with other iron ranges. Recent work has shown very little amphibole, and the dark minerals include minnesotaite, stilpnomelane, and possibly greenalite—products of the precipitation of iron and silica. From these precipitated fine cherts and silicates, the slaty rocks grade locally into more ordinary clay slates with sandy streaks or lenses. As the iron-bearing slates and schists weather, they are oxidized to browns or yellows, or stained red, and thus become “paint rock.” Some schists that had only a little iron are now stained and considerably replaced by iron oxides from adjacent formations.

_Jaspilite_ is laminated black hematite and red jasper, but red jasper is comparatively rare on the Cuyuna. Metamorphism has changed most of the red cherts to gray.

_Magnetite slate_ is a nearly black rock with the considerable variety shown by the other slates. The magnetite may have been in sedimentary grains, but so much iron was precipitated as ferrous and ferric minerals that a slight metamorphism (that was universal in the Cuyuna) may have produced secondary magnetite. This magnetite causes the magnetic attraction which originally located the formation underground and guided the explorations at several mines.

_Quartzites_ are widely distributed; some, like the Pokegama, are below the Biwabik formation, while others are in (and possibly above) the Biwabik formation. These are so numerous and range so widely in thickness, purity, and extent that men disagree as to the proper term to use, and also in their attempts to correlate the quartzites. Locally some impure sandy rocks such as graywackes may be metamorphosed to impure quartzites. After intense recrystallization, even the cherty beds have been recrystallized to granular quartz rocks, not easily distinguished from quartzite (Fig. 11).

It must be admitted that quartzites grade into schists and slates, some by an increase in the proportion of thin slaty laminae, others by an increase in clay minerals between sandy quartz grains. The sandy laminae in a slaty rock are well shown in the north side of the Mahnomen and
Louise pits. It has been noted many times that in a slaty formation sandy streaks are lenticular. As the percentages of sandy lenses increase, the slates grade into quartzites. This sort of occurrence has led several geologists to suspect that all the quartzites of the district are lenses of irregular occurrence and hence of no value in correlation. Nevertheless some persistent beds of quartzite are so related to a sequence of other beds that they are of great value in correlation. Those lenses that are irregularly scattered in slate have only suggestive value. The drill hole in North Hillcrest (Fig. 14) crossed some quartzitic materials, probably in such lenses as are exposed in the open pit.

The writers, recalling the “intermediate slate,” a supposedly clastic sediment in the Mesabi Range, include in the Cuyuna iron-bearing series some altered sands and slates (even those that are 100 to 300 feet thick) where the whole series is many times as thick as the mechanical sediment. Quartzite has long been known to crop out near Dam Lake far east of the Cuyuna mines, but its relation to the Pokegama quartzite exposed in open pits from the Rowe to the Maroco, is not wholly settled by the drill records of adjoining areas. (See Chapter 5.)

Several schists on the Cuyuna are cleavable soft green chloritic rocks which seem to be a result of the metamorphism of basic intrusives or flows. In the pre-Animikie rocks there is a complex of schists, not well explored. In the main producing Cuyuna district there are very few if any such greenstones as the hornblende schists of the Vermilion Range.

Granites and gneissoid granites (with igneous flow structures) are common in outlying areas and some of them send a few dikes, pegmatites, and veins into the ores of the Cuyuna (see Chapter 5). Granite gneisses (resulting from metamorphic deformation) may occur in adjoining areas.

COMMON ROCKS AND FORMATIONS

In Chapter 4, Part II of this bulletin the Cuyuna iron-bearing rocks are reported to occur in four principal members or divisions of the Biwabik formation (in addition to the less productive South Range; see discussion of this part of the Cuyuna in Chapter 5). These four members are analogous to the members of the Mesabi Biwabik formation, with which Wolff is most familiar. It is freely admitted that many beds and members of the formation change along the strike, and that certain beds are lenticular and can be followed only a short way. Still there are distinct differences between the four members that are remarkably persistent, and in Chapter 6 an attempt is made to use them in correlation. If these correlations are in error, corrections can be made as information increases. So much of the area is still concealed under the glacial deposits that it would be surprising to find all the estimates correct.*

Most of the ores are related (1) to two “cherty members” each about 100–150 feet thick, and (2) to two “slaty members” which are thicker.

*As an example, the yellow area (chert) in Plate 2, Sec. 35, T. 136 N., T. 26 W., has been reported to be different from most of the cherts mapped.
and more complex in composition. In the slaty members the ores have been formed at several horizons, possibly at horizons where the original deposits were extra rich in iron, or had more easily soluble gangue during enrichment. The contrast between the cherty and slaty material has been shown by the chemical analyses of some fairly fresh cores from drilling.

The assays of the Upper Cherty member drill cores from the Merritt Mine area (one of those selected for the University research) show the chemical composition at least approximately. These may be contrasted with the average carbonate slate that has been drilled and assayed.

<table>
<thead>
<tr>
<th></th>
<th>Cherty Member, Merritt Mine</th>
<th>Carbonate Slates, Many Mines</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>50%+</td>
<td>29%</td>
</tr>
<tr>
<td>Fe</td>
<td>20-40%</td>
<td>30%</td>
</tr>
<tr>
<td>Mn</td>
<td>1-10%</td>
<td>5.6%</td>
</tr>
<tr>
<td>CO₂</td>
<td>less than 5%</td>
<td>14%</td>
</tr>
</tbody>
</table>

Cherts from the Lower Cherty member (the Maroco and Section 6 mines) have a composition slightly different from that tabulated for the Merritt Mine chert, chiefly because there is less manganese in the cherts of the Lower Cherty member (see Appendix B).

Cherty original rocks have been little changed by metamorphism, but many have recrystallized from the original chalcedony to quartz with grains about the sizes of silt and sand grains. Weathering commonly loosens these grains to incoherent silt, which makes it possible to wash out much of the quartz and thus obtain ore lumps relatively free from silica; this is the “wash ore.” Much of the chert of the cherty members has been replaced by iron-bearing solutions, some from weathering, some from hot waters; but much of the original lean ferruginous chert is enriched by simple leaching and removal of the silica from iron silicates and chert, leaving iron oxides nearly pure. The main belts of Cherty members are shown on Plate 2 as yellow bands.

Green slates, commonly carbonate slates, were fine-grained sediments, perhaps partly claylike mechanical sediments but more largely chemical precipitates of carbonates of iron, manganese, calcium, and others. These rocks, with probably some fine silica cement, may have been very firm as original sediments; but being fine-grained and soft because of the carbonate content, they were easily deformed and metamorphosed to slates, and even to phyllites and schists. Apparently the iron silicates produced by the reaction of these fine grains developed a green color in some cases, depending on the iron content and minerals formed. They are identified by X ray and chemical studies as minnesotaite, stilpnomelane, and greenalite, mixed in varying proportions with the carbonates, cherts, and possibly clays. Where deformation was slight the mixture looks like a chert with thin laminations, as at the Sagamore open pit, but at many places the lamination is crossed by slaty cleavage. Locally, as in the Arko pit, some of these slates have metamorphic cleavages in two directions. Much of the green slate of waste dumps may turn black after a few months’
exposure to air; probably the manganese of the carbonate (nearly colorless) turns to a black manganese oxide. Such oxidation may penetrate some inches in a few years (Fig. 3). The primary sediment of the carbonate slates may locally grade into more ordinary clay slates, or sandy slates, but on the Cuyuna such mechanical sediments are not abundant near the ores. There are clay slates and graywackes south of the Sagamore ores, and below the ore horizon in the Merritt Mine.

Microscopic study of the green slates reveals, in addition to the silicates and carbonates, (1) some fine quartz in many laminae, though there is a good deal of variety in its abundance, sizes, and shapes; (2) biotite in a few specimens; (3) notable amounts of pyrite, leucoxene, sericite, or tale, and traces of zircon, tourmaline, and plagioclase.

Several of the carbonate rocks show microscopic structures suggesting fossils, but the state of preservation is not good. Analyses of carbonate slates of the two horizons are given in Appendix B below. Krey (1919, pp. 28–29) reported a green slate with 14 per cent manganese.

Veinlets are common, and have added to the Cuyuna iron-bearing rocks some quartz, stilpnomelane, pyrite, rhodochrosite, barite, and acmite. Amphibole may occur in a few of the green slates, but is probably not as common in the Cuyuna as in other metamorphosed iron formations in the Lake Superior region.

Near some quartz veins of moderate size (say 10 inches), the green carbonate slates are locally hardened, and turned brown, like the ore, for several feet (farther along some beds than others). A good example may be seen in the Mahnomen pit in the SW\text{1/4} SE\text{1/4} Sec. 3, T. 46 N., R. 29 W.

At the top of the lower slaty beds at the Merritt No. 2 Mine the green slate is locally modified to a hard pinkish brown rock, but it is still thin-bedded. Microscopic sections show that the color results from brown acmite, a pyroxene, in which the dominant metals are sodium and ferric iron. In some small crosscutting veins the acmite is green (Grout, 1946a). Acmite is commonly an igneous mineral, but one other occurrence in an iron ore is recorded — that in Långban, Sweden.* There is no doubt that the acmite on the Cuyuna Range originated by metamorphism of a sediment. Probably hot sodic waters reacted with hematite-bearing thin-bedded cherts.

Gray slates are abundant on the Cuyuna but show a good deal of variety. As the amount of magnetite in a green slate increases, the green color is obscured. Graphite may locally make a dark gray slate from a dominantly green iron-bearing slate. Some attempts have been made to use the black slates as horizon-markers in the series, but they are known at several horizons. Probably the gray slates in the Cuyuna district have less carbonate than the green slates. There are gray clay slates in both the Upper Slaty and Lower Slaty members, and these grade from black

Graphitic rocks to nearly white graywackes. Several prominent exposures of these black graphitic rocks are worthy of note: the west end of the Virginia pit (Sec. 5, T. 46 N., R. 29 W.) has graphitic slate below ores of the Lower Slaty member; Zapffe (1933, p. 76) reported black slates in the lower parts of what he called the Crow Wing formation; Harder and Johnston (1917, p. 14) reported more characteristic black slate associated with ores on the South Range than on the North Range.

Hand specimens of such gray slates show good cleavage and a luster brighter than most roofing slate. The amount of quartz ranges from a trace to 60 per cent. The cleavage clearly results from oriented flakes of sericite and chlorite. There are small amounts of hematite, magnetite, goethite, feldspars, leucoxene, graphite, and accessory zircon, apatite, tourmaline, and pyrite. Carbonate, titanite, and zoisite may be noted locally.

The gray slates and even graywackes are here included with iron formation. Some geologists may object. Not only are the gray and black slates associated with ferruginous cherts and cherty iron carbonate, but they carry more iron in magnetite and carbonate than do other slates. The accompanying table summarizes rather extensive data showing that slaty iron formations are more ferruginous than other gray slates. Even the quartzitic gray slate of the Merritt Mine, drilling showed 19 per cent iron at the bottom.

### Contrast Between Iron Contents in Slaty Members of the Iron Formations, and in Nearby Slate Formations

<table>
<thead>
<tr>
<th>District</th>
<th>Location of Sample</th>
<th>Iron Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuyuna</td>
<td>Merritt Mine</td>
<td>25 to 30%</td>
</tr>
<tr>
<td>Cuyuna</td>
<td>Hillcrest Mine</td>
<td>12 to 24%</td>
</tr>
<tr>
<td>Cuyuna</td>
<td>Northland Mine</td>
<td>5 to 15%</td>
</tr>
<tr>
<td>Mesabi*</td>
<td>Virginia slate</td>
<td>5.61%</td>
</tr>
<tr>
<td>Gunflint*</td>
<td>Rove slate</td>
<td>4.34%</td>
</tr>
<tr>
<td>Carlton*</td>
<td>Thomson slate</td>
<td>5.88%</td>
</tr>
<tr>
<td>Vermilion*</td>
<td>Knife Lake slate</td>
<td>4.21%</td>
</tr>
</tbody>
</table>

* Taken from Grout, 1933. Geol. Soc. America Bull. 44, 989–1039.

The graywackes have generally more quartz and feldspar, and the quartz in the graywackes is somewhat coarser and the carbonate cement more abundant than in the slates. The other minerals of slates occur in reduced percentages. *Fresh igneous rocks are not seen in large volumes on the Cuyuna. Probably some dike (or flow) at the Adams Mine was as fresh as most Keweenawan rocks of Minnesota; and Thiel (1927, p. 791) noted pegma-
tite, and perhaps granites (see pages 90–91, 108 for further discussion) in small dikes cutting basic intrusives in the mines from the Huntington to the Armour. These show little metamorphism. One dike of "pegmatite" is said to carry "adularia," which suggests possible deposition from hot water solution rather than from magma.

The Adams Mine, just cited, shows also a second kind of igneous mass, much more altered. It is now largely chloritic and schistose, and shows only faint remnants of former igneous textures — phenocrysts and other features of intrusives. Wolff, in Chapter 4, Part II, lists a large number of other altered intrusives, which are shown on Plate 2. They may have been mostly basic dioritic or gabbroic in composition. "Diabase" and "porphyry" have been reported (Harder and Johnston, 1918, pp. 32, 52, and 162). Basalt is common in the whole region. Igneous flows are cited by Van Hise and Leith (1911, p. 215), at three places near Brainerd. The variety of more siliceous rocks of different age groups in outlying areas (Chapter 5) shows that several kinds may be expected (Woyski, 1949; Thiel, 1927, p. 791).

The metamorphic effects on both sediments and igneous rocks involve mineralogic changes to hydrous minerals — chlorite, sericite, and many others — and structural developments, such as secondary cleavages (slaty and schistose), folding (including slip folds, see Fig. 5), lineation, jointing, and faulting. Nearly all the rocks of east-central Minnesota that are older than Cretaceous are somewhat metamorphosed.

In summary of metamorphic studies, it should be noted that most of the Animikie rocks on the Cuyuna are much more altered than are similar rocks on the Mesabi Range some forty to fifty miles north. Inside the Cuyuna district there is a tendency for an increase in the intensity of deformation and recrystallization toward the south and southwest. There are many local irregularities, some evidently related to minor intrusives, but the local effects seem slight compared to the general metamorphism of slates in the producing parts of the Cuyuna district. The most southwesterly iron-bearing sediments occurring near Philbrook in Todd County, and near Randall in Morrison County, are most metamorphosed. At both these places local intrusive rocks are known to occur near the iron formation, but it is clear that at both places the iron formation comes close to Keweenawan granitic intrusives which are farther south in these counties.

Questions may be asked whether the metamorphic changes are attributable mostly to intrusives, or to the proximity of the axis of the Lake Superior syncline. That axis was shown by Irving (1883, Plate XXVIII) to be some eighty miles southeast of the Cuyuna and it probably had little influence on Cuyuna ores.

MINERALS RECORDED

The minerals of these rocks are numerous and some have been the subjects of careful study. They are ore minerals, or those significant in de-
terming the processes that operated in the district; stilpnomelane, adularia, barite, and acmite should be especially noted.

The principal primary mechanical sediments carry quartz, clay minerals, feldspars, magnetite, tourmaline, zircon, biotite; others occur in accessory amounts. Chemical precipitation in a shallow sea probably produced the chert, the carbonates (ranging from calcite to manganosite), and possibly pyrite and iron oxides. Greenalite, stilpnomelane, and minnesotaite may be either precipitates or products of hot water reactions on earlier minerals.

Igneous minerals on the Cuyuna Range include quartz, feldspars, biotite, magnetite, and possibly muscovite, and ferromagnesian minerals now altered.

Rocks metamorphosed by heat and deformation carry stilpnomelane, minnesotaite, greenalite, acmite, pyrite, biotite, sericite, chlorite, talc, magnetite, graphite, and muscovite. Probably stilpnomelane and pyrite can be attributed to hydrothermal action. It seems likely that some of the ore minerals have been introduced into slates and cherts by hot waters.

Vein minerals, as noted above, include quartz, adularia, rhodochrosite, pyrite, pyrrhotite, stilpnomelane, calcite and other carbonates, acmite, and perhaps minnesotaite. L. Weis collected barite from the Mahnomen pit No. 4. Cross-fiber veinlets of stilpnomelane are conspicuous in the green carbonate slates of the Alstead-Louise, Arko, and Sagamore pits.

Weathering has produced goethite, hematite, pyrolusite, manganite, psilomelane, groutite, and several silica minerals. Possibly some of the clay minerals are deposits or residuals from the leaching of the iron formation. The igneous intrusives in several pits have been altered to clay-like or chloritic aggregates with clearly residual igneous textures.

Some of these minerals are newly discovered, and some are new to the district, and their descriptions are by-products of the geologic studies that are the main subject of this work. (See "References," Section B, for papers by Leith, 1903; Thiel, 1924a; Grout and Thiel, 1924; Grout, 1946b; Gruner, 1944 and 1947.)

HORIZON-MARKERS

Many varieties of rock and structure serve as guides in stratigraphic studies of the Cuyuna Range, chief among them the major cherty and slaty members described in Chapter 4, Part II. Some horizon-markers in the iron-bearing rocks have proved remarkably persistent and noteworthy. Oölitic rocks (Some examples are shown in Figs. 12 and 13.) have been noted chiefly at the top of the Lower Slaty member. Graphitic slates are noted at several places and have probably developed at several horizons (Van Hise and Leith, 1911, p. 611). Granules (Fig. 22) suggesting original greenalite, are noted in both cherty members and less prominently in some thin-bedded slaty members. Algal structures appear in some cherty beds, besides those noted in the basal beds of the Lower
Cherty member in the Maroco Mine. The colors of cherts — some white and others pink (both commonly stained by iron oxides) — indicate a few restricted horizons. The slates are commonly green where fresh and ferruginous, but some magnetite-bearing beds are black, and other slates have a variety of colors. They range through hundreds of feet of the formation. The Virginia formation, between the North Range and South Range member of the Cuyuna, is variegated — pink, green, and gray — whereas the Virginia at the type locality on the Mesabi Range is gray to black. Magnetite rocks causing compass deflections have been much used as horizon-markers (discussed more fully in Chapter 3).

Dr. G. A. Thiel reports having seen, in about 1922, some questionable algal structure in the Pennington pit. If this is confirmed, it may be a higher horizon-marker than those in the Lower Cherty member on the Mesabi (Gruner, 1946, pp. 38–44). (See Chapter 6.)

With all these key beds, there are other beds, the correlations of which are less certain. Few beds north of the probable extension of the Sagemore fault can be conclusively correlated with those south of the fault. Green carbonate slate beds occur both above and below the Upper Cherty member, and are distinguished chiefly by their position in a sequence of other key beds.
3. THE CUYUNA ORES

DISTRIBUTION OF THE ORES

The Cuyuna Biwabik ores lie above a quartzite that is supposed to be equivalent to the Pokegama quartzite of the Mesabi; they lie below the thick Virginia formation, which is largely slate. The slates of the Virginia formation include a thin iron-bearing member, the South Range belt, which is about three miles south of the North Range belt.

Most of the Cuyuna ore belts are shown in Plate 2, but there has been production in 1951 and 1952 from the Gorman Mine of the South Range member, which is more than 30 miles southwest of the mines on the active producing part of the range. Plans are advanced for production also on the South Range member—at Rice River, Secs. 35 and 36, T. 48 N., R. 26 W., and Secs. 2 and 3, T. 47 N., R. 26 W., and from the lean manganiferous concentrating ore in Sec. 23, T. 48 N., R. 27 W. See Plate 1 for other outlying prospects near Emily, Dam Lake, Bay Lake, and Philbrook. An exploration for sulphur, which was conducted 10 or 12 miles southeast of Aitkin, found not only iron sulphides (see Chapter 5) but some rocks that were originally iron formation and contain more than 30 per cent iron and less than 5 per cent sulphur.

The structures in the Cuyuna mines are very complex and perhaps show more variety than those of most Lake Superior iron districts. In general the ores are crumpled, drag-folded, and faulted. (See Chapter 4, Part II, and Figs. 1-8.) Most of the ores are enriched parts of long persistent beds, but locally some parts of the ore-bearing beds may pinch out as if they were originally lenticular.

FORMATION OF THE ORES

The original sedimentary iron formations carried 15 to 30 per cent iron and 1 to 15 per cent manganese; several were apparently intruded by basic igneous rocks which may have added contact deposits containing iron and manganese and modified the ground water circulation. The porosities of these primary deposits were not uniform, but some fragmental beds may have been more porous than precipitated beds. The more or less porous beds that were folded would guide circulating surface waters downward into synclines (Figs. 1 and 2). Deformation opened up joints and fault cracks along which circulating solutions no doubt added some minerals and leached out others. There is even evidence suggesting that such deformation occurred in two different epochs (Figs. 5-8). Water was available to enter these rock openings; rain and sea waters, and possibly igneous emanations, must have been active.

The formations were long exposed to weathering (before being covered
by glacial drift). There was oxidation of carbonates and silicates, leaching of chert and silica from the quartz and silicates, and replacements of part of the original rocks by ore. Certain Cuyuna horizons are more
favorably affected by these processes than others. Ores are largely in the following beds:

1. Lower Cherty member (e.g., at the Maroco Mine).
2. A zone in the Lower Slaty member (e.g., at the Virginia Mine).
3. Upper Cherty member (e.g., at the Merritt and Mangan mines).
4. Several zones in the Upper Slaty member.
5. The South Range member (e.g., at the Adams and Gorman mines).

Figures 3 through 10 show features of the ore that are visible in hand specimens or outcrops. The metamorphic crenulation of slaty beds can hardly be distinguished, after weathering, from the slump of an ore re-

![Figure 3](image)

**Figure 3.**—Blocks of manganiferous slate, Sagamore open pit, freshly broken to show the darkening resulting from 5 or 10 years' weathering.

resulting from the high porosity of a well-leached bed of iron formation. Some of the large pits, such as the Sagamore and Portsmouth (Plate 2), show such a variety of structures and rocks that no particular structure can be credited with the formation of the ore. Yet so many of the mines show sharp deformations of the bedding that it seems very probable that crumpling and fracturing facilitated enrichment.

Ore bodies in the Cherty members form overlapping layers and lenses with little evident relation to their primary content of iron and manganese. A lens of manganiferous ore in the Section 6 Mine seems to pinch out in about 600 feet, both to the east and to the west. The locations of most of the ores were probably determined by fractures or porous beds, along which secondary contributions of metals were received from associated manganiferous iron-bearing rocks (Figs. 9 and 10), and along which silica was leached. In some mines the higher layers may be re-
placed by ore to a width of 75 feet, whereas the deeper layers show only a few rather narrow lenses of ore. Studies of the Gogebic Range agree on the relation of ores to fractures and to depths (Aldrich, 1929, p. 94; Hotchkiss, 1919, p. 451).

This is rather sharply in contrast with a suggestion made by Zapffe (1933, p. 80), and by Harder and Johnston (1917, pp. 22–23) that ore bodies are related to hanging-wall and footwall horizons, as if the nature of the original beds had more effect on the formation of ore than the
DISTRIBUTION OF THE ORES

pores and fractures. Perhaps both petrography and structures have a good deal of influence, but cherts are likely to fracture under deforming forces that would fold the slates.

Harder and Johnston (1918, p. 129) noted, as we do, that some belts of formation are traceable for miles, with ore bodies formed at spots along them. At a few places, ore is continuous for a mile or more along the formation.

The depths to which crumpling and enrichment of ores extend depend on a variety of factors, such as porosity, folding, fracturing, solubility, and the source and nature of the dissolved material. In 1918 the depths of oxidation (and ore formation) were reported as 200 to 800 feet from the surface. Zapffe (1933, pp. 81-87) reported oxide ores to depths of 1020 feet, and the Croft Mine had been sunk to the 630-foot level. Drilling near Crosby yielded cores assaying 40 to 50 per cent iron at depths of 640 to 893 feet from the surface.

After a reconnaissance of a few open pits, investigators realize the structure is so complex that, where the only data are from scattered drill cores, even the experts may disagree about what is under the glacial drift.

MAGNETICS

A final note on the structure of ore belts deals with magnetic attractions. The South Range member of the Virginia formation was discovered by early drilling near lines of maximum magnetic attractions. Certain beds may be traced for several miles by their effects on magnets, and the general program of drilling extends in all directions from the ore found by magnetics. The subject, however, is a complex one. In the first place, early magnetics were based on compass deflections with a simple dial compass and a dip needle. There has been a progressive improvement of instruments, and later magnetic ground surveys have been made with Hotchkiss' superdips, and other magnetometers. In 1947 air-borne magnetometers (A-2) surveyed vast areas in the state and included the Cuyuna and surrounding areas in traverses a mile apart. These surveys are very suggestive as to the areas that seem to deserve more work. The results of air-borne magnetometer work, that are available to the public, are based on flights at one-mile intervals; but it is recommended that before expensive underground work is begun, flights be made at least 4 or 5 to the mile, and it is commonly profitable to add detailed magnetic ground work before locating drilling operations. The enriched ore along a belt of iron formation is, at many places, less magnetic than the fresh formation, because enrichment by weathering turns magnetite to less magnetic hematite. (Additional information is given below, under "The Origin of Magnetics.")

The lines on the maps of recent surveys do not all agree with lines mapped in earlier years, but such agreement should not be expected. Perhaps the early magnetic survey showed deflection of a compass needle, while some recent instruments record the vertical intensity of the mag-
magnetic force. Again, the early work was done at the surface of the ground and two magnetic formations, 100 feet apart, might give readings that show two belts; but the air-borne magnetometer, carried high in the air for safety, would record as one maximum, two magnetic masses 100 feet apart in the depths of earth.

Used with caution, the magnetic results may be a great help in prospecting. The development of ore bodies in the district has now progressed so far that the student can see the relation of several actual ore bodies to the magnetic belts and intensities. The South Range member proved to have magnetite in the good ore, in a bed about 100 feet wide that stands vertically, and the magnetics led the driller directly to ore. There may be some approach to such simplicity at places outside the South Range, but very few are so simple.

Magnetic belts do help in interpreting the geology, but it has been shown that some iron ores are on the magnetic lines; that some are one side (above or below) a magnetic line as mapped; that some good ores carrying primary limonite and siderite lie in areas of minimum attraction; that some magnetic belts are related to deposits of pyrrhotite (Thiel, 1924b); that the percentage of magnetite in a bed may have been variable in the original deposit at different places; and that there are apparently other factors that confuse the interpretation of magnetics. These features were noted in the field, but they need further study. Thiel (1927) contributed a method of studying the magnetics in central Minnesota by plotting average relative attractions over areas of several townships, rather than along lines.

Zapffe (1933, p. 79) reported that Cuyuna magnetic areas were largely in the "uppermost member," but the geologists of the range have not wholly agreed as to which members are uppermost. There are noteworthy magnetic lines in the Lower Slaty member of the iron formation where drilling shows a magnetite-bearing slate; and no doubt there are some in other members.

Near the Merritt Mine a magnetic maximum follows a line 200 to 300 feet north of the good ore in the underground workings. This is explained by the results of a diagonal drill hole cutting under the best ore and into the footwall (see Chapter 4, Part I). The best ore is in the Upper Cherty member and does not carry magnetite. For about 200 feet northwest of the best ore, the slates underlying the cherty iron formation are green ferruginous carbonate slates which are not magnetic; then for more than 100 feet the slates carry enough magnetite so that the attraction is strong at the surface. Once the succession is understood, it is easy to find the right distance southeast of the magnetic line at which to explore.

Possibly this Merritt belt of magnetics is fairly continuous for several miles, but it should not be assumed to be dependable everywhere in the area. At places these beds may be deeply oxidized, so that the magnetism fades out; and the drift cover may be so thick that the attraction is ob-
In a district like the Cuyuna the magnetic beds may be faulted, as for example, east of the Merritt (Plate 2). And finally there can be found in the district many places where the composition of the beds changes where they are traced along the strike. The magnetic belt on the Merritt property is difficult to trace farther than three miles northeast from the mine. It is possible that the magnetite bed in the slate grows very lean or thin to the northeast.

This illustration is only one of many possibilities for the use of magnetic lines. Another group of mines producing good ore may have been formed in a zone of iron carbonates and silicates, in which no magnetite occurs, and the best ores in such a belt might be found by drilling where the magnetic attraction is at a minimum. In order to make the best use of a survey, each zone in the district has to be studied independently of the others.

**THE ORIGIN OF MAGNETICS**

Magnetic attractions originate in many ways, some of which are as follows (see Chapter 5):

1. Most of the magnetic effects are a result of the magnetite in the rocks, but at several places there may be less magnetite than pyrrhotite, which is also magnetic. The magnetite may have formed in any one of several ways; but the pyrrhotite is largely related to igneous intrusives, either as a segregation, or as an emanation into various contact rocks, or locally in veins. (See Chapter 5.)

2. Magnetite is a fairly common accessory mineral in igneous rocks. Probably in this district magnetite is locally segregated in a gabbro near Philbrook, where it is somewhat titaniferous and associated with abundant segregated apatite and some sulphide. (See Chapter 5.)

3. Contact action of igneous rock on its walls may add magnetite (with or without sulphides). Many of the iron prospects and mines in the Cuyuna district encounter basic intrusives (now altered) which may have added magnetite to their sedimentary wall rocks. Such contact deposits are commonly "bunchy" rather than tabular.

4. Fragmental sedimentary beds commonly carry accessory magnetite sand grains. These are commonly variable within short distances, and are only locally of interest.

5. Sediments precipitated from water may include several iron minerals. Siderite, and other carbonates grading toward siderite, have been widely precipitated in the slates and even in the cherts of the Cuyuna district. Limonite (goethite) is hydrous ferric iron oxide; some is known as "bog ore" because of its abundance in swampy areas. The iron for the deposits on the Cuyuna Range appears to have been derived, directly or indirectly, from basaltic and other rocks, probably reacting with water from rain, streams, and shallow seas. The sideritic slates are among the most abundant rocks in the district, and by weathering and leaching have produced much of the brown ore of the range. The limonite, if origi-
nally deposited in the sea, has probably been locally metamorphosed by heat, so that it has turned to hematite, which is locally abundant in the slaty ores. *None of the iron minerals mentioned in this paragraph has important magnetic properties.*

Where iron carbonate and limonite were deposited together, or the iron carbonate was partly oxidized, metamorphic conditions would favor a reaction to produce magnetite. It is easy to understand that in different parts of a primary bed, the original deposits would differ in the amount of oxidation — probably less at great depth, and less where precipitation was rapid. If the ferric oxide is about equal to the ferrous carbonate, magnetite may be abundant in the metamorphic products.

6. Other precipitates involving iron are likely to be associated with the iron carbonates and oxides; greenalite, stilpnomelane, and minnesotaite are silicates, and these form magnetite grains only by complex alterations and reactions.

7. Once formed, magnetite is rather resistant to oxidation, and many iron deposits have been found and explored by drilling along the belts of high magnetism. The South Range member of the Virginia formation was thus explored.

8. Where an extensive lean magnetite-bearing bed has been long exposed to weathering, as the Mesabi iron formation has been, the silica and other impurities may be leached, leaving the ore notably enriched. Such weathering and leaching is commonly associated with oxidation that changes magnetite to hematite. At many places on the Mesabi Range, the rich hematite ore occurs on a magnetic belt, but at a point on the belt where the magnetic intensity is not at its greatest.

The application of such magnetic variability may be illustrated by an ore body being prospected east of the productive Cuyuna district. In Sec. 23, T. 48 N., R. 27 W., two belts of maximum intensity of magnetic attraction cross each other; but where they cross the intensity of magnetism is not as great as it is a mile away. Two programs of drilling in this area have shown a large body of lean ore at considerable depth (Grosh *et al.*, 1953).

**GRAVIMETRIC SURVEYS**

Gravimetric surveys were made in parts of the district during 1952 and 1953, and give considerable promise. This work requires very much more elaborate engineering and careful instrumental observations than do the super-dip or magnetometer surveys. Some pronounced anomalies have been indicated. In each such case drilling still is required to determine what causes the abnormal gravity record. Ordinarily an iron formation would be expected to be heavier than its associated rocks, but experience shows that if it has been considerably leached and voids have developed in it, an adjacent formation of dense unleached rocks may yield the higher gravity readings. This geophysical method is held in high regard by geologists working in this area.
DISTRIBUTION OF THE ORES

LITHOLOGY OF THE ORES

The lithology of Cuyuna ore is thus described by Harder and Johnston (1918, pp. 134-35).

“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 probable that managanite predominates in the hard ore and pyrolusite and wad in the soft ore.”

The iron ore minerals are magnetite, hematite, goethite, and possibly a little siderite; the manganese minerals are managanite, pyrolusite, psilomelane, and manganosiderite. Groutite is a rare manganese mineral which was discovered by H. J. Hakala and identified by Gruner (1947) in the Cuyuna mines. It has the same composition as manganite.

The accessory minerals of ores are the sedimentary impurities — quartz, chert, clay, feldspars, sercite, graphite, etc. — and the protores, greenalite, stilpnomelane, minnesotaite, and pyrite.

CLASSES OF ORES

Cuyuna ores are variously classified as to their occurrence (in open pit, or in underground mines) or, quite independently of their occurrence, by their grade (to ship direct, or to be concentrated or beneficiated before shipment). Most of the ore now produced is from open pits, but underground mining may increase as the shallow ores are mined out. Recent statistics, based on records of the Minnesota Department of Taxation, indicate that about two thirds of the Cuyuna ore is direct shipping ore, not needing beneficiation; but for the last ten years about half the ore shipped has been beneficiated (A-1). The beneficiation plants have used various processes. Plans are being made to screen some ores for the recovery of enriched nodules, and a large pilot plant is already operating to make “battery grade” manganese oxide, by solution and precipitation (details are given below under “Production, Treatment, and Reserves”).

The ores are also commonly classified as to their texture, color, and composition. In texture the cherty ores show some general differences from slaty ores, and these differences can be detected by men with long experience on the range. The textures grade from original sandy sedi-
ments, which contain some magnetite grains, to chemically deposited ferruginous cherts and thin-bedded carbonate rocks, now largely altered by hot waters and by weathering. Algal structures mark the base of the North Range iron formation, and occur at one or more higher horizons.

Ore colors are red, black, brown, and yellow, with some gradations. There are several inferences as to composition, usually involving the ratio of manganese to iron. Red ores from two or more mines are rich in iron, with very little manganese. There are both brown and black manganiferous iron ores, brown largely derived from slaty iron formation, and black largely from the Upper Cherty member of iron formation. Compared with the brown ores, the black ores are low in phosphorus. Zapffe (1925a) described the black ores as having 10 per cent or more of silica. The yellow ores are much like the brown but are commonly high in phosphorus, and more hydrous, carrying goethite in fine powdery condition.

The final classification, used as the basis for the selling price of ores, is the chemical analysis. Some are iron ores and others manganiferous iron ores. In the early history of the range, the value of ore containing 2 to 8 per cent of manganese was not recognized and some such material was sent to the dump or lean-ore stockpile. Some old manganiferous waste piles have recently been sent to the mill to “sweeten” the lean ores now mined. At present, the selling price is based largely on “combined metals” (iron plus manganese) if manganese is greater than 2 per cent. The Cuyuna Range produces more manganiferous iron ore than all the rest of the United States.

Ores are chemically classified by rather extensive chemical analyses. Records of cargo shipments from the Lake Superior region are published annually in a pamphlet by the Lake Superior Iron Ore Association (A-4), and analyses of Cuyuna ores are reported by the mines which are sources of the cargoes (see Appendix B). The Mining Directory of Minnesota (A-1, 1953, p. 239) gives the accompanying summary table for the Cuyuna Range listing only those shipments that were analyzed:

**Analyses of Cuyuna Iron Ore Shipments for 1952, with Average Analyses for 1943-52**

<table>
<thead>
<tr>
<th>Types of Ore</th>
<th>Total Shipments</th>
<th>Analyses in Percentages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gross Tons</td>
<td>Per Cent Shipped</td>
</tr>
<tr>
<td>High phos.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Bessemer</td>
<td>318,717</td>
<td>13.5</td>
</tr>
<tr>
<td>Manganiferous</td>
<td>1,910,326</td>
<td>81.2</td>
</tr>
<tr>
<td>Aluminiferous</td>
<td>135,220</td>
<td>5.3</td>
</tr>
<tr>
<td>Total</td>
<td>2,354,263</td>
<td>100.0</td>
</tr>
<tr>
<td>Average 1943-52</td>
<td>2,496,092</td>
<td></td>
</tr>
</tbody>
</table>
High-grade ores may contain as much as 67 or 68 per cent of combined metals, but these are exceptional. Manganiferous ores may carry from 2 to 20 per cent manganese.

No large amounts of Cuyuna ore are listed as Bessemer, or as low-phosphorus non-Bessemer grades. The phosphorus in ore samples ranges from a trace to 3 or 4 per cent. Even larger percentages may appear in some associated basic intrusives (Thiel, 1926, p. 689), but little ore containing more than .3 per cent phosphorus is shipped. The Croft Mine ships low-phosphorus Bessemer ores. (See Appendix B, Table C, data for 1918.) Zapffe said (1933, p. 87) the Croft was the only Cuyuna mine shipping such ore, although Armour No. 2 Mine contained similar Bessemer ore.

Somewhat different from the main Cuyuna ores are those of a belt known as the South Range. This is a narrow belt with relatively little manganese (see discussion in Chapter 5, and Plates 1, 2, and 5). The only recent production from the South Range has been at the Gorman Mine.

In the east half of Sec. 31, T. 131 N., R. 30 W., near Randall, there are three small ore concentrations. The one known as the Gorman Mine was operated as an open pit in 1950–52 on SE 1/4 SE 1/4 Sec. 31. The Gorman ore body * is only about 400 feet long by 150 feet wide, the dip is vertical, and there are two basic intrusives into the iron-bearing member. On the northwest side there is a minor drag fold. The ore is a soft, finely banded and hydrated iron oxide of low or medium grade; it may have up to 54 per cent of dry iron, but is shipped with very high moisture content (approximately 17 per cent). The ore and the lean-ore wall material show residual lumps of the fine-banded magnetic slaty iron-bearing beds from which they were derived. The glacial deposits above the ore were 50 to 60 feet thick. An apparently similar but somewhat larger body of ore occurs half a mile north in SE 1/4 NE 1/4 Sec. 31.

Most ore bodies of the South Range member are of such size, shape, and geologic position that they have been mined by underground methods. Because of these facts and the limited market for high-phosphorus ores they have long been considered "non-merchantable." They range in character from soft high-moisture limonitic ores to medium hard red-brown hematite. Local metamorphism by intrusives may have had an influence on the character of the ore.

The composition of ores of the known South Range member is approximately as in the accompanying analyses.

### Analyses of Two Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Iron</th>
<th>Phos.</th>
<th>Silica</th>
<th>Mn.</th>
<th>Alumina</th>
<th>Ignition Loss</th>
<th>Moisture</th>
<th>Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>54.00</td>
<td>.400</td>
<td>10.00</td>
<td>.30</td>
<td>3.00</td>
<td>9.00</td>
<td>16.00</td>
<td>45.36</td>
</tr>
<tr>
<td>B</td>
<td>55.00</td>
<td>9.00</td>
<td>3.00</td>
<td>3.00</td>
<td>9.00</td>
<td>12.00</td>
<td>48.40</td>
<td></td>
</tr>
</tbody>
</table>

* Wolff contributes the notes from this to the heading, "Origin of the Cuyuna Ores."
ORIGIN OF THE CUYUNA ORES

The Cuyuna iron formations originated largely from chemical precipitates, in shallow seas, of chert, carbonates, silicates, and probably oxides; mechanical deposits of clays, sands, and even, locally, of pebbles, played a smaller part in their formation. Concurrently with these deposits, and afterwards, several igneous materials were added, probably some from lavas and others from intrusives; and it seems certain that metals were added to the sea by igneous emanations. The sands and igneous rocks may have contained a little primary magnetite but the dominant sources
FIGURE 10. — Manganiferous ore replacing chert in bunches and along beds, Mangan pit.

FIGURE 11. — Photomicrograph of sand grains of quartz, magnetite, and amphibole, aggregated in Pokegama formation.
of iron and manganese were the chemical precipitates in shallow seas. Later metamorphism made many mineralogical changes, and enrichment of several kinds made these rocks over into the ores.

In outline, the Cuyuna ores were (1) largely deposited in a shallow sea, (2) buried, and consolidated by slight recrystallization and sedimentary cementation, (3) subjected to intrusion of later igneous rocks and mineralized by their emanations, (4) folded and metamorphosed, (5) elevated and (6) exposed by erosion of overlying beds, so that iron formations were (a) weathered, (b) oxidized, and (c) enriched.

It seems almost certain that the common Animikie mechanical sediments were being supplied at a rate that was normal to a shallow sea, and that such erosion and deposition may have continued during the deposition of the iron formation. So little sand and clay is detected in most of the iron formation that one naturally infers a source of abundant temporary supplies and rapid precipitation of the cherts, and iron carbonates and iron silicates. The supplies may have been related to temporary or intermittent outbreaks of igneous activity, with its emanations, its hot springs, and its streams flowing into the sea. It is likely that some Cuyuna lavas came to the shallow sea and reacted vigorously with sea water. Water was no doubt involved in the transportation, and if some of the water was hot and mineralized by igneous gases and hot springs, the alkali carbonates and bicarbonates might have facilitated the solution of silica for the cherts. Carbonic acid, hydrochloric acid, and even sulphur dioxide may have dissolved and transported iron and manganese.

Where iron and manganese precipitation was rapid, the deposits may have been covered before carbonates were oxidized; but where such precipitation was interrupted, mechanical sediments (sand and clay) alternated with the chemical precipitates; or if all sedimentation was restricted, the shallow waters may have oxidized the recently deposited ore minerals.

This general idea of the solution of iron and other metals, and silica, was suggested for some iron ranges discovered earlier than the Cuyuna. But in a range like the Mesabi, the idea was not well supported by evidences of contemporaneous igneous action. The discovery of igneous action related to the Animikie rocks on the Cuyuna may even help to explain the origin of the Mesabi deposits, especially if the correlation of the two ranges can be taken to mean that the shallow sea was continuous from one district to the other.

The ranges differ in that the Cuyuna Range had more carbonate in the primary deposit, and possibly more magnetite before the high-temperature metamorphism. The magnetite may have originated by reaction of ferrous carbonate with a ferric oxide like goethite (limonite).

Harder and Johnston (1918, pp. 130-31) discuss two hypotheses for depositions of iron formation: one assumes that the original precipitates were largely ferrous, the other that they were largely ferric oxides and hydroxides. They find the Cuyuna largely favors that of the ferrous original deposit; but they did find magnetite, which contains both ferrous
and ferric oxides. New data show an abundance of ferrous carbonate, but there is enough magnetite and hematite to indicate an original mixture, perhaps of siderite and goethite, occurring in varying proportions at the several horizons.

Deposition from water dominates the sediments. The Cuyuna Biwabik series shows, above the Pokegama quartzite, an alternation of precipitates and mechanical deposits from water, with rather irregular rhythm. While the major series is alternately cherty and slaty, there are minor modifications, the cherts and slates including local beds that are oolitic (Figs. 11-13) or algal, or iron oxides or greenalite (Fig. 22); and at many places there are some more ordinary sandy and argillaceous beds. There is no large dominant mechanical sediment. Precipitation was probably so rapid at times that iron and manganese formed carbonates without oxides, and so slow at other times that the iron and manganese were wholly oxidized. When precipitation was slow, there were associated mechanical sediments. These facts suggest a wide extension of a shallow sea, with contributions of normal sands and clays, largely interrupted or dominated by precipitates from hot and cold waters. Some of the silicates of iron (greenalite, stilpnomelane, and minnesotaite) seem to be primary bedded precipitates, but others filled veins as if from later introduction. The introduced material may have replaced bedded deposits as well as filling fractures.

The two “Cherty members” are by definition (see Chapter 2) those with chert beds from one inch to many inches thick, in contrast to the...
“Slaty members” described as thinly laminated and ranging in materials from carbonate to iron silicates and thin cherts, with a few more ordinary graywackes, quartzites, and clay slates.

**High-temperature mineralization.** Given such a complex series, the development of an iron ore, with or without manganese, involved a series of processes. Near some intrusive masses, ores may have been formed by contact action. Plate 2 shows many basic intrusives close to producing mines. Dynamic metamorphism involved faulting and folding. Hydrothermal action is perhaps more prominent on the Cuyuna than on other ranges; on this range the iron formation is at many places recrystallized to coarse-grained schists, and mineralized by coarse mineral veins. Thiel (1924a) early reported quartz veins in which the quartz resembled hot-water veins (or even pegmatites); and some of them carried manganite, rhodochrosite, and adularia. Along several small quartz veins, the green slaty iron formation is replaced by cherty limonite for 10 or 15 feet. Clear examples occur in the pits in the SE¼ Sec. 3, T. 46 N., R. 29 W. These effects are largely different from later weathering effects, though some of the vein-fillings include iron oxides. The presence of stilpnomelane and coarse white quartz is taken as evidence that these veins were not formed by weathering. Grout (1946a, Fig. 32) found that veins in the Merritt iron formation carried both acmite and adularia with manganerich carbonate. Near these manganiferous veins the slates are partly replaced by zoned carbonate crystals, probably introduced by hot solutions. The extreme irregularity of the walls of some carbonate veins is further evidence of replacement (Grout, 1946b, Figs. 40 to 53). The formation and the ores were materially enriched by these veins and replacements before weathering (Gruner, 1937; Tyler, 1949; Mann, 1953; James, 1954). Tyler suggests that silica is leached more readily from metamorphic silicates than from cherts; Mann agrees with Gruner as to the importance of leaching by “hot hydrous solutions”; and James opposes the idea of relation of iron-ore formation to intrusive igneous rocks, making no reference to the evidences on the Cuyuna Range.

If metamorphism formed acmite in the iron formation and was accompanied by pegmatite introduction, there may have been high temperatures and hypothermal mineralization, but these features are very local. Weathering has at most places been so intensive that the probably widespread milder metamorphism is obscured.

**Folding and elevation** of the iron-bearing sediments may have accompanied (or preceded, or followed) the high-temperature mineralization. The mechanical effects no doubt included some shatter zones that would guide later mineralizing solutions.

**Weathering.** After deposition as a lean iron formation and some high-temperature alteration, erosion exposed parts of the formation that now underlie the glacial deposits. Before glaciation these rocks were deeply weathered and there was considerable enrichment of the ores, by leaching and by complex replacements (Figs. 9 and 10). These cherty ores on
the Cuyuna give little evidence of any change from chert to silicates (Tyler, 1949) before ore replaced the chert.

Many of the siliceous parts of the formation have had some silica leached, and this leaching left the iron and manganese oxides enriched in the residue. This effect is clearly seen in the cherty members of the formations where parts are rich enough to mine, and where the leaner parts are left exposed in the walls of the open pits. The iron oxide has slumped down along fractures in the cherty beds, forming very porous narrow bands in the abundant chert. Where nearly all of the chert was leached, the slumped manganiferous iron oxide locally made considerable bodies of ore rich enough to mine. A shattered chert may be enriched to ore, even where adjacent unshattered chert is lean.

Structures that guide descending leaching waters probably include both faults and folds; and the high proportion of ores in synclines suggests an important effect of folded beds on the circulation of surface water.

Elsewhere this simple leaching of silica is combined with some solution and deposition of iron and manganese. In some cherty beds, and perhaps even more in the slaty beds, the iron dissolves along with silica and is carried down to lower levels in the formation where the iron is precipitated without the silica that originally accompanied it. Possibly the metals were made locally more soluble by organic acids from surface vegetation. As the solutions mingle with oxidizing waters, the metals reprecipitate at moderate depths. Other reactions may contribute to similar results. The evidence is clear at some places that oxides of the metals now occupy essentially the same space as that once filled by chert, and the carbonates and silicates of the metals. Concretionary growths are common.

This variety in the processes by which ores are formed after the original precipitation of iron formation makes it difficult to select one process as the dominant one on the Cuyuna Range. The abundance of hydrous iron and manganese oxides near bedrock surface, and the way oxide ores finger out at depth suggest weathering processes, but those processes may have been guided largely by the earlier structures resulting from hot water solutions. Probably geologists still differ as to whether more ore was made by replacement than by simple leaching, while they agree that both processes are important. The two constitute a double enrichment, the one removing the silica and other impurities, and the other adding large quantities of oxides of metals derived from solution of overlying beds. As a rule, the thick chert beds become thick-bedded ores, and the thin slaty beds become thin-bedded ores.

A final observation confirming these ideas is that, in the mines from Black Hoof Lake almost to Rabbit Lake, many basic intrusives cut the ore formation; and G. A. Thiel saw evidence at the contact that the late enrichment processes replaced the igneous rock with high-grade hematite for several feet.

Harder and Johnston (1918, pp. 142, 156) considered a suggestion that
most manganiferous iron ores on the Cuyuna were a result of an addition of manganese oxides to an iron-bearing formation. They studied their materials and found that where manganese oxide was abundant, it uniformly replaced iron oxide. A recent study confirms the idea that replacement is common, but that does not imply that the manganese is added from outside the beds involved. The writers, after careful studies of the original formation related to ores, believe that virtually all the good manganiferous ore is derived from a manganiferous original sediment. It is quite possible that during enrichment the manganese continued to migrate a little longer than the iron did, and the observer may get the impression that manganese was introduced.

The two metals involved are, in general, similar in behavior to such solutions as cause enrichment; but there are minor differences between them (Zapffe, 1933, p. 83) which may result in a deposition of more manganese at one place and more iron at another, where both are in the original unweathered deposit. Concretions of manganese oxide may be locally abundant in some slightly manganiferous iron ores; yet many exposed ores show concretionary forms with about the same composition as the matrix.

Results of ore enrichment. Bedding and lamination are likely to be much disturbed, even if there had been only a little faulting and folding before enrichment. Rich ores largely follow fractures a few of which may have been mineralized by hot ascending waters, but most of which guide ores down from the overlying beds of formation. The fractures bearing ore from above commonly finger out below the main masses of ore, into small ore-filled joints. Fractures seem to open wider and extend to greater depths in cherts than in the more “flexible” slates. Many ores have sharp contacts with the nearly primary iron formation. The evidences of replacement are clear (Figs. 9 and 10). At the base of some of the enriched ores, where fingers extend down into green carbonate slates, a little white powdery mineral seems to be residual from the formation of brown ore. This looks like white clay (Royce, 1952), but Gruner has shown that it consists largely of fine quartz and carbonate. The leaching, oxidation, and enrichment may extend down more than 800 feet from the surface of bedrock exposed to weathering. There may be some differences in the susceptibility of slate and chert to enrichment, the slates being “relatively impervious” (Aldrich, 1929, p. 140). On the Cuyuna Range, there are more mines in the Slaty than in the Cherty members, but that may be a result of the very much greater thickness and area of the slaty carbonate formation than of the cherts.

PRODUCTION, TREATMENT, AND RESERVES

Data on shipments of ore from the Cuyuna Range are published annually by the Mines Experiment Station of the University of Minnesota (A-1). Statistics for 1952 were compiled by H. H. Wade and Mildred Alm. (See also Appendix B.)
DISTRIBUTION OF THE ORES

Cuyuna Shipments of Ore in 1952

<table>
<thead>
<tr>
<th>Ore</th>
<th>Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct, open pit</td>
<td>1,146,000</td>
</tr>
<tr>
<td>Direct, underground</td>
<td>290,000</td>
</tr>
<tr>
<td>Concentrates, open pit</td>
<td>1,696,000</td>
</tr>
<tr>
<td>Concentrates, underground</td>
<td>6,000</td>
</tr>
<tr>
<td>Total shipments</td>
<td>3,138,000</td>
</tr>
</tbody>
</table>

Much of the ore mined on the Cuyuna is beneficiated. Of the treated ore about 20 per cent is dried, nearly 40 per cent is washed, about 25 per cent is separated by "hi-density" or "sink-float" methods, about 10 per cent is jigged, and 5 per cent is sintered or nodulized. Roasting, de-sliming, flotation, and electrolytic treatments have been suggested in addition.

Much of the cherty black ore, when partly weathered, shows the cherty material so altered that it is fine-grained and loose. If the black manganese ore is fairly coherent, as it commonly is, a simple washing carries out the fine quartz, leaving lumps much richer in metallic ore. Such "wash ore" is abundant.

The tailings from some "sink float" mills still carry considerable manganese, and a mill was put in operation at Riverton in 1953 by the Manganese Chemical Corporation to extract the manganese as "carbamate" and to precipitate a valuable "battery grade" manganese. Magnetite is recovered as a by-product (see Appendix A; Dean, 1952).

Reserves of ore are estimated yearly by the Minnesota Department of Taxation. (The general situation is shown by the estimates in a series of years in Appendix B.) In brief the reserves in 1920 were about 55 million tons, and in 1950 about 51 million tons (including some inactive South Range properties). Some of the older mines have been closed, but may be reopened if the market should demand the kind of ore left in them.

The new ore reserves, which maintain the totals, have not been so much "new discoveries," as re-estimates of the known ore bodies. The urgent wartime demands since 1940 have so raised the prices of ore that it has been possible to beneficiate and sell low-grade ores that were never before marketable.

ECONOMICS AND EMERGENCIES

It is especially important that all lean manganiferous formations should be segregated in a stockpile, and considered an emergency reserve in case the country could not import or produce enough high-grade manganese ore for wartime demands (see Chapter 7).

The commercial possibilities of the magnetite-bearing slates, both inside and outside the restricted Cuyuna area, were discussed years ago (Thiel, 1924c), and the present work adds only a little to the knowledge of magnetite-bearing belts. Thiel found that some of the Cuyuna magnetite rocks were so fine-grained that it was much more difficult to sepa-
rate the magnetite from them than from the Mesabi taconite. Probably there is little prospect of using Cuyuna magnetite rock as taconite is being used. Property owners and explorers, however, may well keep in mind two factors which might modify the costs of making magnetite concentrates in this district. First, there may be, at least locally, a good deal of recrystallization, coarsening the grains in the ores near the south and southwest parts of the Cuyuna district, so that the magnetite may be more easily concentrated. Second, the drift cover over most of the Cuyuna Range would make mining more expensive than the mining of taconite on the Mesabi Range; but if some pits already opened in the Cuyuna for the mining of ores, exposed an adjoining lean protore formation carrying 30 per cent iron in magnetite, then the magnetite could be easily obtained from the sides of the pit.

These possibilities for the use of low-grade iron formation, for magnetic concentration, or for supplies of manganese in wartime emergency needs, are not suggested as matters for immediate exploration. If the prices of ore increase, or if the country should require the metal for an emergency, such low-grade deposits may be important producers.
4. PART I. STRATIGRAPHIC SUCCESSION
INDICATED BY DRILLING

by Frank F. Grout

THE PROJECT

Early papers commonly reported that no definite stratigraphic succes­

sion had been established on the Cuyuna Range, and writers who sug­

gested definite series disagreed. All the rocks and ores lie 50 to 150 feet
under sandy glacial deposits that cover the district. Harder and Johnston
(1918) reported it “impossible to work out any definite stratigraphic suc­

cession for . . . the district.” Wolff (1919) proposed a succession analo­
gous to that on the Mesabi, here restated (see below, pp. 56–58) with
considerable detail. Zapffe (1933) and Royce (1938) disagreed with Wolff
and with each other. The general tendency was to consider the beds as
lenticular and gradational so that the succession in any one place would
be no guide to what might be expected a mile away. Some generaliza­
tions are attempted in this report, that may bring at least a partial
acceptance. They are based on data which accompany the generaliza­
tions, and it is hoped that any who may disagree will be equally careful
to present observations to support their opinions. Just as in the case of
stratigraphic succession, there have been differences of opinion as to the
age of the Cuyuna ore-bearing rocks, and their correlation with the for­
mations in other Lake Superior districts. The writers of this bulletin have
attempted what Hewett, in charge of manganese for the U.S. Geological
Survey, suggested in 1941 when he wrote (personal communication) that
“if any field work were done on the Cuyuna manganese resources it
should involve precise stratigraphic studies.”

Wolff’s suggestion of correlation with the Mesabi was made in 1919,
and is but slightly modified in Part II of this chapter. He is probably
more thoroughly familiar with the succession of beds and groups on the
Mesabi than any other geologist.

One bed in the Cuyuna district is a relatively thin iron-bearing mem­
ber known as the South Range member. This is several miles from the
North Range and differs considerably from any materials or structures
in that more productive north part of the district. It seems so distinctly
different from the main North Range that no new drilling is needed to
support its interpretation.

In 1941 the wartime need for manganese focused attention on the man­
ganiferous ores of the Cuyuna, and the writer proposed as a research
project to obtain more complete data as to the thickness and quality of
manganese-bearing rock layers. (See Appendix C.) Several thousand dol­
ars were granted for drilling at points recommended by those long fa­
miliar with the district, and four holes ranging from 275 to 818 feet in
length were drilled. Two factors were kept in mind: first the need of the
country for manganese, and second the hope of determining the stratig­
raphy, or succession, of beds. The search for ores, it was felt, would be­
come progressively easier if men could be told whether the best ore
formations were above or below the beds drilled. In the selection of
places to drill an effort was made to avoid the igneous rocks which locally
confuse the sequence for which search was made.

Brief summaries of progress were sent to the Minnesota Geological
Survey and several mimeographed compilations of data were made avail­
able to any who were interested. Three papers were published (Grout,
1942, 1946a, and 1946b).

Most of the cores of these drill tests were split so that half the material
is kept available for examination by anyone interested; they are stored
in Pillsbury Hall at the University of Minnesota, in the charge of the
Minnesota Geological Survey. The other half of the cores furnished ma­
terial for various chemical analyses, laboratory tests, and microscopic
studies.

Minerals in the Slaty members are very fine grained, and not easy to
identify. Several cores were x-rayed by Dr. J. W. Gruner who reports
(personal communication) that besides the carbonate (which effervesces
in acid) and magnetite (detected by a magnet) there are minnesotaite,
stilpnomelane, and chlorite; less abundantly a few cores show quartz,
biotite, sericite, and hematite.

Data from Research Drilling. The southwesternmost, which was also
the first, hole of the recent University drilling, is on the North Hillcrest
property (see record on page 43) about 200 paces east of the center of
the NE\(1/4\) Sec. 9, T. 46 N., R. 29 W. (now considered an east extension
of the Alstead pit). The open-pit operation cleared off an exposure of
some 20 feet of green carbonate slate in a gently rolling, nearly horizontal
position (Fig. 14). The top of the exposure of green slate is oxidized to
ore. The total original thickness of green carbonate slate must be at least
20 feet greater than what was revealed in the drilling plus an unknown
thickness that has been mined out.

The drill hole was put down vertically, but the beds cut by it are not
uniformly horizontal. They dip irregularly at angles shown in Figure 14,
so that 500 feet of drilling cut about 335 feet across the beds. The record
shows that the green carbonate slate ends within 30 feet of the top of the
hole and is underlain by green slate that carries very little carbonate —
there are thin cherts and quartzite layers or lenses, through a zone nearly
50 feet thick. Below these lie thick interbedded gray slates and coarse
graywackes, some badly sheared and contorted. Similar rocks are exposed
in the anticlines north and south of the Hillcrest-Alstead open pit. The
good exposures show very lenticular sandy beds.
The second hole, farther north, was about 10 feet north of the north wall of the Arko pit in 1941-42. The bedding shown in the walls of the pit is gently rolling with no steep dip in any direction near the north wall. Nevertheless, the drill hole going down vertically ran nearly parallel to the bedding of the green carbonate slate for 240 feet. The hole was abandoned as not likely to give any information about the succession of beds. Assays of 240 feet of core by the Minnesota School of Mines Experiment Station indicated that the whole depth averaged 25.46 per cent iron, 5.60 per cent manganese, and 12.86 per cent carbon dioxide.

Near the northeast corner of Sec. 9, the green carbonate slate in the Arko pit is faulted into contact with cherts, probably of the Upper Cherty member. Structurally, where the green carbonate slate turns down so abruptly and so far, it is probable that the overlying beds are dragged down a short distance north of the Arko drilling. Only one drill hole is known between this one and Mahnomen Lake. Possibly Upper Cherty member rocks also lie nearby, to the north of this Arko drill hole, and the cores of the University drilling may be from the Lower Slaty member. Wolff has studied the slaty cores, however, and believes he recognizes some features that correlate them with Upper Slaty member. They are so shown on the map and section, Plates 2 and 4.

The third hole is on the Merritt No. 2 property (Fig. 15). Early drilling and mining showed a belt of black manganiferous ore folded in a synclinarium plunging 60 degrees east. The north limb of the fold is nearly vertical and has slaty rocks both north and south of the ore belt, whereas the freshest rock associated with the ore is thick-bedded and cherty. The location, angle, and direction of the new drilling were selected so as to avoid the thickening at the nose of the folds, and to undercut the best ore and show the fresh rocks in sequence across the ore horizon.* This succeeded very well except that the slaty rocks overlying the ore horizon (to the south-southeast) are much oxidized. Where least weathered they are green slates. A series of five samples of green slates collected in the corresponding crosscut in Merritt No. 2 Mine averages 9.16 per cent manganese.

From 145 feet to 255 feet or more, the formation is thick-bedded and cherty, and has granule textures much like the cherty taconite of the Biwabik formation on the Mesabi Range and its equivalents south of Lake Superior. (This cherty layer was identified by Wolff in 1917 and 1918 when he examined the Merritt and Ferro mines.) Making allowance for the dip of the beds, this chert was probably more than 80 feet thick — enough to represent a considerable member of an iron-bearing series. The Merritt ore has been mined from a zone near the middle of the chert. Where this new drill hole cut that zone, the core recovery was small but

* Plate 2 shows that the Merritt synclinarium plunges east; but it does not show how steep the structure is. In the mine workings the plunge is about 60 degrees, so that if it continued for a mile east, the Upper Cherty member would be 9000 feet below the bedrock surface. It is possible that the white areas on Plate 2 may indicate the overlying Virginia formation.
included chert and black oxide, and the cuttings for 10 feet carried more than 50 per cent of combined iron and manganese. Above the well-identified chert, for about 30 feet, the cuttings looked somewhat slaty, but assays show more than 50 per cent silica (Fig. 15), and it is probable that the cherty member was entered at a depth of about 130 feet.

North of (below) the chert the core recovery was better and, below some thin-bedded acmite rock, the formation is a green carbonate slate for about 250 feet of drilling (200 feet across the beds). This is no thicker than had been guessed by men who know the range, but this is the first place discovered where the evidence of such a thickness is clear and the quality of the rock is known. The green carbonate slate carries 2.77 to 10.55 per cent manganese and will average nearly 5 per cent manganese over the whole thickness. This zone and, to some extent, the overlying cherts are commonly oolitic. The green carbonate and some lower beds are cut by veins of high-temperature minerals, including rhodochrosite, acmite, feldspar and quartz (Grout, 1946a and 1946b). There are relatively few places on the Cuyuna Range where the characteristic manganiferous Upper Cherty member has been drilled through (or exposed) to show, as well as this core does, Slaty members both above and below the cherty rock.

North of (below) the green manganiferous carbonate slate there is a transition to gray slate. For nearly 200 feet the green and gray slates contain finely disseminated magnetite, which makes them very magnetic. Carbonate is also disseminated, and some small veins containing both quartz and carbonate cut the iron formation. The magnetite is so abundant that this black slate just below the manganiferous carbonate slate is definitely part of the Cuyuna iron-bearing formation, and is not related to any lower slate series such as the Thomson formation.

Next below the highly magnetic slates are gray slates that seem to be derived from more ordinary mechanical sediments, and some associated graywacke. The gradation is complete and there can be no doubt that common clays were deposited in the same body of water as the precipitated iron-bearing minerals. It should be noted also that the iron content is high even in the graywacke. This creates a problem in the nomenclature of the series. Bruce (1945, p. 600) contrasts iron-bearing formations with sediments of elastic material; but on the Cuyuna there are evidently intermediate rocks. Beds of mechanical sediments in a series of iron-bearing formations of greater thickness are here considered lean members of the iron formation. (See Fig. 24 and Chapter 6.) Even the graywackes in the last 150 feet of core from this drilling assayed about 20 to 30 per cent in iron.

The fourth hole was drilled at the Northland property to see if the Northland beds could be correlated with the belt from the Merritt northeast, in a petrographic series. (See Figs. 16 and 17.) The green carbonate slate on the dump of the Northland Mine closely resembles the green slate below the chert at the Merritt and elsewhere, but there may
be such slates at two or more horizons. There are also quartz-carbonate veins resembling those in the Merritt green slates. A deep angle hole was located west of the shaft, and directed diagonally north to show the sequence of beds below the carbonate. It cut first a green slate low in carbonate, and then a very thick black slate and graywacke; but the cores show very little of the fine-banded magnetic iron formation such as that in the Merritt hole. Some of the green slate has a granule texture like that from greenalite (depth 594 feet). This lack of a thick magnetite-bearing bed seems evidence enough to correlate the Northland slates with the Upper Slaty member. If doubts remain, they may be settled if the Upper Cherty belt northeast of the Merritt Mine could be traced farther east than Sec. 22, T. 47 N., R. 29 W. There is room enough in the great area of slaty material for several large folds.

Assays have been made by the University of Minnesota Mines Experiment Station and their findings are reported in the accompanying records.

**RECORD OF DRILL HOLE ON NORTH HILLCREST PROPERTY,**
**UNIVERSITY DRILLING 1941-42**

(Vertical hole about 1180 feet south and 725 feet west from NE corner Sec. 9, T. 46 N., R. 29 W. Drilled from a bench in the open pit.)

See Figure 14.

<table>
<thead>
<tr>
<th>Materials (depth in feet)</th>
<th>Analyses, Dried at 212° F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Per Cent of Fe</td>
</tr>
<tr>
<td>Green carbonate slate</td>
<td></td>
</tr>
<tr>
<td>10-15</td>
<td>36.21</td>
</tr>
<tr>
<td>15-20</td>
<td>23.96</td>
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<tr>
<td>20-25</td>
<td>26.90</td>
</tr>
<tr>
<td>25-30</td>
<td>27.06</td>
</tr>
<tr>
<td>Green slate, part oxidized</td>
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</tr>
<tr>
<td>30-40</td>
<td>32.64</td>
</tr>
<tr>
<td>40-50</td>
<td>15.04</td>
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<tr>
<td>50-60</td>
<td>4.65</td>
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<td>60-65</td>
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<td>100</td>
<td>6.13</td>
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<tr>
<td>Gray slate</td>
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<tr>
<td>105-165</td>
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<tr>
<td>Sheared slaty quartzite</td>
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</tr>
<tr>
<td>165-250</td>
<td>4.94</td>
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<tr>
<td>Gray slate</td>
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<tr>
<td>250-340</td>
<td>4.49</td>
</tr>
<tr>
<td>Graywacke and gray slate</td>
<td></td>
</tr>
<tr>
<td>340-500 (bottom)</td>
<td>12.33</td>
</tr>
</tbody>
</table>
THE CUYUNA RANGE

RECORD OF DRILL HOLE NEAR MERRITT SHAFT NO. 2,
UNIVERSITY DRILLING 1941-42

(Hole directed N. 25° W., inclined 55° from horizontal; hole at about 2180 feet south and 440 feet east of NW corner Sec. 33, T. 47 N., R. 29 W.)

See Figure 15.

<table>
<thead>
<tr>
<th>Materials (depth in feet)</th>
<th>Analyses. Dried at 212° F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Per Cent of Fe</td>
</tr>
<tr>
<td>Glacial deposits</td>
<td></td>
</tr>
<tr>
<td>0-78</td>
<td></td>
</tr>
<tr>
<td>Cherty and slaty, mixed cuttings (red near surface, grades into green below)</td>
<td></td>
</tr>
<tr>
<td>78-85</td>
<td>14.50</td>
</tr>
<tr>
<td>85-90</td>
<td>13.35</td>
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<tr>
<td>90-95</td>
<td>13.72</td>
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<td>95-100</td>
<td>17.91</td>
</tr>
<tr>
<td>100-105</td>
<td>8.76</td>
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<td>105-110</td>
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<td>110-115</td>
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<td>11.32</td>
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<td>140-145</td>
<td>12.90</td>
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<tr>
<td>Cherty cuttings</td>
<td></td>
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<tr>
<td>145-150</td>
<td>43.99</td>
</tr>
<tr>
<td>150-155</td>
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<td>155-160</td>
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<td>35.43</td>
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<tr>
<td>175-180</td>
<td>30.08</td>
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<tr>
<td>Cherty, some core, mostly cuttings</td>
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<tr>
<td>180-185</td>
<td>42.95</td>
</tr>
<tr>
<td>185-190</td>
<td>43.34</td>
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<td>190-195</td>
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</tr>
<tr>
<td>250-255</td>
<td>28.87</td>
</tr>
<tr>
<td>Locally oolitic, hard, thin-bedded core (slaty structure)</td>
<td>24.65</td>
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<tr>
<td>255-310</td>
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<tr>
<td>Green carbonate slate cores</td>
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</tr>
<tr>
<td>310-317</td>
<td>18.92</td>
</tr>
<tr>
<td>317-325</td>
<td>20.78</td>
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<td>325-330</td>
<td>27.99</td>
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<tr>
<td>330-385</td>
<td>20.93</td>
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</table>
## STRATIGRAPHIC SUCCESSION

### RECORD OF DRILL HOLE NEAR MERRITT SHAFT NO. 2—Continued

<table>
<thead>
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<th>Materials (depth in feet)</th>
<th>Per Cent of Fe</th>
<th>Per Cent of Mn</th>
<th>Per Cent of SiO₂</th>
<th>Per Cent of CO₂</th>
</tr>
</thead>
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<td>5.10</td>
<td>11.82</td>
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<td>405-410</td>
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<td>410-415</td>
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<td>415-420</td>
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<td>440-445</td>
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<td>445-450</td>
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<td>4.88</td>
<td>14.58</td>
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<td>450-455</td>
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<td>14.16</td>
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<td>455-460</td>
<td>26.67</td>
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<td>14.70</td>
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<td>460-465</td>
<td>26.05</td>
<td>4.99</td>
<td>14.40</td>
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<tr>
<td>465-470</td>
<td>26.28</td>
<td>4.46</td>
<td>11.00</td>
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<td>470-475</td>
<td>22.23</td>
<td>5.85</td>
<td>19.92</td>
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</tbody>
</table>

Green carbonate, slate, magnetic cores

| 475-480                   | 30.78          | 3.78           | 10.60            |                 |
| 480-485                   | 31.01          | 4.01           | 11.76            |                 |
| 485-490                   | 33.88          | 3.59           | 11.34            |                 |
| 490-495                   | 33.88          | 3.33           | 10.32            |                 |
| 495-500                   | 33.34          | 3.38           | 10.36            |                 |
| 500-505                   | 34.19          | 3.26           | 11.16            |                 |
| 505-510                   | 33.73          | 2.77           | 7.68             |                 |
| 510-515                   | 32.72          | 2.84           | 9.48             |                 |
| 515-525                   | 32.18          | 2.92           | 8.78             |                 |
| 525-535                   | 30.92          | 3.78           | 11.08            |                 |
| 535-540                   | 29.77          | 3.63           | 10.78            |                 |

Green carbonate slate

| 540-555                   | 25.56          | 5.51           |                  |                 |

Gray and green slates

| 555-645                   | 30.20          | 3.71           |                  |                 |

Graywacke, gray slaty formation

| 645-712                   | 30.81          | 2.38           |                  |                 |

Gray slate and quartzite *

| 712-782 (bottom)          | 19.68          | .33            |                  |                 |

* Magnetite in scattered beds to 735 feet.
THE CUYUNA RANGE

RECORD OF DRILL HOLE ON ARKO PROPERTY, UNIVERSITY DRILLING 1941-42
(Vertical hole about 20 feet south and 1600+ feet west of NE corner Sec. 9, T. 46 N., R. 29 W. Drilled from a bench at the northwest edge of the Arko pit, near some cherts.) See Plate 2.

<table>
<thead>
<tr>
<th>Materials (depth in feet)</th>
<th>Per Cent of Fe</th>
<th>Per Cent of Mn</th>
<th>Per Cent of CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green carbonate slate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40-70</td>
<td>26.47</td>
<td>2.97</td>
<td>3.76</td>
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<tr>
<td>70-100</td>
<td>24.06</td>
<td>5.60</td>
<td>11.66</td>
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<tr>
<td>100-150</td>
<td>23.60</td>
<td>6.07</td>
<td>14.72</td>
</tr>
<tr>
<td>150-200</td>
<td>24.69</td>
<td>5.74</td>
<td>14.26</td>
</tr>
<tr>
<td>200-250</td>
<td>22.90</td>
<td>6.07</td>
<td>14.02</td>
</tr>
<tr>
<td>250-280 (bottom)</td>
<td>21.19</td>
<td>6.37</td>
<td>15.78</td>
</tr>
</tbody>
</table>

RECORD OF DRILL HOLE ON NORTHLAND PROPERTY, UNIVERSITY DRILLING 1941-42
(Hole directed north, inclined 55° from horizontal; about 3760 feet north and 5240 feet west of SE corner, Sec. 20, T. 47 N., R. 28 W.) See Figure 16.

<table>
<thead>
<tr>
<th>Materials (depth in feet)</th>
<th>Per Cent of Fe</th>
<th>Per Cent of Mn</th>
<th>Per Cent of P</th>
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<tbody>
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<td>Glacial deposits</td>
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<td></td>
</tr>
<tr>
<td>0-155</td>
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<td></td>
<td>0.313</td>
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<tr>
<td>Brown oxidized cuttings</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>155-160</td>
<td>26.76</td>
<td>0.57</td>
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<tr>
<td>160-165</td>
<td>18.53</td>
<td>1.78</td>
<td>none</td>
</tr>
<tr>
<td>165-170</td>
<td>23.80</td>
<td>0.76</td>
<td>none</td>
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<td>170-175</td>
<td>20.55</td>
<td>3.18</td>
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<td>175-180</td>
<td>14.81</td>
<td>3.52</td>
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<tr>
<td>180-185</td>
<td>18.76</td>
<td>1.18</td>
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<td>185-190</td>
<td>26.28</td>
<td>0.12</td>
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<tr>
<td>190-195</td>
<td>34.97</td>
<td>0.05</td>
<td>none</td>
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<tr>
<td>195-200</td>
<td>43.11</td>
<td>0.16</td>
<td>none</td>
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<tr>
<td>200-205</td>
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<td>0.313</td>
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<td>26.36</td>
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<td>29.54</td>
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<td>28.77</td>
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<td>27.68</td>
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<td>35.73</td>
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<td>0.49</td>
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<td>295-300</td>
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<tr>
<td>300-305</td>
<td>49.16</td>
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STRATIGRAPHIC SUCCESSION

RECORD OF DRILL HOLE ON NORTHLAND PROPERTY—Continued

Analyses, Dried at 212° F.

<table>
<thead>
<tr>
<th>Materials (depth in feet)</th>
<th>Per Cent of Fe</th>
<th>Per Cent of Mn</th>
<th>Per Cent of P</th>
</tr>
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<tbody>
<tr>
<td>Pink cuttings with 4% core</td>
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<td></td>
</tr>
<tr>
<td>305-310</td>
<td>50.94</td>
<td>0.04</td>
<td>0.430</td>
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<td>310-315</td>
<td>33.50</td>
<td>0.82</td>
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<td>43.65</td>
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<td>32.95</td>
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<tr>
<td>330-335</td>
<td>20.16</td>
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<td>335-340</td>
<td>17.37</td>
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<td>16.67</td>
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</tr>
<tr>
<td>345-350</td>
<td>15.58</td>
<td>none</td>
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<td>Green cuttings with 4% core</td>
<td></td>
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</tr>
<tr>
<td>350-355</td>
<td>12.17</td>
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<tr>
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<td>13.80</td>
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<td>Core green slate (magnetite at 350)</td>
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<td>380-390</td>
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<tr>
<td>Core dark</td>
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<tr>
<td>390-400</td>
<td>10.47</td>
<td>0.11</td>
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<td>Core gray slate</td>
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<tr>
<td>400-410</td>
<td>6.28</td>
<td>none</td>
<td></td>
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<tr>
<td>Core graywacke and gray slates</td>
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<tr>
<td>700-818 (bottom)</td>
<td>5.97</td>
<td>0.19</td>
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LOCAL CORRELATIONS SUGGESTED

Attempts to correlate the formations in the three deep drill holes are not wholly satisfactory. The magnetite-bearing bed in the Northland core is much thinner than that in the Merritt core; and the gray slates below the green carbonate slaty iron formation in the North Hillcrest cores have much more sheared quartzitic material than the other two. The North Hillcrest quartzite lenses and the Northland graywackes are probably Upper Slaty member, as classified by Wolff (see page 57), but there is some doubt.

The most obvious relation suggested by the diagram of the three holes (Fig. 17) is that the gray slates and graywackes at the bottom of each should be equivalent, but this leads to difficulties since the beds above the gray slate are different in the three holes. The magnetite slate bed, which is 200 or more feet thick in the Merritt core, is hard to correlate with a very thin one in the core at the Northland. Plate 2, nevertheless, shows the Northland area as Upper Slaty material.

The Upper Cherty member may have been eroded at the North Hillcrest and Louise pits, or it may be deep underground, as Plate 4 indicates. Thick slates lie both above and below the chert of the Merritt
Mine. The high position of the North Hillcrest (see upper part of Fig. 17) is favored, largely because quartzite lenses occur in the North Hillcrest cores, and in some adjoining open-pit mines but are not found in the cores of the Lower Slaty member of the nearby Merritt Mine.

Attention is directed to the fact that mapping should not be based on an assumption of continuity of each of the belts, or even within large members of the formation. There are breaks, faults, and sharp changes of dip and strike (Harder, 1917a, p. 1321). The Upper Cherty member at the Merritt Mine is probably faulted away from the corresponding belt a mile east. Many such breaks may be concealed under the surface formations.
There are green manganosiderite slates in beds 200 feet thick as measured on the limb of a fold at the Merritt No. 2 property; and mining has shown that beds are thinner on such limbs than in the crests and troughs of folds. It is desirable to explore the thickness at other points. The continuity of the bed along the strike had been fairly well established by earlier drilling but there had been no very satisfactory evidence as to its thickness.
Carbonate slates of the Merritt drilling lie below the Upper Cherty member but there were slaty cuttings indicating one slate above and another below that cherty member.

Both of the green carbonate slates assay from 10 to more than 40 per cent iron, from .2 to 15 per cent manganese, from 5 to 20 per cent carbon dioxide, and from 20 to 40 per cent silica.

Aside from scattered thin-bedded cherty lenses in the slates, there are genuine cherty zones, with thick beds and continuity enough to be considered as members of the iron formation.
The cherts (and even some carbonate slates) have granule textures, which suggest that they originated from greenalite or related silicates.

The abundance of iron in the green carbonate slates and in some of the black slates makes it clear that these slates are facies of the iron formation. The lower part of the Merritt drilling, reported as "gray slate
and graywacke," carries 30.81 per cent iron and 2.38 per cent manganese from 645 to 712 feet; and the lowest core, from 712 to 782 feet, still carries almost 20 per cent iron and .33 per cent manganese. These graywackes and quartzites have more iron than most slates. As a corollary, the iron formation is not measured by the thickness of a cherty bed or any other single member; it is many hundreds of feet thick. It is no longer correct to say that "the formation" of the north Cuyuna district is a thick slate in which thin beds of iron formation make separate members at uncertain horizons. (Such a remark may apply to the South Range member in the Virginia formation; exploration has not yet proved that the South Range member involves more than one bed.)

The Cuyuna Biwabik formation exhibits a fourfold division analogous to that on the Mesabi Range. The ores should be studied to see if one characteristic kind of ore is closely related to one certain member, or possibly to a small bed of the iron formation. There have been several suggestions that the original rock of the manganiferous ores is carbonate slate, but clearly not all the manganese is in slaty members, for the "black ore" of the Merritt Mine is in a cherty member, and there are locally some similar ores in the Lower Cherty member. At places the green carbonate slate may be fresh and unoxidized almost up to the surface of bedrock, whereas the zone of oxidation and leaching in the chert extends far down; possibly chert is more subject to shattering and replacement than the fine slates; or possibly a zone of oxidation may follow a layer originally containing more manganese carbonate than the other layers.

Published preliminary notes (Grout 1942 and 1946) emphasized the occurrence of a slaty zone about 200 feet thick, probably continuous for many miles, which had enough manganese so that it might supply the country's needs if a submarine campaign prevented such imports as normally supplied about 90 per cent of our needs. The assays of core samples were mimeographed for Cuyuna Range miners who might be interested (see Appendix B).

The University drilling was classified in terms of Wolff's scheme (see column, pages 56-57). None of it reached the Lower Cherty member as was hoped, but three holes came to some gray slates and graywackes that closely resemble those exposed in the eastern approach to the Maroco pit, where the Lower Cherty member is characteristic and well exposed (when the pit is pumped out). It seems very clear that in the three mines that have been deeply drilled the beds lie above the Lower Cherty member.

The failure of the University drilling to give a record from Upper Cherty member to Lower Cherty member, probably indicates that the old estimate of the thickness of Lower Slaty beds was too small. There are probably almost a thousand feet of Lower Slaty member. It should be noted also that the concentrations of magnetite may lie in beds that differ in thickness along the belt, and that sandy or quartzitic lenses may
pinch and swell irregularly, and, pending further drilling, may be ex­pected to appear in either the Upper or Lower Slaty members, or both.

The generalized sequence for the Cuyuna Range is to be credited to Wolff (see Chapter 4, Part II), and the University drilling fits it very well. With some open pits along the Lower Cherty member and a series of pits from the Martin Mine to the Manuel, to show the Upper Slaty member, the drilling at the Merritt Mine— and possibly that at the North Hillcrest Mine— gives fairly satisfactory data for the interme­diate sequence.

Here then is a sequence which has strong supporting evidence: (1) Underlying quartzite is exposed in the Rowe, Section 6, and Maroco Mines. (2) The Lower Cherty member, which is about 100 feet thick, produces chiefly iron ore in the same pits. (3) Above that cherty zone (neglecting green altered intrusives) lies a thick series of lean clay slates and gray­wackes, which are almost certainly equivalent to those reached by drill­ing at the Merritt. (4) Above that is the carbonate slate, partly mag­netitic and nearly black, but largely green and manganiferous. (5) Then comes the Upper Cherty member, roughly 100 feet thick and locally enriched to manganiferous black ore. (6) Above that chert is a thick series of iron-bearing beds, partly manganiferous, largely slaty in texture but with some thin-bedded cherty streaks. (7) The South Range is largely distinct and appears to be an iron-bearing member, 100 to 200 feet thick, in the Virginia formation at a much higher horizon in the Animikie series.

PROBLEMS

If facts appear to cast doubt on such a sequence, they should be pre­sented with supporting data. The U.S. Geological Survey now has C. E. Dutton and Robert Schmidt mapping structures and exposed materials in detail. Further work may settle some of the questions, which cannot now be answered.

1. If a zone of quartzite lenses in gray slates is at one definite horizon, and not in both Upper and Lower Slaty members, such a zone of quartzites may prove to be a good horizon-marker (rather than a source of confusion). The Pokegama quartzite is more massive and in a sequence different from that showing lenses.

2. Deep drilling near the south edge of the North Range, where the belts show little crumpling or confusion, might give a typical cross sec­tion of Upper Slaty member down to the Upper Cherty member. It would help correlations to know how thick the Upper Slaty member is from top to bottom.

3. Drilling to extend the cross section from Upper Cherty member down farther than the Merritt hole went, should give a more accurate thickness of the Lower Slaty member. Present estimates are based partly on the Merritt hole and partly on drilling near Emily by the Oliver Iron Mining Company.

4. Drilling might well follow some of the magnetic lines in the North
Range in order to answer these questions: Are the thicknesses of magnetite beds variable along the strike? Do they differ in percentage of magnetite along the strike? Are the belts carrying magnetite faulted or offset? Is the magnetite locally so oxidized that it loses its magnetism? (See page 26.)

5. In considerable areas that have been explored by drilling but not by open pits, the formations have not been well identified. For example, a cherty bed runs several places through Sec. 3, T. 46 N., R. 29 W., and may be equivalent to the belt from Sec. 34 to 36, T. 47 N., R. 29 W. Another belt, probably at a different horizon, runs from Rabbit Lake to the Portsmouth Mine (and apparently farther west; see page 76).

South of the Virginia pit, near Jeune Lake, the Pokegama formation is mapped in a wide area around a syncline of iron formation. Some recent holes found iron formation where quartzite is mapped.

The belts of magnetite concentrates may pinch out, or decrease along a bed, or be offset by faulting. Actual maps are not easily interpreted. For example, a magnetic line runs through Secs. 8 and 9, T. 46 N., R. 29 W., crossing the supposed Sagamore fault without any prominent offset or change in intensity. A different problem arises in the formation mapped by drilling, from Sec. 3 to Sec. 6, T. 46 N., R. 29 W., and west into Sec. 12 of the next township. At this west end the magnetic attraction is prominent, but it has not been traced east.

The chert belts mapped from the southeast corner of Rabbit Lake to Ironton may reappear in small or weathered exposures for a mile or two west of the Ironton shaft. In 1953, drilling cut thick-bedded cherts in S½ NE¼ Sec. 9, T. 46 N., R. 29 W., and a chert belt of uncertain thickness seems to run east, toward the west extension of the Mahnomen pit.

6. There are few horizon-markers or sequences north of the Sagamore fault which can be clearly identified south of the fault, except perhaps the fault block in Sec. 3, T. 46 N., R. 29 W.

PART II. DESCRIPTION OF GEOLOGIC MAPS AND CROSS SECTIONS

By J. F. Wolff, Sr.

A description of the geologic map of the Cuyuna district, the structural cross sections through the district, and the detailed geologic column showing the character and thickness of the different rock layers in the iron formation, are presented in this chapter.

The writer has been familiar with the drilling explorations in the Cuyuna district since 1908 and spent most of 1918 among the Cuyuna
mines, many of which are now abandoned so that the underground workings are no longer available for inspection. Since then he has repeatedly visited many of the mines and explorations in the district.

By 1918 the similarity between the rocks and sequences of the Cuyuna district and those of the Mesabi district was evident (Wolff, 1919) and in the course of a few years it was possible to compile an areal geologic map and structural cross sections of the district, which have been revised as subsequent information has become available. (See Plates 2, 3, and 4.) In this work the writer has had available the records of most of the drilling done in the district, and has personally examined and recorded in detail the structure of the ore bodies in open pit and underground mine workings.

One of the greatest difficulties of geologic interpretation in the district has been the lack of outcrops of any kind in the area. All records had to be obtained from diamond-drill and churn-drill information and from mine workings. Because of the very close folding of the rocks of the district, every formation in the area has been classified as schist by some engineer or drill foreman. In compiling a map, therefore, one must sift the data and make a pattern to fit the facts. The records of a few thousand drill holes have been scrutinized closely and the samples from several hundred have been examined.

The Cuyuna district is commonly considered as made up of two parts: a large North Range, and a smaller South Range member of the Virginia formation, in the midst of barren slates several miles wide. The active part of the North Range is roughly ten miles long northeast and southwest, and four miles wide. The South Range member is a narrow slaty iron formation about 200 feet thick, which has been followed by magnetic surveys and explorations in a northeast-southwest direction for more than sixty miles. For about half this length there are two or more subparallel magnetic belts, believed to be repetitions of a single bed by folding. Other magnetic lines to the south may result from a further repetition by folding of the same iron-bearing layer; but there seem to be still others resulting from magnetite concentrations at other horizons in the sediments.

NORTH CUYUNA RANGE GEOLOGIC COLUMN

The Animikie iron formation of the Mesabi Range was subdivided by the writer, about 1912, into four major members: a Lower Cherty, followed by a Lower Slaty, then an Upper Cherty, and on top, an Upper Slaty member. These were technically described in detail, as follows: Cherty members have a dominance of thick-bedded cherts; Slaty members rarely show cherts dominating a large exposure, and whatever cherts there are, are thinly laminated. It is essential to keep these definitions of terms in mind. Since these major members can be recognized also in the Michigan and Wisconsin iron districts, it was natural to look for
them in the Cuyuna district; and fortunately they have not been difficult to recognize. On top of the Mesabi iron-bearing rocks is a gray and black slate formation of great thickness named Virginia slate or formation; and thick slates also lie above the Animikie iron formation in Michigan and Wisconsin. Slates in abundance also overlie the North Cuyuna Range, but not all are uniformly gray.

The approximate geologic column of the North Cuyuna district, supposedly the equivalent of the column on the Mesabi, is shown on pages 56–58. This column shows not only the four members, but some subdivisions, and gives the names of the better and larger ore bodies of the

<table>
<thead>
<tr>
<th>Formations and Beds</th>
<th>Thickness in Feet</th>
<th>Properties and Ore Bodies Showing These Formations and Beds</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIRGINIA FORMATION</td>
<td>(5000 plus)</td>
<td>(South Range member, thin beds)</td>
</tr>
<tr>
<td>BIWABIK FORMATION</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**UPPER SLATY MEMBER**

- Manganiferous slaty iron formation. 200–350* Armour No. 2, Ironton, Thompson, Meacham, Croft, Manuel
- Banded thin-bedded cherty iron formation 175–400* Armour-Croft group
- Gray slate or schist† 330–330 Armour No. 1, Pennington, Feigh, Huntington, Martin, So. Hillcrest, Portsmouth, Kennedy, Yawkey, Rabbit Lake, Mallen
- Evenly banded thin-bedded cherty iron formation 180–250* Portsmouth, Yawkey, Mahnomen No. 1, Mangan No. 2, T. 137 N., R. 26 W.? 
- Sericitic and graphitic slates 50–50
- Manganiferous carbonate slate 150–185
- Banded iron formation 150–175 Mahnomen group, Mangan No. 2, Louise and Portsmouth, T. 137 N., R. 26 W.? , Milford, Northland?
- Gray siliceous slate with quartzite lenses 80–80 Louise-Alstead group, Hopkins, Arko, Sultana, Sagamore, Northland?
- Green manganiferous carbonate slate with cherty bands 210–250 Louise, Hopkins, Sultana, North Hillcrest
- Green siliceous slate with lenses of quartzite and graywacke 170–230

Subtotal, Upper Slaty Member 1695–2300
## Formations and Beds

<table>
<thead>
<tr>
<th>Thickness in Feet</th>
<th>Properties and Ore Bodies Showing These Formations and Beds</th>
</tr>
</thead>
</table>

### UPPER CHERTY MEMBER

- **Granular and banded cherty taconite** with black manganiferous iron ores: 80-165 ft. [Joan, Mangan No. 1, Louise, Hopkins, Sultana, Merritt group, Gloria, Preston, Hunter, Pontiac]

### LOWER SLATY MEMBER

- **Fine-banded pink taconite** slaty iron formation: 40-140 ft. (Mahnomen Lake, Virginia, Maroco. Section 6 and Rowe mines; Merritt Group; Ruth Lake Group (sections 22 and 27, T. 138 N., R. 26 W.).
- **Dark green and gray manganiferous slaty carbonate iron formation**: 115-115 ft. (Rowe mines; Merritt Group; Ruth Lake Group (sections 22 and 27, T. 138 N., R. 26 W.).
- **Black magnetic slaty iron formation**: 80-80 ft. (Rowe mines; Merritt Group; Ruth Lake Group (sections 22 and 27, T. 138 N., R. 26 W.).
- **Gray slate, graywacke and thin quartzite lenses**: 330-380 ft. (Rowe mines; Merritt Group; Ruth Lake Group (sections 22 and 27, T. 138 N., R. 26 W.).

**Subtotal, Lower Slaty Member**: 700-750 ft.

### LOWER CHERTY MEMBER

- **Lean chert**: 15-25 ft. (Maroco, Section 6 and Rowe mines; Ruth Lake Group (see above); T. 138 N., R. 26 W.).
- **Granular and banded cherty taconite**: 70-150 ft. (Maroco, Section 6 and Rowe mines; Ruth Lake Group (see above); T. 138 N., R. 26 W.).
- **Granular manganiferous cherty taconite**: 10-30 ft. (Maroco, Section 6 and Rowe mines; Ruth Lake Group (see above); T. 138 N., R. 26 W.).
- **Slaty manganiferous taconite**: 3-10 ft. (Maroco, Section 6 and Rowe mines; Ruth Lake Group (see above); T. 138 N., R. 26 W.).
- **Contorted jaspery chert (algal) and conglomerate**: 2-5 ft. (Maroco, Section 6 and Rowe mines; Ruth Lake Group (see above); T. 138 N., R. 26 W.).

**Subtotal, Lower Cherty Member**: 100-250 ft.

**Total thickness, iron formation**: 2575-3465 ft.

### UNDERLYING POKEGAMA FORMATION

- **Quartzite and quartz slates**: 350 or more ft. (Maroco, Section 6 and Rowe, Sagamore. Emily and Ruth Lake areas (see above).)
- **(Unconformity)**: 250 or more ft. (Maroco, Section 6 and Rowe, Sagamore. Emily and Ruth Lake areas (see above).)

### PROBABLY EARLIER PRECAMBRIAN

- **Dense limestone and chert (dolomitic?)**: 250 or more ft. (T. 137 and 138 N., R. 26 and 27 W.)
- **(Unconformity)**

### PROBABLY ARCHEAN

- **Green schists (pyritiferous)**: 2 ft. (Sections 5 and 6, T. 46 N., R. 29 W.; Section 32, T. 47 N., R. 29 W.)

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* For those marked, the wide range of thickness may result from igneous intrusives.
† See below, pages 65-67.
‡ These thicknesses may have been exaggerated by folding.
district in which the rocks of the different members are believed to occur. The series cannot be seen in a single continuous exposure, and no single drill hole of 3000 to 4000 feet is likely to reveal the complete series because of the complex folding and faults in nearly all parts of the area. The column is frankly an attempt to compile a series from (1) analogy with the Mesabi Range, (2) a series of exposures in mines, both open pits and underground, (3) cross sections of folds cut in underground drifts, and (4) the study of a great many drill cores, including some from a few rather deep holes.

The writer takes sole responsibility for compilation of the accompanying geologic column, the geologic maps and cross sections on Plates 2, 3, 4, and 5, and the correlation diagram on Plate 6.

The total thickness of the three lower members on the Cuyuna, which ranges from 880 to 1165 feet, is greater than that of the same members on the Mesabi, whose maximum thickness is 690 feet. The Upper Slaty member on the Cuyuna is many times as thick as the correlated member on the Mesabi (37 to 261 feet). If the Upper Slaty rocks were ever as thick on the Mesabi as on the Cuyuna, it is likely that much was eroded before the Virginia slate was deposited.

The geologic map, Plate 2, shows in distinctive colors the areal distribution of the four major members of the Biwabik iron formation in the North Cuyuna area. Two minor cherty layers are shown interbedded in the Upper Slaty member north and northeast of Ironton, toward Rabbit Lake. Should the reader question whether these layers might not be a part of the Upper Cherty member, the differences in character and composition between the Upper Cherty member and the “Rabbit Lake to Pennington cherty beds” and ores are shown by the accompanying tabulation.

### Distinction between Cherts of Major Members and Those of Minor Beds

<table>
<thead>
<tr>
<th>Upper Cherty Member</th>
<th>Cherty Beds, Rabbit Lake to Pennington Pit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation</td>
<td>100 to 200 feet thick. Thick-bedded, oölitic, pink (algal on Mesabi), with magnetite bands.</td>
</tr>
</tbody>
</table>

### Average Analysis, Dried at 212° F.

<table>
<thead>
<tr>
<th></th>
<th>Upper Cherty Member</th>
<th>Cherty Beds, Rabbit Lake to Pennington Pit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>34.0%</td>
<td>47.0%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>less than .10%</td>
<td>.26%</td>
</tr>
<tr>
<td>Silica</td>
<td>16.5%</td>
<td>12.0%</td>
</tr>
<tr>
<td>Manganese</td>
<td>16.0%*</td>
<td>5.0%†</td>
</tr>
</tbody>
</table>

* Range is 10 to 30 per cent.
† Range is 3 to 8 per cent.
These differences might be discussed at some length, but the evidences reported here are sufficient to distinguish the cherty member from minor cherty beds at most places.

GEOLOGIC CROSS SECTIONS

In using the following descriptions, the reader should consult the two geologic maps: Plate 2, of the North Cuyuna district and part of the South Range, and Plate 5 of the west part of the South Range. On Plate 2 are shown three lines for the cross sections A-A, B-B, and C-C that are shown on Plates 3 and 4. Section A-A is through the western part of the North Range, and Section B-B through the central part. Beyond a poorly explored belt, Section C-C in the South Range is a continuation of Section B-B.

The locations of most of the drill holes whose records and/or locations were available are shown on the map, except in some of the larger open pits or in areas where holes are so numerous that their plotting on the map would confuse it. It is noteworthy that some of the mine sections are more complex than was suspected when Bulletin 15 of the Minnesota Geological Survey was printed (Harder and Johnston, 1918). Wolff (1919) measured and reported a cross section near the center of Sec. 3, T. 46 N., R. 29 W.; on a line 1 1/4 mile long there are eight synclines and nine anticlines. It should be noted also that there are few cherty members thicker than 150 feet. (Compare with Harder and Johnston, 1918, Plate XIX, which suggests thicker beds.)

DESCRIPTION OF CROSS SECTION B-B, PLATE 4

There are three drill holes at the north end of cross section B-B, on the NE\(\frac{1}{4}\) NE\(\frac{1}{4}\) Sec. 32, T. 47 N., R. 29 W. The northern hole was in quartzite, but since few miners have any interest in the width and character of Pokegama quartzite, its lower or northern boundaries were not explored. The two southern holes are in the Lower Cherty member, like the formation exposed at the Maroco Mine, Sec. 4, T. 46 N., R. 29 W.; at Section 6 Mine in T. 46 N., R. 29 W.; and elsewhere in the district. The mapped extension of this Lower Cherty material for about a mile southwest of the cross section is based largely on the known structure of the Upper Cherty member in Secs. 32 and 33, T. 47 N., R. 29 W. Records in the Oliver Iron Mining Company files, of drilling in NW\(\frac{1}{4}\) NW\(\frac{1}{4}\) Sec. 33, and notes from the Ferro shaft on SE\(\frac{1}{4}\) NE\(\frac{1}{4}\) Sec. 32, disclosed slaty iron formation, across which a dip-needle survey by the writer showed a prominent magnetic attraction.

In 1943 Grout directed the drilling of an angle hole northwest from the center of the SW\(\frac{1}{4}\) NW\(\frac{1}{4}\) Sec. 33, Merritt No. 2 property (see record given above, pages 44-45). A similar hole was drilled many years ago on the Gloria property, SE\(\frac{1}{4}\) SE\(\frac{1}{4}\) Sec. 28, T. 47 N., R. 29 W., the cores of which were in possession of Mr. J. D. Lamont of Virginia, Min-
nesota, in 1942. A crosscut from the Gloria shaft confirms the sequence indicated by the two drill holes. Another hole showing similar stratigraphy was drilled in 1949 by the U.S. Bureau of Mines from the northwest corner of the Gloria property through the pink slaty top of the Lower Slaty member, and the writers have examined the cores. These drill holes (especially Grout’s Merritt hole) have disclosed 75 feet or more of granular Upper Cherty iron formation containing black manganiferous iron ore. Underlying this material are 405 feet (measured at right angles to beds) of fine-banded and gray, dark-green and black slaty iron formation, the upper part of which contains much iron and manganese carbonate and the lower 200 feet of which are very magnetic. The Merritt hole was bottomed in graywacke and gray slate with some thick layers of fine quartzite, assaying 20 to 30 per cent iron (see pp. 45–46).

Recent drilling by the Oliver Iron Mining Company in Sec. 21, T. 138 N., R. 26 W., northwest of Emily disclosed 300 to 350 feet of similar graywacke and gray slate above Lower Cherty member taconite, in a sequence like those in Plates 3 and 4. The Oliver drill hole, however, showed that the Lower Slaty member is 700 to 750 feet thick, nearly twice as thick as indicated on the accompanying cross sections (Plates 3 and 4 in pocket).

The Gloria shaft (on SE¼ SE¼ Sec. 28, T. 47 N., R. 29 W.) and a crosscut northwest from it encountered about 170 feet of the Upper Cherty member and some black manganiferous ore. A crosscut was driven southeast from the Gloria shaft through green slates and into slaty brown manganiferous ore. This slaty formation is believed to overlie the Upper Cherty, and to be the base of the Upper Slaty member. This sequence of layers may be the same as that shown in Louise underground workings (Plate 4), and several other explorations confirm this.

The synclinorium at the Merritt Mine in the SW¼ NW¼ and NW¼ SW¼ Sec. 33 was determined from underground workings by the writer in 1918 and confirmed by him in 1944 just before the workings were allowed to flood.

From the Merritt Mine, belts of three members of the formation run northeasterly toward the Preston property, and easterly (passing a fault) to Rabbit Lake. (The belt of the Upper Cherty member is shown in Plate 2 as considerably wider than is indicated by measurement, the exaggeration being necessary to show the local ore bodies.)

A crosscut south from the Ferro shaft (SE¼ NE¼ Sec. 32) cuts 75 to 80 feet of hard granular Upper Cherty taconite. South of that chert, the crosscut passes through a tight synclinal fold of siliceous slate and beyond that, through more Upper Cherty member in an anticline. In the Joan No. 4 property, south of the Ferro (NE¼ SE¼ Sec. 32), there is a syncline of Upper Cherty member plunging northeast. This syncline yielded some of the highest grade manganiferous ore of the district.

Mine workings on the Algoma, NE¼ NW¼ Sec. 33, T. 47 N., R. 29
W., disclosed similar rocks and ore dipping steeply south. At the southwest end, the Algoma shows a complex drag fold connecting with the Ferro. The drill records for the Preston and Hunter areas (Secs. 22 and 27) to the northeast, show material similar to that in the Merritt group, which is believed to be in the Upper Cherty member. The manganiferous ore shown on NE\(\frac{1}{4}\) NW\(\frac{1}{4}\) and NW\(\frac{1}{4}\) NE\(\frac{1}{4}\) Sec. 27 may be, in part at least, from the lower layers of the Upper Slaty member. The cherty belt shown on the map in the SW\(\frac{1}{4}\) NW\(\frac{1}{4}\) Sec. 27 has not been well explored, but there may be a fault.

Both iron and manganiferous ores are derived from the Upper Cherty member shown on the map, but only mixed high-manganese iron ore has been shipped from the mines in the Merritt belt. This mixed ore is characterized also by its relatively low phosphorus and high silica content. It is the "black ore," in contrast with the brown manganiferous ores derived from the slaty members, which are characterized by high phosphorus and low silica.

The slaty materials stratigraphically above and below the Upper Cherty member may be leached and enriched to ore locally at places along the "black ore" belt. (See, for example, the description of Sec. 3, T. 46 N., R. 29 W. on pp. 64-65.)

South of the Merritt Mine and north of the Maroco open-pit mine in Sec. 4, T. 46 N., R. 29 W., there is an area of quartzite and quartz slate, no doubt Pokegama. The writer has examined Pokegama drill cores from Secs. 33 and 34 and similar material from the north tier of forties of Secs. 3 and 4, and from Sec. 6, T. 46 N., R. 29 W. Between this Pokegama formation and the Upper Cherty material of Merritt there is probably a fault with an estimated throw in excess of 1000 feet. This fault probably continues across Sec. 33, east of the Merritt Mine, and is traced by the black slate north of the Upper Cherty material in the NV\(\frac{1}{2}\) SE\(\frac{1}{2}\) Sec. 33. The black slate resembles the slates north of the Pontiac.

The structure across the Pontiac property* in the S\(\frac{1}{2}\) N\(\frac{1}{2}\) Sec. 34, T. 47 N., R. 29 W., involves two or more folds of Upper Cherty member, but part of the cherts stand vertically or are a little overturned. A wide area of green carbonate slate lies on each side of this cherty member (Plate 2). There is some doubt as to the interpretation of the drill data, and this may not be settled until the mine is opened up. It is clear that the main ore body is in the Upper Cherty member, and the width of the ore is so much greater than that of most exposed Upper Cherty belts that most investigators agree that the ore formation is doubled in a close fold.

It is not certain whether the main ore body is an anticline or a syncline, though stratigraphy favors a syncline; whether the beds next to the cherty formation on the north and south sides are Upper Slaty or Lower Slaty member, though the latter is more probable; whether there is an important fault within a mile of the ore body; or whether the minor

* Including the former Clark and Joan No. 3 properties.
belts of cherty formation north of the best explored deposit are similar anticlines and synclines, or repetitions of one limb at a time.

Plate 2 and cross section B-B show a fault crossing the N1/2 SW1/4 Sec. 33, T. 47 N., R. 29 W., and running west across the S1/2 Sec. 32. The drill cores from the NE1/4 Sec. 33 look like the Upper Slaty member; and those from four holes beginning a quarter of a mile east of the center of Sec. 33 and from there south about 450 feet, are mapped as Lower Slaty member. The several drill holes just west of the north-south quarter line near the center of Sec. 33 may also be in Lower Slaty material. They were examined by the writer about fifteen years ago. If these interpretations are correct, there is a fault running N 60° E, as indicated on Plate 2.

Across the N1/2 SE1/4 Sec. 33 there is a belt of Upper Cherty member, which continues east through the Pontiac property in Sec. 34, T. 47 N., R. 29 W., and beyond; scattered drilling indicates a belt with minor folds, continuing to the east bay of Rabbit Lake (Plate 2).

Drill cores of the Upper Cherty member on the Pontiac in Sec. 34, T. 47 N., R. 29 W., and of the southwest extension from it across N1/2 SE1/4 Sec. 33, exhibit the same pink granular and oölitic chert with the layers of black iron and manganese oxides as are found in the Merritt, Ferro, and Algoma properties. This chert is similar to the Upper Cherty taconite on the Mesabi Range. The only marked difference is that the oölites and granules of the Cuyuna formation have been elongated by deformation (Fig. 22B).

Immediately south of the Upper Cherty material in NE1/4 SE1/4 Sec. 33 are four drill holes which reached Pokegama quartzite and slate formation. The core from the hole nearest to the iron-bearing beds shows a great deal of shattering, and is believed to be on the south edge of a fault zone, where Upper Cherty material is in contact with Pokegama formation. About a quarter of a mile east of these holes, the quartzite is offset to the southeast in the SW1/4 Sec. 34, T. 47 N., R. 29 W., probably by a fault, or possibly along a cross-anticline (Plate 2). Drill records of holes in the north half of the south half of Sec. 34 report "schist and slate," which the writer considers the Lower Slaty member of the iron formation, for reasons discussed below. These rocks probably extend to the east bay of Rabbit Lake (though one core from NW1/4 NE1/4 Sec. 35, T. 47 N., R. 29 W., was described as "quartzite," and is possibly an interbedded lens in the Lower Slaty member).

The map, Plate 2, shows Upper Slaty member south of the Upper Cherty in the areas just mentioned, Secs. 34 and 35. If this area is Lower Slaty, it could be separated from the Upper Slaty beds of Secs. 1 and 2, T. 46 N., R. 29 W. by a northeast extension of the major Sagamore fault from Lot 2, Sec. 3, T. 46 N., R. 29 W. to the vicinity of the Kennedy and Rabbit Lake mines. The upper beds of Upper Slaty member seem to be exposed in the Rabbit Lake open pit (Sec. 29, T. 47 N., R. 28 W.)
and a fault may well be assumed to separate them from the Upper Cherty member on the north, because of the insufficient space between them to account for the great thickness of Upper Slaty member beds. Explorations in this area are not sufficient to establish this fault.

At the Maroco open-pit mine in the north half of Sec. 4, T. 46 N., R. 29 W., the Pokegama formation is exposed in contact with the Lower Cherty member. The Pokegama and overlying iron formation stand very steeply and have two or more drag folds at the eastern end of the open pit (only one of which is shown on cross section B-B). Practically the entire ore body was of washable ore, bounded on the south by fine gray slate and/or a green chloritized basic intrusive. At the west end of the open pit the intrusive is narrow, and is enclosed in gray slate. Similar intrusives are indicated by drilling on the south edge of the cherty member for a mile or more west of the pit. One is exposed in the Section 6 Mine. The gray slate south of the Cherty iron formation is the base of the Lower Slaty member, and is much like that in the bottom of the Merritt hole drilled by Grout (see Part I of this chapter).

From the Maroco Mine this belt of Lower Cherty material has been traced by drilling, west for more than a mile and east to the NW1/4 NE1/4 Sec. 3, T. 46 N., R. 29 W., in Mahnomen Lake, where it may be cut off by a fault. This belt is the north limb of a syncline, the south limb of which may extend, as shown on Plate 2, fromJeune Lake far to the southwest. The synclinal area between the two limbs is the Lower Slaty member, probably in repeated shallow folds.

South of the Maroco open pit are two ore bodies, one of which has been opened as the Virginia Mine. The formation in this mine is very highly folded, much more so than is shown in cross section B-B. The map of drag folds in the Maroco Mine suggests that the folds of the Virginia may be along the axes of the minor drag folds. The Virginia ore body includes lean iron and manganiferous iron ores concentrated in a thin-bedded formation, probably a fairly rich part of the Lower Slaty member. One slaty bed underlying the ore near the west end of the Virginia Mine is rich in graphite.

Extensive drilling under Lake Mahnomen has shown highly folded (probably Lower Slaty) iron formation, cores of which the writer has examined. The map and cross section B-B suggest that a fault may extend under Mahnomen Lake near the southeast shore. At the location of cross section B-B, this fault has an estimated throw of nearly 1000 feet (much greater than shown on Plate 4).

On the southeast side of Lake Mahnomen drilling and open-pit development show a belt of Upper Cherty member manganiferous ores, with some Upper Slaty iron ore on the west. Two pits, Mangan-Stai and Joan No. 1, have been opened, and marketable iron ore has been made by washing. This leaves a little Upper Cherty member black manganiferous material in place, only slightly weathered; and the slaty formation south-
east of the pits may be partly Lower Slaty, or a complex of two or three members. The ores of these pits are thus derived partly from a cherty member, but also largely from the Upper Slaty member.

In the center of the NE¼ SW¼ Sec. 3 and between the Mangan open pit and the Louise shaft in Sec. 3, the structure shown in Figure 18 is more complicated than the simple syncline shown on cross section B-B, Plate 4. Some faulting is possible in the folded area between Mangan-Joan and Hopkins-Louise.

Across the south half of Sec. 3 from Mangan open pit, cross section B-B shows folded Slaty and Upper Cherty beds. Two prominent Upper Cherty anticlines, and the synclinal slaty structure with interbedded manganiferous ores between them in the Louise underground mine, were mapped by the writer in the 1920s. In 1949 this structure was checked by the mapping of a similar crosscut running northwest and southeast from the old Louise shaft (about 850 feet north and about 4300 feet west of the southeast corner Sec. 3, T. 46 N., R. 29 W.). This crosscut is a short distance west of cross section B-B, and was observed and recorded by a large group of engineers and geologists of the district (see Fig. 18). The material encountered south of the shaft is probably part of the Upper Slaty member. For about 170 feet from the north end of the crosscut there is green (altered to yellow) siliceous slate; next the green slate alternates with carbonate slates from which weathering has produced brown manganiferous ores. Similar stratigraphic cross sections were drawn by Krey (1919) and by the writer (1923) from underground observations.
and drill hole data of the Hopkins and Sultana mines (both in SE\(\frac{1}{4}\) Sec. 3) about a quarter mile east of cross section B-B.

Plate 2 shows a fault south of the Louise, Hopkins, and Sultana mines, but there is little evidence to indicate whether, south of that fault, the slates are thrown down or up. This fault is not exposed in the Louise open pit in SE\(\frac{1}{4}\) SW\(\frac{1}{4}\) Sec. 3. (Cross section B-B and the map, Plate 2, place the north bank of the open pit a little too far north.)

The Louise open pit, the structure of which is shown on cross section B-B, includes two faults in the east end. Both iron and manganiferous ores have been mined, the iron ore occurring probably at the same horizon as that in the Mahnomen open pit to the east. The Louise open pit, and Mahnomen No. 1 ore bodies (NW\(\frac{1}{4}\) NE\(\frac{1}{4}\) Sec. 10) are separated by an anticline of quartzitic phyllite or quartz-slate (visible in the open pit), from which overlying ore has been largely eroded.

The stratigraphic succession near the Louise open pit is uncertain, because faulting is complex and data are meager. The syncline shown in the pit is traceable southwest into the North Hillcrest open pit (E\(\frac{1}{2}\) NE\(\frac{1}{4}\) Sec. 9, T. 46 N., R. 29 W.), which was explored in 1943 by a drill hole 500 feet deep (Fig. 14). There were lenses of quartzitic slates in the slaty beds.

The manganiferous green carbonate slates north of the Louise open pit have a thickness exceeding 200 feet. These are not far from a siliceous slate layer about 80 feet thick in which thin quartzite lenses are interbedded. Such a layer underlies the iron ore of the Louise, North Hillcrest, and Mahnomen open pits. The original Mahnomen iron-rich layer was probably about 175 feet thick.

Immediately south of the Louise open pit, cross section B-B is offset northeast along the strike about 2300 feet, so as to continue the cross section through the Mahnomen and the Armour No. 1 and No. 2 mines where good mine records were available. Section B-B shows the U-shaped trough of the Mahnomen main open pit, with axial plane dipping steeply to the south; iron ore is on the bottom and slaty manganiferous ores are infolded. These rocks and structures were mapped in detail underground by the writer. Between the main Mahnomen trough and the folded formation to the south (formerly Mangan No. 2 in NE\(\frac{1}{4}\) NE\(\frac{1}{4}\) Sec. 10, T. 46 N., R. 29 W.) is a fault observable in the pit. Above the Mahnomen iron ore, the thickness of the manganiferous slaty beds, measured in the Mahnomen and Armour No. 1 mines, is 150 feet.

South of the Mahnomen iron and manganiferous ores on cross section B-B is the Armour No. 1 ore body which connects along the strike to the southwest with the Pennington, Feigh, South Hillcrest, and Huntington ore bodies, whose evenly thin-banded iron formation ranges in thickness from 180 to 250 feet. In the Feigh open pit the north footwall of graphitic and sericitic slates is about 50 feet thick. This thin-banded iron formation of the Armour No. 1 is believed to connect to the east (across the south end of the cross anticline shown on Plate 2) with the highly folded,
thin-bedded, cherty iron formation in the southwest end of the Portsmouth open pit.

The Armour No. 1 ore body is divided into two parts by a schist (altered intrusive) layer of varying thickness, the ore on the north being manganiferous and that on the south entirely iron ore. The schist layer is not shown on Plate 4. The mine map indicates, and Harder and Johnston state (1918, Plate XXI and p. 145), that to the west the schist pinches out at the Pennington property line, and on the east splits into layers separated by iron formation and finally pinches out. The manganese in the north layer occurs as separate lenses, apparently replacements in the iron ore by which most of them are surrounded.

Between the Armour No. 1 and Armour No. 2 ore bodies is a very thick irregular mass of chloritic schist, originally a basic intrusive, now altered near its contact with the iron formation to a red hematite schist. This intrusive ranges in thickness (Harder and Johnston, 1918) from 650 to 1000 feet. The crosscut from Armour No. 1 shaft to its ore body is in this chlorite schist for about 400 feet. The crosscut from Armour No. 2 shaft to both ore bodies cuts entirely through the schist, which includes layers of iron formation (Harder and Johnston, 1918, p. 147).

There is a question as to how accurately the material in these crosscuts was classified and recorded. Drill records of holes between the two Armour shafts indicate a thickness, of about 330 feet, of "gray slate" extending northeast and southwest within this intrusive mass, and this thickness is recorded in the geologic column (see column, pp. 57f.). It is possible that the material cut by the drill holes may be leached schist of igneous origin, and if so the recorded thickness of Upper Slaty iron formation and interbedded slates is 330 feet too great. There is some evidence, however, supporting the record of slate. The north footwall of the Thompson ore body joining the Armour No. 2 to the northeast (Harder and Johnston, 1918, pp. 149–50) "consists of light gray to dark gray or red siliceous and ferruginous argillite (or slate). It is very thin bedded and . . . in places it is stained dark red by hematite. Ferruginous layers are interbedded with siliceous and argillaceous layers. . . . Between the north and south lenses (of Thompson mine) is a great thickness of slate and green chloritic schist with bands of iron-bearing formation." Farther northeast, in the Croft ore body (Harder and Johnston, 1918, p. 151) the schists comprising the footwall "are locally quartzose, and are probably sedimentary in origin as indicated by their banded and laminated character."

Northeast along the strike from Armour No. 1 Mine a similar even-banded iron formation is exposed in the southwest part of the Portsmouth Mine; this formation is again exposed still farther northeast at the Kennedy Mine shaft. The ores exposed in the Rabbit Lake open pit are very finely bedded soft goethite and limonite, obviously derived from finely bedded slaty formation. (See Fig. 20.)
The thick intrusive between the Armour ore bodies can be traced southwest and forms the hanging wall of most of the Pennington, Feigh, South Hillcrest, and Huntington ore bodies, like a sill above the ore. In the Pennington and Feigh, possible offshoots from this intrusive transgress some beds of iron formation, or are enclosed by them. In the east face of the Feigh open pit such an intrusive is 15 to 50 feet or more thick. Plates 2 and 4 show (near the south end of cross section B-B) the ore body of the Armour No. 2 and Ironton mines enclosed by the thick intrusive (now schist). This schist is believed to extend for a quarter of a mile south of the Ironton ore body to a contact with the overlying Virginia formation. The Feigh shows local overturned folds.

The banded cherty iron formation of the Armour No. 2, Thompson, Meacham, and Croft mines is from 200 to 400 feet thick. A specular hematite layer with phosphorus below Bessemer limit (the only such occurrence in the district) is a striking feature of these ore bodies. The southwest end of the Armour No. 2 ore body is of this very high-grade Bessemer iron ore (up to 66 or 67 per cent iron), but the northeast end of the ore body grades into hard brown and limonitic ore containing irregular inclusions of manganese oxide apparently as replacements. Cross section B-B indicates that dikes from the enclosing large intrusive cut the ore body of Armour No. 2 Mine.

On top of these ore bodies of Armour No. 2 and associated mines is a somewhat slaty, low-manganese layer, up to 350 feet thick. From this layer manganiferous ores were mined in 1952 from the open pit, SE\(\frac{1}{4}\) NW\(\frac{3}{4}\) Sec. 11, and in 1953 from the Manuel open pit in SE\(\frac{1}{4}\) NE\(\frac{1}{4}\) and NE\(\frac{1}{4}\) SE\(\frac{1}{4}\) Sec. 1, T. 46 N., R. 29 W. Drilling on the Croft disclosed a similar layer (Harder and Johnston, 1918, p. 151) separated from the footwall ore body by green chloritic schist (not shown on Plate 2). Along the south side of the Armour No. 2 open pit a basic chloritic intrusive similar to others in this area is exposed (not shown on Plate 2). It may connect with those shown on Plate 2 on the Ironton and Meacham properties.

Attention should be called to the two cherty belts (indicated on Plate 2) extending from near Ironton three or four miles northeast. These cherts are thin-bedded and not like the Upper Cherty member, as was mentioned earlier. Some thin cherts in the mines farther west may be remnants of these same belts.

Careful drilling explorations for about a mile structurally above and to the southeast of these ores have encountered only slates and schists with various colors. They are believed to be equivalent to the Virginia slate, which overlies the Mesabi Range Upper Slaty member on the southeast; but the formation on the Mesabi is more uniformly gray. About four miles south of the Ironton-Meacham belt is the South Range member (see cross section C-C) of the Virginia formation. Chapter 6 suggests some more remote correlations of these beds.
In March, 1918, the writer had an opportunity to examine drill samples from an area in Sec. 6, T. 46 N., R. 29 W., then under lease and development by shaft-sinking. The material in the northwest quarter was described by the driller as gray siliceous schist, but the writer considers it equivalent to the Pokegama quartzite and gray schist in the S1/2 S1/2 Sec. 32, T. 47 N., R. 29 W. The geologic sequence is shown on Plate 3, cross section A-A. At the center of Sec. 6 are vertical green schists containing pyrite crystals, probably pre-Animikie*; these are overlain to the south by Pokegama quartzite and quartz-slate, followed on the south by a steeply dipping Lower Cherty member of the Biwabik iron formation 125 to 175 feet thick, and followed in turn by argillaceous gray slate. The drill cores from Sec. 6 showed that the quartzite and quartz-slate formation has a thickness of probably 350 feet or more. Many of the lower interbedded slates have been classified as schists. At its top the quartzite is coarse-grained and vitreous, and is interbedded with thin slaty layers.

The bottom of the cherty iron formation for 3 to 4 feet is gnarled or contorted jaspery iron formation (algal structured), and shows many pebbles. This is followed by a few feet of slaty or even-bedded iron formation. In these, and in the overlying 25 feet or more of granular cherty and slaty iron formation, there is a little manganiferous material. It was from a single piece of core of such material that the Section 6 Mine was originally "promoted" as a manganiferous iron deposit. Drilling indicates that the manganiferous bed thins out both east and west of the open pit within 600 feet.

Above this layer in Sec. 6 lies about 75 feet of the best ore-producing part of this Lower Cherty member, containing alternating wavy layers of hematite and chert. Where enriched, this layer provided the wash ore produced from the Section 6 open-pit mine in 1951 and 1952. The stripping and opening of the pit of Section 6 Mine checked and fully confirmed the structure inferred from the 1918 drilling, though the beds dip more steeply than they are shown in the cross section A-A. The ore lies on the north limb of a southwest-plunging syncline (see Plates 2 and 3). The rocks of the sequence in the Lower Cherty member are well exposed in the pit, and lie south of the basal quartzite of the series; this sequence is a very satisfactory basis of correlation (see page 100) with the Mesabi Range, and is typical of the Lower Cherty member on the Mesabi Range. Local concentrations of manganiferous ores occur in this member on both ranges (Wolff, 1951, p. 15).

Between the cherty member or washable ore and the overlying gray slates in the Section 6 open pit, there is a sill of basic green chloritic schist very similar to that along the south side of the Maroco open pit.

* Leith, Lund, and Leith (1933, p. 15) question the evidence of pre-Animikie rocks, saying "one would expect considerable outcrops" to show the unconformity. There are no outcrops in any direction for 25 miles, and none can be expected.
Overlying this Cherty member are graywackes and gray slaty rocks. Similar cherty and slaty rocks were cut by drilling across the SW1/4 SW1/4 Sec. 5, and across most of Sec. 7. This very slaty iron formation is identified as equivalent to the rocks south of the Maroco ore, and to those of the Merritt drilling in SW1/4 NW1/4 Sec. 33, T. 47 N., R. 29 W. discussed in Chapter 4, Part I. The slaty beds along cross section A-A on the south side of Section 6 Mine dip south over the Lower Cherty beds and both probably come up on the south side of a syncline at about the SE1/4 Sec. 7, and dip into another syncline with cherty beds to produce the Rowe ore body. The wider northern syncline of Sec. 7 was thoroughly drilled in the hope of finding a central syncline of Upper Cherty member. When none was discovered, the inference was that the lower parts of the Lower Slaty member were rather thick, and that they were probably repeated in shallow folds as shown diagrammatically in cross section A-A.

A small iron ore body lies in a minor syncline near the NE corner of Sec. 18, northeast of the Rowe Mine.

Sparse drilling west and southwest of the Section 6 Mine and even across the Mississippi River, indicates that the Lower Cherty member may ultimately be traced for some miles. Examination of early drill records of holes in Sec. 12, T. 46 N., R. 30 W., shows the extension of a cherty member. Several holes show manganiferous ore, and there is much more magnetic attraction than at Section 6 Mine. Although no quartzite has been reported, the siliceous schist north of the cherty member is believed to be the basal Pokegama formation.

Explorations in the area from Jeune Lake (NW1/4 Sec. 9, T. 46 N., R. 29 W.) southwest to the S1/2 of Sec. 33, T. 135 N., R. 27 W., records of which the writer has seen, locate the Lower Cherty member approximately between the Lower Slaty rocks and the quartzite south limb of the syncline. It is possible that this Lower Cherty south limb may ultimately be traced southwest across the Mississippi River, as suggested above for the north limb and as indicated by scattered drilling in the area shown on Plate 2.

Immediately south of this syncline is a small anticline in Pokegama formation, followed to the south by a small syncline of Lower Cherty and Lower Slaty rocks. Bends and offsets in cross section A-A have been made, in order to utilize the best available exploration and mining information.

In the N1/2 SE1/4 Sec. 18 is the Rowe Mine, situated at the southwest end of a small syncline in Lower Cherty iron formation which is correlated with the Maroco and Section 6 ore bodies. At the southwest end of the Rowe pit the drainage shaft was in the underlying quartzite (Pokegama). The Rowe syncline is overturned to the north. Along the south side of the Rowe pit the Lower Cherty ores were somewhat manganiferous, analogous to those along the north side of the Section 6 ore body. The Rowe Mine was operated for iron ore in early years when
manganese was not wanted, and some manganiferous ore that was put on the waste dumps has been used in recent years for its manganese. The area south from the Rowe Mine to the Sagamore is largely Pokegama quartzite and quartz slate. Between the Rowe and Sagamore is to be found one of the major faults of the district, early inferred by the writer and now clearly visible along the northwest wall of the Sagamore pit.

Cross section A-A runs through Pokegama formation to this major fault in SE\(\frac{1}{4}\) SE\(\frac{3}{4}\) Sec. 18, T. 46 N., R. 29 W., then is offset southwest along the fault to a point one quarter of a mile west of the center of Sec. 19. For a length of some 300 feet in the northwest bank of the Sagamore open pit there is a brecciated zone in the generally flat-lying or gently northwest-dipping quartzite, in fault contact with the green manganiferous slates and brown ores which dip southeast.

Cross section A-A shows the main structure of the Sagamore Mine, two synclines with an anticline between them; there is shown, also, a second anticline on the southeast, so that at the southeast wall of the pit the beds dip southeast. Some minor folding between the two synclines is well shown in the open pit where ore was mined in a cut between the synclines. (See the Sagamore pit on Plate 3.) In the northeast end of the mine, the major anticline is broken by a minor fault which can be followed for some distance southwest in the pit.

The fresh green slates in different parts of the mine carry rather different percentages of manganese. In both Sagamore synclines a layer of green slate interbedded in the ore bodies provides a good horizon-marker. Where well leached and oxidized this layer is ore or paint rock.

The Sagamore ores are difficult to correlate with ores in other mines, for lack of any good horizon-markers. The material mined consists of brown low-silica manganiferous iron ores, part of them limonitic, that carry more moisture than other brown ores. They require partial drying before shipment. Some beds have a little more manganese than others (see Appendix B). Ores are derived from green slaty beds which may be equivalent to those which produced the brown ores of the Louise Mine (SE\(\frac{1}{4}\) SW\(\frac{1}{4}\) Sec. 3, T. 46 N., R. 29 W.), the Arko and Alstead mines (NE\(\frac{1}{4}\) Sec. 9, T. 46 N., R. 29 W.), and the Northland Mine in Sec. 20, T. 47 N., R. 28 W.; but the stratigraphic sequence differs in details in these five mines. Southeast of the Sagamore east pit, no ore seems to have been derived from higher layers, such as those from the Huntington to the Pennington mines. Drilling done in the west half of Sec. 20, T. 46 N., R. 29 W., has shown only barren green and brown slates and schists, which are believed to be part of the overlying Virginia formation. There may be other faults.

Between the southwest extensions of the two Sagamore synclines is a basic intrusive, now green-gray and chloritic, that is well exposed in the south side of the more western part of the pit. It cuts across some beds of the slaty iron formation, and drilling shows that it widens con-
siderably to the southwest. The southwest end of the open pit shows lean slaty beds dipping steeply southeast.

In the SW$\frac{1}{4}$ SW$\frac{1}{4}$ Sec. 17, T. 46 N., R. 29 W., a quarter of a mile northeast of the Sagamore Mine, is a body of ore— the Snowshoe Mine—in an open pit. Its iron ore has the highest phosphorus of any North Range ores, and this is probably related to its derivation from slaty iron formation. This ore body lies in a sharp synclinal fold plunging northeast, so that there is probably a cross anticline between this mine and the Sagamore, whose folds plunge southwest (see Plate 2).

Another open pit, the Mallen Mine, lies in the NW$\frac{1}{4}$ NE$\frac{1}{4}$ Sec. 17, T. 46 N., R. 29 W. The small ore body is of red iron ore, probably derived from Upper Slaty material, faulted into contact with Lower Slaty beds to the west.

The transgressive contacts between the areas shown on Plate 2 as Upper Slaty iron formation and the Virginia formation areas farther south suggest an erosion unconformity at the top of the iron formation before the deposition of the thick overlying slates.

**Cross Section C-C and the South Cuyuna Range; Plates 1, 2, 3, and 5**

Nearly four miles S 30° E of the Armour Mine is the shaft of the Adams Mine on the South Range (SE$\frac{1}{4}$ NW$\frac{1}{4}$ Sec. 30, T. 46 N., R. 28 W.). Cross section C-C shows the structure of the ore body at this mine. The iron formation member is a very thinly banded siliceous magnetic slate about 200 feet thick. Neither the iron-bearing member nor the slates show the granule or oölitic textures of the Biwabik formation in the Cuyuna and other districts. The ore is surrounded by slates, which are believed to be equivalent to Virginia formation. These slates may be highly folded in the area between the two parts of the Cuyuna District, but even with repetition by folding, there must be a thickness of several thousand feet of slates between the North Range Biwabik formation and the South Range member of the Virginia formation.

Six mines, five of them underground, have been developed on the South Range member. Most of them show monoclinal structure, iron ore dipping steeply south. Manganese was reported from only one ore body—the south part of the ore in NE$\frac{1}{4}$ SW$\frac{1}{4}$ Sec. 36, T. 45 N., R. 31 W. It is probable that the concentration of ore at the Adams Mine does not extend 300 feet below bedrock surface. The main ore body in underground workings is about 150 feet wide. On the north or footwall side, an intrusive 60 feet wide has cut off a 30-foot layer of ore, north of which is a further thickness of about 100 feet of intrusive. This intrusive is described on mine maps as “diorite,” but rocks on the dump near the shaft are of two kinds—one was a granitoid rock, possibly diorite, now altered to green schist, and the other a fresh porphyry. Probably the Animikie intrusives are altered to green schists, and the later Keweenawan intrusives are fresh.
About half a mile southwest of the Adams shaft (Plate 2) there is a belt which can be traced with few gaps by magnetics and drilling for thirty miles to the southwest. The belt is believed to be the south limb of a fold that brings the South Range iron-bearing member to the bedrock surface again. On cross section C-C the southern belt, a little south of the Adams Mine, is represented as an anticline covered by Virginia formation.

Northeast of the Adams Mine for three quarters of a mile, drill holes show an intrusive which may be a continuation of the intrusive at the mine. Three or four miles northeast, in Sec. 10, T. 46 N., R. 28 W., the iron-bearing member has been displaced about half a mile, apparently by a fault, northeast of which the member is further distorted by a drag fold. Harder and Johnston (1917, p. 24) report quartzite near Cedar Lake; possibly this quartzite is equivalent to a quartzite reported in SE1/4 NE1/4 Sec. 3, T. 46 N., R. 24 W. near the South Range member. It is probable that these quartzites are thin beds in the Virginia formation. Southwest of the belt shown in Plate 2, the South Range extension is shown in Plates 1 and 5. (See Chapter 5, under “South Range and Associated Formations.”) The magnetic readings indicate another fault near the point where boundary lines between Ts. 46 and 47 N. and Rs. 27 and 28 W. would intersect. The Hassman area in T. 48 N., R. 26 W. shows several parallel bands that probably result from folding.

**MARGINAL AREAS OF PLATE 2**

*Iron formation.* A belt of manganiferous iron formation in the north half of Sec. 22, T. 47 N., R. 29 W., extending into Sec. 15 to the north, and a belt extending from the north half of Sec. 29 across Sec. 30, T. 47 N., R. 29 W., and into Sec. 25, T. 47 N., R. 30 W., are derived from a siliceous slaty formation, cores of which the writer has examined. Even where weathered, the rocks remain strongly magnetic. The north footwall, as seen in some angle drill holes inclined to the northwest, is an oxidized slate. Since the most magnetic bed known in the entire North Range geologic column is that of the Lower Slaty beds in and near the Merritt Mine, it is probable that the iron formation of these areas is part of the Lower Slaty member. The geologic structure in this area is not yet well determined, but the U.S. Bureau of Mines drilled several holes in 1954.

An area northeast of the main formations in the active Cuyuna district has been explored, and slates interbedded with iron formation have been found in Secs. 17, 20, and 21, T. 136 N., R. 26 W., north of the Mississippi River (not shown on Plate 2).

**INDETERMINATE NORTH RANGE AREAS**

There are two areas (Plate 2) in which exploration is insufficient to show the formation or member. First, the area west of the west part of
Rabbit Lake may be one of the slaty divisions. It deserves more explorations. Second, the area including parts of Secs. 34, 35, and 36, T. 47 N., R. 29 W., and parts of Secs. 1, 2, and 3, T. 46 N., R. 29 W., has been drilled at a few places and the rocks are reported as "schist"; this is probably one of the slaty members with some possibility of ore bodies.

INTRUSIVES

The foregoing descriptions have noted several basic intrusives in the iron formations in the Maroco, Section 6, Armour No. 1 and 2, and Sagamore Mines on the North Range, and the Adams and Gorman Mines on the South Range. One is exposed in the southeast and in the southwest of the Feigh open pit, in the N\(\frac{1}{2}\) SW\(\frac{1}{4}\) Sec. 10, T. 46 N., R. 29 W. One lies on the south side of the South Hillcrest and the Huntington, Sec. 9, T. 46 N., R. 29 W. Along the north side of the ore body of the Martin open pit NW\(\frac{1}{4}\) NW\(\frac{1}{4}\) Sec. 16, T. 46 N., R. 29 W., a sill 35 to 40 feet thick is intruded between the ore body and the lean iron formation; this sill may be an extension from the large sill in the Huntington-Armour area.

Records of drilling on the Meacham property indicate a large intrusive extending across the N\(\frac{1}{2}\) NW\(\frac{1}{4}\) Sec. 12, T. 46 N., R. 29 W., and into Sec. 11. Other large intrusives are known by drilling in the N\(\frac{1}{2}\) NE\(\frac{1}{4}\) Sec. 31, T. 47 N., R. 28 W., extending north into Sec. 30; and small ones are known in the Kennedy Mine area, Secs. 29 and 30.

Smaller intrusives are cut by drill holes in the SW\(\frac{1}{4}\) NW\(\frac{1}{4}\) Sec. 35, T. 47 N., R. 29 W.; north of the Portsmouth Mine in the SW\(\frac{1}{4}\) SE\(\frac{1}{4}\) Sec. 2, T. 46 N., R. 29 W.; in the SW\(\frac{1}{4}\) NW\(\frac{1}{4}\) Sec. 6, T. 46 N., R. 28 W.; south of the Northland shaft on the SW\(\frac{1}{4}\) NW\(\frac{1}{4}\) Sec. 20 T. 47 N., R. 28 W.; and in the NW\(\frac{1}{4}\) NW\(\frac{1}{4}\) Sec. 15, T. 46 N., R. 29 W.

On the South Range, intrusives occur in Secs. 3 and 16, T. 46 N., R. 28 W.; and in Secs. 2, 3, and 8, T. 45 N., R. 29 W.

Some two or three miles south of the South Range member, and beyond the limits of Plate 2, intrusives occur in Sec. 17, T. 45 N., R. 28 W., south of Clearwater Lake; and south of Lac Wiben in T. 46 N., R. 25 W., an intrusive may be the source of a sulphide deposit of commercial importance. (See Plate 1, and Chapter 5.)

MAJOR STRUCTURE OF NORTH CUYUNA DISTRICT

Although explorations are far from being complete enough to permit final conclusions as to the major structure of the North Cuyuna district, the accompanying geologic map and cross sections, and Plate 1, showing the connection between the Cuyuna and the Mesabi, permit some interpretations.

The area north of the Mississippi River, toward the southwest end of the Mesabi Range, is known to be variously folded. A study of Plate 1 suggests at least three large synclines and two anticlines in this area, but probably there are many more smaller folds.
When Plate 1 is compared with maps of the Lake Superior region, the Cuyuna structure appears to be a complex drag fold on the northwest limb of the Lake Superior geosyncline. The Thomson formation and pre-Animikie granite south of the Cuyuna would be the core of an anticlinal structure with possible faulting in the major drag fold. This would confirm the early hypothesis by Irving and Van Hise (1880), with which Leith later concurred (1903, pp. 178-79).

In the area south of the active North Range (from Rabbit Lake to the Sagamore Mine), there may be a general synclinal structure marked by the South Range, a 70-mile belt from north of Kimberly to Randall. (See Chapter 5.)

Plate 2, based largely on drilling, shows several features of the Biwabik formation that end abruptly at its contact with the Virginia formation as if the iron formation beds had been eroded before the slates were deposited. The cherty zone extending from the Armour No. 2 and Manuel mines to the northeast seems to end completely at the east side of Sec. 31, T. 47 N., R. 28 W. The Armour No. 2 Mine is known to have a specular hematite layer, but no evidence of such a bed is reported west of the intrusive that surrounds the west end of the Armour-Ironton ores. Between the Huntington and the Sagamore little specular ore has been discovered, and if such ores were deposited they may have been eroded or faulted out. Just at Little Black Hoof Lake the drilling indicates that Virginia formation south of the North Range iron formation fills an embayment that was probably eroded before the slate was deposited.

Second order structures may well be listed from northwest to south: a large synclinorium, at the west end of which are the Merritt group of mines and at the east end of which is iron formation, extends farther than is shown on Plate 2; next south of the Merritt structure is an anticline of Pokegama; next south is a westerly-plunging syncline, the east end of which probably is cut off by the northeast extension of the Sagamore fault, concealed in Mahnomen Lake, and the west end of which is not well explored; another Pokegama quartzite anticline; a small canoe-shaped syncline from Rowe Mine at the southwest extending two miles northeast nearly to Jeune Lake; southeast of the structures just listed are some rocks and ores of the Upper Slaty member with monoclinal dips to the southeast, overlain, probably unconformably, by Virginia formation, including the South Range iron-bearing member several miles south.

More minute structures modify the details of these folds, down to minute crumpling in hand specimens (Fig. 5).

**Structures Noted in Preparing Cross Sections and Examining Ore Bodies**

(a) The Sagamore Fault. This important observed fault, which has been referred to in the descriptions of cross sections A-A and B-B, is well exposed for some 300 feet in the northwest wall of the Sagamore open
pit (see Plate 2), and may extend in a slightly undulating line far to the
northeast. Southeast of the Rowe open pit the fault brings the Pokegama
quartzite into contact with slaty iron formation.

In the SW1/4 NW1/4 and NW1/4 SW1/4 Sec. 9, T. 46 N., R. 29 W., ex-
plorations by drilling and shaft sinking have disclosed both the Lower
Cherty member and underlying quartzite formations. In the SW1/4 SW1/4
Sec. 9, T. 46 N., R. 29 W., drill records disclose slaty iron formation.
Possibly the Sagamore fault here brought the Upper Slaty member into
contact with the Lower Cherty member and Pokegama quartzite. About
a mile northeast, the same fault may have brought the Lower Cherty
member (as disclosed by drill holes) into contact with slaty material west
of the Arko open pit. These changes along the probable fault would be
difficult to explain by folding.

A little farther northeast, drilling through the ice of Mahnomen Lake in
Secs. 3 and 4, T. 46 N., R. 29 W., and west and southwest of the lake
(cores from which have been examined by the writer) has disclosed slaty
iron formation, probably the Lower Slaty member, not far from the
Upper Slaty member visible in the north and west exposures of the
Mangan and Joan ore bodies. Upper Slaty material lies above the Upper
Cherty belt at the southeast shore of Mahnomen Lake.

In Mahnomen Lake, drilling through the ice has traced the Lower
Cherty iron formation and its underlying quartzite from the Maroco pit
to a point three eighths of a mile north of the center of Sec. 3, T. 46 N.,
R. 29 W. About one eighth of a mile east of this drilling, other drilling
on the Joan property has traced the Upper Cherty member north to the
bay at the northeast end of Mahnomen Lake. The probable northeast
extension of the Sagamore fault separates these formations at this place.
(See the fault and cross anticline in the NW1/4 NE1/4 Sec. 3, T. 46 N.,
R. 29 W., Plate 2). It is probable that the Sagamore fault extends this
far, but exploration is not sufficient to prove it.

The displacements along this possible extension of the Sagamore fault
differ in different places. It seems that either the northwest side is thrown
up or the southeast side down. In the Sagamore Mine the displacement
is believed to be approximately 1200 feet. In Mahnomen Lake where
cross section B-B crosses the fault, the displacement is estimated as 650
feet.

(b) The ore bodies of the Mahnomen group in the SE1/4 of Sec. 3 and
N1/2 NE1/4 Sec. 10, T. 46 N., R. 29 W. are in southwest-plunging syn-
clines with intervening anticlines. Within half a mile to the east are the
ore bodies of the Portsmouth Mine (the west end of which was the origi-
nal Evergreen Mine), in two eastward-plunging synclines and anticlines.
The opposite plunge of these synclines (Mahnomen and Portsmouth) re-
quires a cross anticline or break between them as indicated on Plate 2.
A fold may grade into a fault in Sec. 34, T. 47 N., R. 29 W., with dis-
placement enough to bring Pokegama formation on its west side into
contact with slaty iron formation on the northeast.
(c) In the main Mahnomen open pit along the south side of the synclinal ore body there is a visible fault between the ore of the old pit and the iron formation and ore of the open pit farther south on N1/2 NE1/4 Sec. 10, T. 46 N., R. 29 W. (formerly known as Mangan No. 2, but shown as part of Mahnomen on Plates 2 and 4).

(d) In the early open-pit operations of the Portsmouth Mine, ore was mined from a syncline on the north and from an anticline on the south. A fault was visible along the south side of the upper benches at the east end (see Fig. 19). This fault probably extends far along the south side of the pit, possibly to the cross anticline discussed under (b) above.

(e) Along the south side of the North Alstead open pit, a little south of the center of NE1/4 Sec. 9, the steeply dipping ore layers of the south limb of the syncline are cut out at a fault.

(f) At the west end of the Milford ore body in the SE1/4 SW1/4 Sec. 23, T. 47 N., R. 29 W., is a northwest-trending fault and shear zone, encountered by the crosscut from the shaft to the ore body. The sheared Upper Slaty ore was very fibrous (and was called “petrified wood” by the miners). The Milford ore body has a monoclinal southeast dip of about 70 degrees.

(g) A drag fold in Upper Cherty member is mapped in the Preston ore body (west part of Sec. 27, T. 47 N., R. 29 W.) and may be complicated by faulting. The structure is known only by drilling and no drilling was done in the S1/2 NW1/4 Sec. 27. The width of the belt suggests widening by folding and repetition of beds.

(h) Cross section B-B shows two faults mapped in the east bank of the Louise open pit. One of these appears to be a major fault (Plate 2) extending from the east line of Sec. 3, to the Sagamore fault near the center of the south side Sec. 4, T. 46 N., R. 29 W. This may be the same.
as the one visible in the northeast corner of the Arko open pit at the NE corner Sec. 9, T. 46 N., R. 29 W. It may be one of those mapped by the writer in the underground workings of the Louise Mine (formerly Cuyuna-Mille Lacs) thirty years ago (see Fig. 18).

(i) The faults south of the Merritt group in Secs. 32 and 33, through the N½ SE¼ Sec. 33 and the SW¼ Sec. 34, T. 47 N., R. 29 W. have been described above (pages 61-62). As Plate 2 and cross section B-B indicate, the structure of the Merritt group is a synclinorium plunging 60 degrees northeast. The ore is in the Upper Cherty member, with Lower Slaty rocks underlaying it to the west and northwest, and Upper Slaty rocks above it to the east and northeast; and some slaty Pokegama formation is faulted into contact with the ore on the south. The mines of the group were Merritt No. 1 and No. 2, Ferro, and Joan 4. The faults south of the Merritt Mine may continue from the center of Sec. 33 a long distance; even past the west arm of Rabbit Lake.

(j) The east part of Rabbit Lake has been drained, and open-pit mining was started in 1952. Figure 20 is a cross section of the pit in 1953, from north to southeast. The anticline on the north side is more closely folded than the broad syncline on the southeast. The formation may be high in the Upper Slaty member, and if so that would suggest a fault between the ore and the cherty belt on the map.

(k) Southeast of the shaft at the Gloria Mine some manganiferous ore was encountered in the Upper Slaty member, above the cherty zone. Here, and also at the Algoma and Zeno, the structure is monoclinal, dipping 75 to 80 degrees southeast, with local minor folds.

(l) A drift north from the Northland shaft (W½ NW¼ Sec. 20, T. 47 N., R. 28 W.) showed definitely synclinal structure.

(m) At the Arko pit (Lot 1, Sec. 9, T. 46 N., R. 29 W.) the ore was in folded green carbonate slates. South of it is an anticline of underlying lean slates with quartzitic lenses, and north of it the slates turn down vertically about 300 feet. A fault is mapped here, extending the one visible at the northeast corner of the pit (NE corner, Sec. 9), where the Upper Cherty member is in contact with the ore-forming green slates. Between this fault and Mahnomen Lake the structure is confused. The long narrow belt of Upper Cherty member in the S½ SW¼ Sec. 3, is at least locally an anticline, observed underground by the writer farther east in three crosscuts in early underground explorations, and confirmed by Krey (1919) in the Hopkins.
(n) Miscellaneous structures. The monoclinal structures at Maroco and Section 6 mines have been noted in the descriptions of cross sections A-A and B-B, and are sketched in Plates 3 and 4.

Similarly the ore bodies of Armour No. 1, Pennington, Feigh, South Hillcrest, Huntington, and Martin mines have, for the most part, a monoclinal 75 degree dip to the southeast. At least two of them—the Feigh and South Hillcrest—have southwest-plunging drag folds. The Martin appears to be offset by a fault or sharp fold from the west end of the Huntington. The intrusive along the south side of the Huntington cuts across the beds and narrows the ore body to 50 feet at the west end.

The Croft, Meacham, Thompson, and Armour No. 2 ore bodies are tabular and dip steeply southeast. The Armour No. 2 and Ironton ore bodies and their extension west onto NE1/4 SE1/4 Sec. 10 appear to be cut off in a large intrusive, dikes from which cut into the ore body (see cross section B-B). The slightly manganiferous iron ore now being mined from the Armour No. 2 open pit on SE1/4 NW1/4 Sec. 11 has a monoclinal steep southeast dip, and is overlain on the south by intrusive chloritic schist, not shown on the map.

The structure of the Kennedy Mine (Sec. 30, T. 47 N., R. 29 W.) has never been determined accurately. Zapffe described considerable folding but published no record (see paragraph j above). The South Range member of the Virginia formation, though not yet carefully studied, has a structure that may be dominantly synclinal.
5. OUTLYING AREAS IN PLATE 1

The areas around that shown in Plate 2 are not as well explored as the actively producing Cuyuna Range. The rocks discovered in these areas include a variety of formations, some older and some younger than those that are of interest in connection with iron and manganese production. Explorations have been undertaken at several different times and at many different places. One or two have led to "shipping ore" and several may be expected to produce ore in the future, whenever there are urgent demands for iron and manganese, because of wartime shortages or other emergencies.

Considerable data on this larger area south of the main Mesabi Iron Range are shown in Plate 1. A number of natural exposures were photographed to illustrate Bulletin 15 of the Minnesota Geological Survey (Harder and Johnston, 1918, Plates II to X). The general area, lying at the west end of Lake Superior, has often been thought to lie in the trough of the major Lake Superior syncline. That structure, however, turns southwest, south of the Apostle Islands and hardly reaches Minnesota at eastern Pine County (Irving, 1883; Van Hise and Leith, p. 422). The Cuyuna and surrounding areas lie in the northwest limb of the major fold, but crumpling, intrusion, and metamorphism have left a complex record in the whole surrounding area, and the glacial deposits make the records of bedrock history difficult to read.

One of the largest of the areas that has not been well explored is that from the Mesabi Range to Duluth and Mille Lacs. This is shown on most geologic maps as slate, but the area seems to show different slate formations at the two extremes. All along the active Mesabi Range, the rock above (south of) the iron formation and ore is the Virginia slate, but hardly any of it shows the secondary or metamorphic cleavage of a slate. This was recognized by Van Hise and Leith (1911), though they used the term slate because the mining men of the district know the formation by that name. Argillite would be a more accurate term.

Near Duluth and Thomson, the characters of slates and graywackes are such that Schwartz (1942a) believes they are older than the Virginia slates. Their concretionary structures can be traced far across the country toward Little Falls. They are recognizable in outcrops for about 10 miles northwest of Thomson. Northwest of these Thomson slates for about 50 miles to the Mesabi district there are no exposures. Much of the slate east and northeast of the active Cuyuna Range lies in this intermediate area where true slates are known by drilling, but information
is not complete enough to tell whether they are Virginia argillite metamorphosed to true slates, or older slates of the Thomson formation. They are shown in Plate 1 as slates, without other designation.

Magnetic mapping has been a popular method of studying the rocks as near the iron ranges as the areas mapped in Plate 1. After the early U.S. Land Office surveys had shown compass deflections, the early search for an iron range revealed a series of lines of maximum attraction (Harder and Johnston, 1918, Plate XI). Several commercial explorations followed, and copies of reports are on file in the office of the Minnesota Geological Survey. Thiel (1927) studied the magnetics of the area between the Mesabi and Cuyuna and reported that magnetic attractions averaged slightly higher in the areas west of the great area of slate. Schwartz (1943) used magnetics to trace the eastern boundary of the slate area north of Duluth. Dougherty and Fitzhugh (1946) made an instructive series of magnetic traverses from the Cuyuna district past the western Mesabi and north to some areas probably related to the Vermilion formations. More recently the U.S. Geological Survey and Minnesota Geological Survey (1949) cooperated in issuing aeromagnetic maps of a large area in north-central Minnesota (A-2).

Recent magnetic explorations south from the Mesabi Range, from Grand Rapids to Hill City, led to some drilling, which found true slates with secondary cleavage within 10 or 15 miles south of the iron formation. The cores are available in the storage room of the Minnesota Geological Survey in Minneapolis, through the courtesy of the exploration company. Several magnetic belts in slate areas have been drilled, but the material that caused the magnetic anomaly was not found; possibly the magnetic material is at great depths.

It is clear from the results of these surveys that many belts of iron formation are magnetic, but probably most of the Cuyuna formations are not especially rich where the maximum magnetism is mapped, as discussed in Chapter 3. With the help of a small amount of drilling the magnetic lines are at least suggestive of the trends of formations.

THE NORTHWEST AREA

A large area (mapped as the northwest part of Plate 1) probably has a basal Archean foundation, and besides the common green schist there are likely to be Laurentian granites under considerable glacial drift. Certain magnetic lines in the northwestern side of the area resemble those of the Vermilion Range; they are not the subject of this study. (See Dougherty and Fitzhugh, 1946.) The rocks are no doubt older than the Animikic rocks of the central area.

Plate 1 shows the general setting of the active Cuyuna Range in the larger area of east-central Minnesota. After a series of formations, from Keewatin to Keweenawan and Cambrian, had been deposited and considerably folded, the whole series was eroded and Cretaceous sediments
were widely deposited. Remnants are abundant under the glacial drift in a broad belt running southwest across Aitkin County from its northeast corner. A natural exposure of Cretaceous sediment occurs at Two Rivers, 10 or 12 miles south of Little Falls. The larger area of Plate 1 shows a somewhat larger percentage of rock exposures than occurs in the active Cuyuna area, but nearly everywhere, glacial deposits make the bedrock geology difficult to decipher.

**AREA SOUTH AND SOUTHWEST OF THE MESABI RANGE**

Drill explorations have shown that the cherty members of the iron formation at the southwest end of the Mesabi Range grow considerably leaner in iron than in the main range, and probably the whole Biwabik formation is thinner there than in the more active part of the range. It is still associated, however, with underlying Pokegama quartzite, and overlying Virginia formation (argillite); and all these have been traced by drilling to points near Remer.

In Sec. 4, T. 54 N., R. 26 W. near Pokegama Lake, there are 186 feet of Upper Cherty, Lower Slaty, and Lower Cherty members between Virginia slate and Pokegama quartzite. In Sec. 21, T. 54 N., R. 27 W., there are only 83 feet lying Virginia slate and underlying quartzite. Near these are some drill holes showing some Upper Slaty member. These records are hard to explain in any way except by unconformity or interfingering (pages 110-11) between Mesabi iron formation and Virginia slate (White, 1954, p. 45).

There has not been enough drilling from Remer to south of Emily to permit mapping the belts as if they were known to be continuous, but the evidence strongly suggests that they are. In 1913 the late Louis Rouchleau did some drilling and found granite in Sec. 31, T. 140 N., R. 26 W., and crystalline dolomite rock in Sec. 33, T. 138 N., R. 27 W. and Sec. 2, T. 137 N., R. 27 W. Wolff has seen these cores and believes the rocks lie west of (below) the Mesabi series. He reports that recent drilling (1952) in the southwest corners of Twps. 137 and 138 N., R. 26 W. has disclosed thick dolomite underlying Pokegama formation, as shown on Plate 1. This dolomite probably connects with that found by Rouchleau.

Twenty to twenty-five miles south of Remer (in T. 138 N., R. 26 W.) diamond drill holes passed about 300 feet (perhaps steeply tilted) of such rocks as the Lower Cherty member of the Biwabik formation, and found contorted looking jaspery (algal) beds at the base, and Pokegama quartzite and quartz slate below (Wolff, 1951, p. 15). Above the Cherty member near Emily there are 400 feet of Lower Slaty rocks, largely gray slate and graywacke, resembling the cores from Merritt drilling and exposures in the Maroco pit.

Manganiferous iron ore was drilled in Sec. 4, T. 137 N., R. 26 W. south of Emily; some records are in Minnesota Geological Survey files. The
Rouchleau (1913) drilling and subsequent drilling in the area indicate a steeply dipping formation, and the association of iron ore with manganeseiferous iron ore resembles that on the Cuyuna North Range. The area west and northwest of the iron formation shows scattered older schists, dolomite, quartzite, and granites.

North of Lake Emily, drilling (Wolff, 1951, pp. 15 and 16) has disclosed slates dipping 30 degrees north, lying above cherty iron formation, which lies above quartzite, as in the Maroco pit series. The cores of the underlying gray slates and graywackes (400 feet thick) closely resemble the cores from the deeper part of the University drilling at the Merritt No. 2 Mine, near the base of the Lower Slaty member. The Lower Cherty member north of Emily (about 250 feet thick) is not very ferruginous, but locally along beds or fractures iron oxide replaces the chert. The bottom quarter of the Lower Cherty material is finely banded and has considerable manganese. Even the top of the underlying quartzite is partly replaced by iron and manganese oxides, which are probably from higher beds. The iron formation just above the quartzite is "contorted" or algal-structured chert, exactly like the Lower Cherty member at the Maroco pit, and includes some pebbly beds.

Wolff reports (1951, p. 27) that in the SW¼ Sec. 23, T. 137 N., R. 28 W. there are two large very angular boulders of highly folded crystalline dolomite, and he believes that they were not transported far by glaciers. They resemble the dolomite disclosed by drilling in Twp. 137 and 138 N., R. 26 W. as reported above. Schwartz (1942a) has reported dolomite in the area near Denham (SE¼ Sec. 25, T. 45 N., R. 21 W.). These are somewhat similar to the Kona and other dolomites that underlie some iron formations in Wisconsin and in Michigan. Probably they all underlie the Biwabik and equivalent iron formations.

Explorations near Emily are difficult because the glacial materials cover the iron formation to depths as great as 300 feet. Some drilling was carried to more than 800 feet. Even the magnetic lines are feeble where the magnetic rocks are so deep. For many years the mining men in the Cuyuna district have generally thought of the iron-bearing beds near Emily as too deep to be mined profitably.

The Emily drilling however has shown a partial series, from quartzite through a Lower Cherty member to a Lower Slaty member with so many features that closely resemble the Mesabi and Cuyuna series that correlation is good. South and southeast of Emily considerable drilling has disclosed not only more quartzite, but slaty iron formation and interbedded slates. A drill exploration in Sec. 2, T. 136 N., R. 25 W. found a deposit which for some distance was unusually rich in manganese.

The location of Emily is so nearly halfway between the two ranges, that no further proof seems needed that the Mesabi belt and the north part of the Cuyuna belt are connected.
There remain a few other outlying areas in which some drilling has been done, but more is needed to explain doubtful areas nearby. To begin with, east of the strongly folded belt through the Emily area is a large area in Aitkin County in which there were several scattered explorations. In 1928 the Great Northern Iron Ore Properties drilled a series of holes to explore a wide area largely in Aitkin County. The Great Northern's officials have placed the material in the Fort Snelling storehouse of the U.S. Bureau of Mines, Division V (whose offices are at 2908 Colfax Avenue South, Minneapolis). The cores have been studied by the geologists of the company and by several other men who were interested. Three of the 30 holes drilled show characteristic iron formation with up to 30 per cent iron and up to 6 per cent manganese, and two of the holes showed ore that enlarges a continuous iron-bearing area. The third hole is in the SW\(\frac{1}{4}\), SE\(\frac{1}{4}\) Sec. 35, T. 50 N., R. 26 W.; probably it penetrated an outlying minor fold or lens of iron formation.

Another drilling program in T. 49 and 50 N., R. 25 W. showed green and gray slates and a few carbonate slates. The slates that were the dominant cores from most of this drilling have been variously identified as Thomson and Virginia slates; but most of them have better cleavage than the Virginia slates at the type locality. The secondary cleavage in the slates of Aitkin County, like that near Emily results from folding and deformation; it may be in part caused by igneous intrusions, which crop out about 50 miles south of the Mesabi Range, but perhaps no more than 10 miles south of the Cuyuna Range. Plate 1 shows as Virginia slate that which occurs for a few miles near the Biwabik formation of the Mesabi (and Cuyuna), and as Thomson formation that from Thomson (T. 48 N., R. 16 W.) southwest; but the slates between are left unclassified. Wolff thinks they are equivalent to Virginia slates.

Several of the Great Northern Iron Ore Properties holes passed through soft Cretaceous sediments before reaching slates. Small fossils are abundant in these sediments, and Edward J. Bolin, working under Fred M. Swain, paleontologist at the University of Minnesota, reports four new species of Cretaceous fossils. Bolin says: "The nature of the fauna suggests a near shore, cold, and probably brackish water environment." Such Cretaceous fossils and conglomerates are well known along the western two thirds of the Mesabi Range, but have not been recognized on top of any Cuyuna Range ore bodies, although Wolff reports thin conglomerates of uncertain age on top of the Kennedy and Portsmouth ore bodies. The Cretaceous material from drilling is scattered over an area perhaps 30 miles long and 15 miles wide — roughly from T. 137 N., R. 25 to T. 52 N., R. 23 W. (Plate 1). Through the same area that has such young sediments there were a somewhat larger number of holes, in the cores of which the drillers recognized only older metamorphic rocks. The Cretaceous may originally have covered all the area, and may have con-
nected with the larger Cretaceous area in western Minnesota; but only some remnants left after erosion occur in the Cuyuna district. Such remnants are locally more than 200 feet thick. F. S. Adams (1910) reported Cretaceous beds (no fossils) in Sec. 8, T. 45 N., R. 29 W., overlying the South Range member of the Virginia formation.

One of the Great Northern Iron Ore Property holes in the NE¼ SE¼ Sec. 35, T. 51 N., R. 26 W. showed Cretaceous over a thick slate, but the "choppings" at a depth of 350 feet assayed 35.38 per cent iron, and 25.12 per cent loss on ignition.

A large area of leaner manganiferous iron ore (known as the Scallon-Todd lease) is in Sec. 23, T. 48 N., R. 27 W. It has been drilled at several places, and Grosh et al. (1953) describe the tests made. A substantial tonnage of ore, carrying about 3 per cent manganese, is assured. The ore is covered by some 150 feet of glacial material, and it is well to be very sure of the nature of the deposit before excavating to that depth for the ore. The magnetic lines near this ore are numerous and confusing. They run northeast with no clear connection to the magnetic lines of the Hassman area at Rice River, which have been mentioned previously.

A report has come in that ore, perhaps not very rich, has been found by drilling in Sec. 21 and 22, T. 49 N., R. 26 W., west of Palisade. Slate was drilled in the SW¼ Sec. 27, T. 47 N., R. 25 W. The arrangement of iron formation belts near Palisade (Plate 1) suggests that a fold of the formation here plunges underground.

SOUTH RANGE AND ASSOCIATED FORMATIONS

A considerable area has been explored by a series of drill holes in Secs. 22 and 23, T. 48 N., R. 25 W., and iron formation with 25 to 45 per cent iron has been found. Near the outlet of Rice River, T. 47 and 48 N., R. 26 W. a considerable exploration (the Hassman area) has shown iron deposits. These seem to be part of the South Range member of the Virginia formation. The exploration shows that ore beds are steeply tilted and probably in double belts as if closely folded. Few of the deposits are manganiferous. Both of these features suggest that the ores are part of the South Range member of the Virginia formation. From T. 48 N., R. 25 W., this iron-bearing member of the Virginia formation, with a few minor faults and folds, is traced southwest for about 70 miles. (See Plate 1.) East of Crosby the belt passes close to Deerwood (see Plate 2) in Sec. 21, T. 46 N., R. 28 W.

Southwest of the Adams Mine (productive in 1914), the South Range iron-bearing member is surprisingly continuous (Plates 2 and 5).* Drilling and underground workings of the Brainerd-Cuyuna Mine in Sec. 36, T. 45 N., R. 31 W. at the southeast edge of the city of Brainerd, and drilling on Sec. 31, T. 45 N., R. 30 W. disclosed iron-bearing beds and some ore dipping 70-75 degrees to the southeast. Drilling in Sec. 32, T.

* Wolff's report (1951, pp. 13-14) is the source of the notes in this and the two following paragraphs.
45 N., R. 30 W. shows vertical iron formation and some ore. These occurrences are interpreted as being northwest and southeast limbs of a syncline slightly overturned to the northwest so that its axial plane dips about 80 degrees to the southeast. It is probable that this structure is characteristic of most of the South Range member.

At places in T. 45 N., R. 29 and 30 W., and T. 44 N., R. 31 W., and in Sec. 7, T. 45 N., R. 29 W., the duplication of iron-bearing bands suggests minor drag-folding on the northwest limb of the South Range member. Farther southwest, two parallel magnetic lines have been followed beyond Brainerd, to Fort Ripley Reservation in T. 131 N., R. 30 W., Morrison County, and north of Randall (NW¼ NE¼ Sec. 7, T. 130 N., R. 30 W.). A little northeast of Randall is the already mentioned Gorman Mine (Chapter 3), the only South Range development attempted since 1918. The northwestern belt has been traced into the northeastern corner of Sec. 12, T. 130 N., R. 31 W., and a few miles south it approaches the granites in T. 127 and 128 N.

In addition to the Adams and Gorman Mines mentioned above, the only developments attempted on the South Range member have been underground work at the Hobart in Sec. 8, T. 45 N., R. 29 W.; at the Omaha (or Wilcox) in Sec. 13, T. 45 N., R. 30 W., which was the main producer on this Range (but the ore was so wet a drying plant had to be installed); at the Brainerd-Cuyuna in Sec. 36, T. 45 N., R. 31 W.; at the Barrows in Sec. 10, T. 44 N., R. 31 W.; and at the Rowley in Sec. 16, T. 44 N., R. 31 W. Total production has been about 450,000 tons, most of it from the Omaha. Drilling has disclosed some 20 similar small ore bodies on the South Range, possibly mineable in the future.

It has been said (Harder and Johnston, 1917, p. 14) that carbonaceous slate is the common associate of ores in the South Range member, but such slate is discontinuous. It is also remarked that quartzite lenses are locally associated, but it is not yet possible to correlate them.

Northeast of this South Range syncline the iron formation is fairly continuous to some iron-rich deposits between McGregor and Palisade, in Ranges 24 and 25 West. Magnetic lines have led to explorations farther east, but few of the explorations have been encouraging. It can be said only that the Cuyuna iron-bearing formations are hard to trace in the more abundant slates of uncertain age east of R. 24 W. The iron-bearing beds there may (a) grow lean, or (b) thin (in the Virginia slate), or (c) plunge east or west under other slates. The structures are not well known.

The South Range member does not have all of the features of the North Range formations. For example, chert is not known to occur in beds as thick as 1 to 12 inches; there are no reports of granules suggestive of greenalite; manganese is low (except at the south part of the Brainerd-Cuyuna Mine in Brainerd) and few assays show as much as 3 per cent; few samples show coarse silicates or carbonates. If there are exceptions to these features, the data should be reported. Evidence to date indicates
that the South Range member differs from the North Range too much to be correlated; but farther southeast than the South Range there seems to be another belt with the character of North Range formations (see pages 87–90).

OUTLYING AREA OF SULPHUR PROSPECTS

A few miles south and southwest of the Dam Lake quartzite exposures (See Fig. 21) is an area of considerable size that shows magnetic belts and has been prospected for iron. Drilling did not show any very promising iron ore bodies, but several cores show enough pyrrhotite and pyrite (iron sulphides) so that an area a few miles south of Long Lake (Sec. 9, T. 46 N., R. 25 W.) has been prospected again, and more carefully, as a possible source of sulphur. Following an early report of work about 1904 by B. Magoffin (Thiel, 1924), careful drilling was done by Charles J. O'Connell; the area is said to be now in control of the M. A. Hanna Company.

Figure 21.—Sketch map of the Dam Lake area, showing quartzite outcrops.

Other sulphides have been explored in Carlton County. (Pennington and Davis, 1953, Figs. 1 and 2, and pp. 29 and 30.)

Some of the possible methods of concentration of Cuyuna manganese may require sulphur, and a local deposit would be of considerable interest. Iron sulphide from these and other Minnesota deposits could be burned to produce sulphur dioxide gas, now used successfully in the recovery of manganese. (See Appendix A, Item 5G.)
Several formations may be involved. In this bulletin on iron formation, the question arises whether original Animikie iron formations have been mineralized to make pyrrhotite and perhaps pyrite. Most of the cores do not closely resemble cores of Cuyuna iron deposits but no doubt iron formations can be mineralized by sulphur-bearing waters. Some of the cores that are low in sulphur carry more than 20 per cent iron, and if sulphur were absent they might resemble Cuyuna iron formations. Both iron and sulphur may be recoverable from the deposits.

A study of cores from the northern part of Secs. 28 and 29, T. 46 N., R. 25 W., near Clear Lake, shows slaty, graphitic, and cherty materials; and in one hole there was cherty carbonate, more or less recrystallized to marble. These seem to be partly mineralized iron formation. Other cores from the sulphide area resemble altered igneous rocks, and the structure of the township is no doubt complex.

IRON PROSPECTS SOUTH OF THE SOUTH RANGE

Overlying the long Cuyuna ore belt (say from near Palisade to north of Brainerd) there is a belt of slate five or six miles wide, which is here correlated with the Mesabi Virginia formation. Near the center of this slaty belt lies the South Range iron-bearing member, with iron ores of such different character from those of the Biwabik that the two cannot be correlated. Much of the South Range member lies in a double belt that suggests folding, but most geologic reports seem to imply that, except for a few drag folds, the ores and slates of the South Range member continue to dip southeast.

On the contrary a whole series of evidences indicate that the South Range member is a narrow syncline and that iron formations equivalent to the North Range Biwabik series are to be expected farther south and southeast.

An early suggestion of this came from Harder and Johnston (1918, Plate XI), who published a map of the main magnetic belts known at that early date. The lines on their map clearly show the South Range member in a belt about three miles south of the North Range Biwabik ores near Ironton and Crosby. East of Clearwater Lake (Secs. 8 and 9, T. 45 N., R. 28 W.), and near Bay Lake, is another belt of iron formation about three miles south of the South Range member. If the dips are about as steep south of the South Range as north of it, but in a reversed direction, the North Range (Biwabik) might reappear at this Clearwater belt. The available records are dated 1913, and include no information as to manganese content, such as might indicate Biwabik beds.

The reports on this belt south of the South Range member are here listed from northeast to southwest:

1. At or near Kimberly (Sec. 1, T. 47 N., R. 25 W., and Sec. 6, T. 47 N., R. 24 W.) an ore body was explored by early drilling. Four cross sections were drilled; some sections had iron formation in every hole.
Samples assayed up to 40 per cent iron, but not all were tested for manganese. One assay recorded 4.12 per cent manganese. The relation of this iron formation to quartzite was not reported.

2. Near Dam Lake early discovery of outcrops of quartzite led to drill explorations. At the west end of Dam Lake, a road following the shore meets another which runs west along a town line on the south side of Sec. 34, T. 47 N., R. 25 W. About 600 paces west of the Lake, there is a swampy spot on the north side of the road; the quartzite outcrops can be reached and examined by walking north and northeast about 150 paces on the dry ground northwest of the swamp (Fig. 21). The quartzite exposures are not large. They somewhat resemble those of the Pokegama formation, under the Mesabi Biwabik formation, and those in the Maroco and Section 6 mines, under North Range Cuyuna iron formation; but correlation is not entirely certain.

These outcrops led to considerable exploration in the hope of finding iron formation like that near the quartzites of the Rowe and Maroco mines, but the only iron formation reported was small and lean. F. S. Adams (1910, p. 734) reported drilling north of the Dam Lake quartzite, that "showed iron formation underlain by . . . quartzite." Harder and Johnston (1918, p. 122) suggested the quartzite might run from Dam Lake to Clearwater and Bay lakes. They even extend the suggestion (1917, p. 24) to Cedar Lake near the corner of T. 46 and 47 N., and R. 27 and 28 W., but that is close to the main South Range.

3. It has been noted, in the discussion of sulphur prospects above that some drill cores from Sec. 9, T. 46 N., R. 25 W., near Long Lake, included cherts and iron-bearing carbonates.

Wolff reports that some iron formation more than 200 feet thick has been drilled in Secs. 19, 20, and 30, T. 46 N., R. 25 W., nine miles southeast of Aitkin. The iron formation dips about 20 degrees but the direction of dip is uncertain. Northwest of this iron formation is quartzite and conglomerate containing fragments of slaty iron formations; it does not resemble the quartzite near Dam Lake, in which no iron formation fragments have been reported. About a quarter of a mile to the south, another drill hole found graphitic and pyritic slates, probably not iron formation.

An old drill exploration in Sec. 30, T. 46 N., R. 25 W. yielded several iron formation cores; and one core from about 1000 feet north of the center of Sec. 30, had 8.4 per cent manganese for a vertical range of 25 feet; cores for 60 feet average 5.14 per cent manganese. Some drilling (reported by Wolff, Marsden, and Knutson at a Minneapolis meeting in 1951) indicated there may be ore for a depth of 100 feet or more.

4. As mentioned above, explorations near Bay Lake and Clearwater Lake since 1918 show that there is an ore horizon. The records show some nearby quartzite, and this suggests that the iron formation may be the lower part of the Lower Slaty member of the Biwabik. (See the sequence
on pages 56-57.) Early cores were not tested for manganese. Harder and Johnston (1918, Plate XI) show a belt of ore in Secs. 5 and 8, T. 45 N., R. 28 W.

Several drill explorations, made about 1914, reported iron formation in Secs. 3, 4, 6, and 18, T. 45 N., R. 28 W. These would be distinctly south of the South Range as mapped, but here again no tests were made for manganese.

5. Harder and Johnston (1918, Plate XI) show magnetic belts in T. 43 N., R. 31 W., about three miles southeast of the South Range magnetic belt near the Northern Pacific railroad. The more southeastern belt may be either North Range or South Range. Leith, Lund, and Leith (1935, Plate 1) plot a magnetic belt in this township, several miles southeast of the South Range belt.

The air-borne magnetometer maps (A-2, 1949, Map 6) show a line of maximum magnetic attraction in Sec. 13 to Sec. 34, T. 43 N., R. 31 W., about four miles southeast of the South Range belt.

6. In Morrison County (Sec. 6, T. 130 N., R. 30 W.) six holes were drilled by the Crosby Exploration Company. The sketch and drill records indicate that three of the holes have noteworthy magnetite. These are on a line of maximum magnetics of the main South Range, and there are similar magnetics three miles farther east with a line of minimum magnetics between. The belt in Secs. 2 and 10, T. 130 N., R. 30 W. should be explored.

In composition, the lean ores of these several belts south of the South Range are not like the ores of the South Range member. They are notably cherty, and several are manganiferous like many Biwabik belts of the North Range. Manganese is rare in the South Range member of the Virginia formation. One may well expect that the North Range Biwabik formation passes under the South Range syncline to rise again near Bay and Dam lakes.

These several items give strong support to a suggestion that the major structure of the South Range is a sharp syncline (with possibly minor drag folds); and that the manganiferous iron formation of the North Range, after plunging under the South Range member, rises again about three miles farther south to expose the south limb of a major syncline. These beds of Animikie rocks probably rest on older Thomson slate, but they have not been well traced. This suggestion of a synclinal belt shows a remarkable agreement with an early tentative sketch by Leith (1903, p. 203).*

A question may arise whether a geologic section involving the great thickness of Biwabik iron formation in the North Range can pinch out

* If the North Range Biwabik formation does not reappear south of the South Range member of the Virginia formation, as has been suggested, the iron-bearing beds and quartzites there noted may be beds high in the Virginia formation, dipping south under the major Lake Superior syncline. In that case the structure must be very complex to bring up the supposedly older Thomson and the younger Keeweenaw into the series from Cuyuna Range to Lake Superior.
to one as thin as is indicated near Dam and Clearwater lakes. Possibly the dips are steeper in parts of the south belt, and there seem to be few repetitions by drag folds, such as are common in the North Range Biwabik. Wolff says the old explorations rarely reported thick-bedded or massive cherts.

SOUTHEAST AND SOUTH OF THE ANIMIKIE SERIES

The area southeast of the iron formation, with its complex of sulphur deposits, manganiferous and non-manganiferous ores, Virginia formation and intrusives, is a complex that is not well explored. A zone about five miles wide has Thomson formation and a few basic intrusives. That zone is interrupted near Mille Lacs by a series of granitic to granodioritic intrusive rocks. Schwartz (1949, Plate 10) has shown that some folds in the Thomson formation plunge east, and others west, at angles of from 0 to 80 degrees in the well-exposed area near Thomson. Southeast of this complex are belts of Keweenawan and later sediments, and Keweenawan flows (see Plate 1). Southwest of Mille Lacs, the complex seems to include Keweenawan granite stocks and batholiths.

South of the Gorman Mine there are several rock exposures. Harder and Johnston (1918, pp. 30–63) reported chlorite schists without sedimentary bedding, exposed in a railroad cut southeast of Randall, and folded phyllites intruded by igneous rocks along the Mississippi River near Little Falls. Such rocks have not encouraged explorations.

Near Philbrook there are prominent magnetic attractions and a few outcrops. Drilling of some of the magnetic belts has shown iron formation somewhat recrystallized; these rocks are coarser than those in the iron formation of most of the Cuyuna district. Probably some beds are metamorphosed sedimentary iron formation. The outcrops are of gabbro, with more than average ilmenite and coarse apatite; if the tonnage is large, it deserves careful tests. A gap of 10 miles that has been very little explored makes it difficult to relate these rocks to the rest of the range.

The most southerly magnetic lines mapped are those in Sherburne County, where attraction seems related to lines in an altered sediments enclosed in granite.

Finally, north from Philbrook, T. 133 N., R. 32 W., through Wadena, Hubbard, and parts of Cass counties there are magnetic lines which may be related to formations in the older rocks. The best known are the Soudan formation of the Archean, and the minor belts of Agawa formation in the Knife Lake series. Those shown in Plate 1 have not been much studied, and no attempt is made here to distinguish which formation is involved.

GRANITES SOUTH OF THE IRON FORMATIONS

The south-central parts of the area indicated in Plate 1 show masses of several different granitoid rocks, which have been given close study by Margaret Skillman Woyski (1949). Some are probably intrusive into
Thomson formation, but not into Cuyuna slates. They are mapped as "Gr" (Granite, etc.) and include older granites, granodiorites, and quartz diorites. Others are mapped as probably Keweenawan granites, and it is believed that small apophyses from such granites have intruded and altered the Animikie rocks of the Cuyuna Range. Thiel (1927, pp. 789-91) reported pegmatitic and granitic stringers cutting the North Range ore bodies; he states that "field relations suggest that they [the stringers] owe their origin to the larger granite masses . . . granites younger than the Cuyuna series." Thus the sediments, both Thomson and Cuyuna slates, may be only slightly altered at the northeast and much more re-crystallized near the Keweenawan intrusives at the southwest. The large outcrops of granite are perhaps ten or fifteen miles south of the good ores; but beneath the glacial drift and iron formations, granites of large size may lie under the mines of the productive Cuyuna Range at moderate depths—say from 100 to 1000 feet.

With newly developed methods for determination of the age of granites by zircons and radioactivity, some of these relations of Algoman to Keweenawan masses may soon be more accurately determined. The Director of the Minnesota Geological Survey has asked the experts of the U.S. Geological Survey to make age determinations on a number of Cuyuna granites.

CONCLUDING REMARKS ON THE GENERAL AREA

Any attempt to reconstruct the probable conditions at the time of deposition of the Cuyuna formations is naturally only tentative and preliminary, but it may contain some ideas that will guide further explorations.

The Animikie sea was no doubt widespread, reaching from the Mesabi-Cuyuna belt to the Wisconsin-Michigan belts, and depositing similar rocks in the two areas. Iron was probably contributed to the basin from several districts where volcanoes were active. At the same time the shores of the basin may have been contributing some mechanical sediments. Volcanoes may have been high enough to start rapid erosion; and older sediments (Knife Lake and Thomson) may have stood high in folded mountains. These would contribute locally to the same basin in which iron formations were deposited.

Between the Animikie deposition and the time of Keweenawan flows and sediments, there was probably another period of uplift and folding. This deformation raised both the Animikie and the older slates in folds so high that erosion cut through the Animikie in large areas. It is possible, of course, that minor synclines of Animikie beds lie in local troughs in the general area of Thomson formation. Magnetic belts occur widely in the Thomson area, but few have been explored.

Applying this brief outline to the Cuyuna Range, it seems evident that more mechanical sediment was deposited as part of the Biwabik forma-
tion in the Cuyuna district than in the Mesabi district. The sequence of major members and the details in the several members are very clearly equivalent in the two districts (see Chapter 6), but the Cuyuna Biwabik formation has more associated slate and graywacke and is much thicker than the Mesabi Biwabik formation. No doubt the Cuyuna received more mechanical sediment along with the chert and iron precipitates. It may have been in an embayment, with relatively high ground to the west.

After deposition of the Cuyuna and Mesabi beds, there was a major deformation of the Lake Superior syncline. Possibly the Minnesota Animikie beds connect at great depths with the Animikie iron ranges of Wisconsin; but there may be intrusive rocks and other interruptions in the parts below Lake Superior. The Cuyuna beds show evidence of a moderately large syncline and one may well suspect that the deeper parts of the basin received thinner deposits than did the shallow borders. The beds that dip east and south, in apparent original continuity with the Mesabi, form a very irregular belt to Philbrook or beyond. In Aitkin County, the axes of major folds appear to plunge northeast, but the structure is not clear farther east.

SUGGESTIONS AS TO DESIRED RESEARCHES

1. The correlation of Cuyuna and Mesabi ranges would be strengthened if the Pokegama belt could be followed in closer detail by drilling between the holes where Pokegama is now recognized: from Remer to Emily; and both north and southwest of the Pokegama areas shown in Plate 2.

2. The idea that Virginia formation lies unconformably above the North Range iron formation might well be checked by more drilling along the supposed contact.

3. Scattered drilling from Dam Lake and Kimberly southwest to T. 130 N., R. 29 W. might support the idea that this relatively narrow belt of iron formation resembles the North Range rather than South Range member of the Virginia formation. A series of holes south or southeast from Bay Lake would cross such a series if it exists, and might find the relation of the Animikie to the Thomson slate.

4. If the Biwabik beds do not occur south of the South Range member, as suggested earlier in this chapter, iron formation lenses may be shown to lie high in the Virginia formation, with the whole series faulted out of sight before reaching the Thomson formation.
6. CORRELATION

INTRODUCTION

There has been much discussion as to the correlation of the Cuyuna with other Lake Superior iron ranges (Wolff, 1919; Thiel, 1924a, b, c, and 1927; Zapffe, 1925; Leith, Lund, and Leith, 1935; Royce, 1942; Schwartz, 1942a, b). These papers exhibit three different opinions, and new data are needed. A sequence that could be agreed upon might serve as a guide to exploration, and wasteful drilling might be avoided.

General remarks about Cuyuna correlation commonly neglect to note that the South Range member of the Cuyuna is so isolated from the rest (by three or four miles of barren slate) that it should not be thrown in with the rest of the iron formation of the Cuyuna district. (The “Deerwood” as a term for Cuyuna iron formation has been loosely defined in several different ways, as discussed in Chapter 1 of this volume.) Gruner (1946, p. 66) said “more and more geologists believe that the iron formation of the Cuyuna Range is stratigraphically equivalent to the Biwabik formation.”

The facts are that the Cuyuna district carries two iron-bearing formations: first, a thick and complex one analogous to the Biwabik, and second, a thin member at a much higher horizon in the Virginia formation. It is no longer safe to refer to “the Cuyuna iron formation.” More emphasis should be placed on the occurrence of two formations with different textures and characters and in different sequences of associated beds. The terms which have so far been used for these two formations have only increased the difficulty of correlation.

Harder and Johnston (1918, p. 113) wrote that “some geologists believe . . . bands of iron-bearing rock of the north range may be referred to a single layer, but the bands in the south range represent a different and probably higher stratigraphic horizon.” They did not feel certain that this belief was correct, but developments in the forty years since they worked in the area confirm it, and the idea seems to be a satisfactory basis for correlation with other districts. However, the North Range “single layer” proves to be enormously thick and complex, whereas the South Range member is only about 200 feet thick and is included in the very thick Virginia formation area that is five or ten miles wide.

In terms corresponding to those used on the Mesabi Range, the north part of the Cuyuna Range shows the well-known series, (1) Pokegama formation at the base, (2) Biwabik iron formation, and (3) Virginia formation; and most of the items can be well correlated. The South Range member on the Cuyuna, however, has no known equivalent on the Me-
sabi. It is thin, and is probably best named an "iron-bearing member" of the Virginia formation.

In this bulletin, the term "South Range member" is used for this iron-bearing zone in the Virginia, because the term is familiar in the district. The early productive mines of the South Range member lie in a belt three or four miles south (and southeast) of the mines that are now active producers in the Cuyuna district. The ores and the sequence of beds are different in the two belts. The South Range member, however, is not the most southerly (or southeastern) belt of iron formation. As has been previously indicated, a few occurrences resembling those cherty and manganiferous ores of the North Range are well known three or four miles south of the South Range. The terms should be changed to fit the facts. Probably the South Range member lies in a syncline, at least at some places as noted by Wolff (see above, page 85), and the North Range is the north limb of a larger, more productive syncline. The south limb of that larger syncline may be several miles south of the so-called South Range. The belts should not be called North or South, but perhaps if our correlation is approved, the term Biwabik, as used on the Mesabi, will serve for both the main or North Range and the few belts found by drilling south of the South Range member of the Virginia formation. The Animikie series on the Cuyuna (expanded from page 7) is as follows:

Virginia formation — several thousand feet (including an iron-bearing member, 100–200 feet, high above the base of the slate in the Cuyuna district; called the "South Range member").

Biwabik iron formation (in 4 members), 2000–3000 feet.

Pokegama formation, quartzite and quartz slates, 200–500 feet.

While no one has reported iron-rich beds in the Virginia slate on the Mesabi Range equivalent to those on the South Range, there seem to be iron formations in Wisconsin and Michigan corresponding to those on the South Range (see pages 107–9).

Throughout the Cuyuna district, many beds and groups of beds can now be assigned to members well correlated with the Mesabi, but since the only Cuyuna beds exposed are those explored by mining and drill sampling, there may be errors. The data are now believed to be complete enough to map, but attention is called (see pp. 53 and 58) to some uncertain areas in which estimates were made without wholly satisfactory data.

CORRELATION INSIDE THE CUYUNA DISTRICT

Inside the restricted Cuyuna district where production is largest, many features mark particular beds and can be traced long distances. They are as follows:

* The writers considered "Railroad belt" and "Upper Animikie iron formation" as possible terms for the "South Range member" (which is not farthest south).
1. The granule textures, probably derived from greenalite (Fig. 22), are common in the cherty divisions and locally in the slaty divisions of the Biwabik series. They have not been reported as occurring in the “South Range” iron-bearing member of the Virginia slate.

2. The sequence of major formations and beds is as given on pages 56-57.

3. The thicknesses of each of the members and beds are fairly constant in the Cuyuna producing district.

4. The detailed petrographic sequence inside some of the members (for example, the Lower Cherty) can be traced across the district. (See section, below.) Note (a) colors: fresh, weathered, and leached; (b) textures: cherty, slaty, sandy, algal, oolitic, or pebbly; (c) minerals: graphite, chert, quartz, carbonate, silicates (such as acmite and stilpnomelane); and (d) characters of derived ores: the hardness, colors, and textures of the ores, the ore minerals (see pp. 16-17 above) and the contents of manganese, iron, phosphorus, moisture and others.

5. Relation of magnetic belts to certain members and beds; Minnesota examples have been cited under “Magnetics” in Chapter 3.

6. The Upper Slaty member can often be distinguished from Lower Slaty by its appearance, according to Wolff.

As an example of detailed correlation, the features of the Lower Cherty member of the Biwabik formation in the Cuyuna district may well be listed (see page 57 for position in the longer sequence).

Gray slaty rocks and lean graywackes of the Lower Slaty member, hundreds of feet thick, above the chert.

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**Transition — 15 feet**

- **Lower Cherty Member, about 120 feet**
  - Thin cherts (yellow ore, with decomposed chert, looks sandy), 5-15 feet
  - Thick-bedded pink to yellow * (mostly “wash ore,” brown iron ore), 70-100 feet
  - Scattered manganese, thick to thin lenses, near the base, 0-20 feet
  - Slaty beds, 4-10 feet
  - Coarse algal cherts, 3-4 feet

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* Note absence of magnetic layers.

The sequence is almost identical at the Rowe, Section 6, and Maroco pits — a range of several miles — with quartzite below and lean Lower Slaty iron formation above for several hundred feet.

Another cherty member lies above the Lower Slaty member and has many features that make certain it is distinct from the Lower Cherty member. Within a mile of the Maroco exposures, at the Merritt Mine in Sec. 33 and at the Mangan pit in Sec. 3, a well-explored Cherty member of approximately the same thickness and similar granule textures has the following features: for 600 feet below it, slaty carbonate manganiferous iron formation, magnetite slates, and graywacke slates, instead of quartz-
ite; more ferruginous manganiferous slates above it; much more "black" manganiferous iron ore than the dominant iron ores and scattered lenses of manganiferous ore of the Maroco; and belts of ore formation that are traced several miles without in any case approaching the character of the Lower Cherty member or its sequence of beds, ores, and internal peculiarities as tabulated above.

High in the Upper Slaty member of the Cuyuna Biwabik formation are two other somewhat cherty belts. Plate 2 shows them as extending from near Rabbit Lake to the Ironton Mine and the Portsmouth open pit. Traces of such material occur farther west. Harder and Johnston (1918, p. 143) reported chert in the north wall of the Pennington and Feigh mines. Recent drilling and pits show cherts (probably not as thick as Upper Cherty member) in a zone south of the South Alstead pit and its extension toward Mahnomen pit.

Magnetite-bearing key beds can be traced by surface or aeromagnetic surveys. A few major horizons can thus be followed for long distances, but some beds pinch out and some are probably oxidized locally. (See above, pages 23-25.)

The South Range member of the Virginia formation has no beds resembling these thick-beded cherty members, and there is no correlation of the South Range with the North Range (Biwabik). Magnetite in the South Range iron formation member makes it easy to trace by magnetic mapping, but drag folds and faults complicate the belts.

REGIONAL CORRELATIONS

Correlations of the Cuyuna series with those of the Mesabi Range, and with the ranges in the Marquette (Michigan) and Gogebic (Wisconsin), involve greater distances, and the changes from place to place are greater than those inside the Cuyuna district. For such long-distance correlations, Van Hise and Leith (1911, p. 598) suggest a series of noteworthy principles:

1. Relations to recognizable horizons or groups.
2. Unconformities.
3. Lithological likenesses.
4. Like sequences of beds.

Besides these four, there are four others that are worthy of note, but they may not be so strongly suggestive:

5. Similar origin of formation.
6. Similar relation to intrusives.
7. Similar amount and nature of deformation.
8. Similar degree of metamorphism.

This series of ideas and methods has been kept in mind and will be here applied to support, first, correlation of the Cuyuna with the nearby and well-known Mesabi, and later the correlation with the iron ranges south of Lake Superior.
CORRELATION

CORRELATION OF MESABI (BIWABIK) AND CUYUNA (NORTH RANGE)

Recognizable Formations and Groups

A. The rocks of the Cuyuna and Mesabi ranges are known chiefly from open-pit mines and drill samples, but the data have progressively improved since the period 1910–15, when several Cuyuna mines began shipping. The Mesabi Biwabik and associated beds have been satisfactorily correlated along a belt from the Gunflint beds in Cook County, Minnesota (and east in Ontario) (Leith, Lund, and Leith, 1935), to the southwestern extensions of the Mesabi iron formation in Cass County, Minnesota. The gap from these extensions to the Cuyuna Range has commonly been believed to be about forty miles, and thick glacial deposits have delayed active explorations of the intervening area.

Drilling near Remer and Emily shows recognizable Animikie formations in normal sequence (see pages 81–83) — quartzite, iron formation, and slates. The trend of belts can be indicated approximately, and the gaps for which information is least, are hardly as long as ten miles. Some records for these areas are in the Minnesota Geological Survey file. Several key beds are well correlated from the western Mesabi to the North Range of the Cuyuna. Much previous criticism of such correlations has been based on the South Range member of the Virginia formation, which is not known at the type locality of the Virginia slate along the Mesabi Range (Grout et al. 1951, pp. 1041–51, 1064), probably because the dips are low on the Mesabi and consequently any South Range member would be farther southeast than the Mesabi has been explored. The North Range has the characters of the Biwabik formation.

B. The granule-textured (greenalite) iron formation is characteristic of the Biwabik formation in both ranges. (Figs. 22–23.) Such textures and minerals have been noted at many places and suggest correlation. After nearly a hundred years of observation, it may be said that this odd granule texture is known only in the Biwabik formation, not in two formations of different periods (Grout et al. 1951, pp. 1064–65).* Gruner (1946, p. 50) remarks that in parts of the Mesabi Range "the absence of any granule texture in about 10 to 15 feet of drill cores is almost always a sure sign of the presence of Virginia slate."

Granules of greenalite, or minerals derived from it, occur in all four divisions of the Biwabik series in the North Cuyuna Range (Fig. 22), but none has been noted in the South Range member of the Virginia formation.

C. The geologic columns of the North Cuyuna and Mesabi are compared in Plate 6. They are much alike. Gruner (1946, Plate I, in pocket) shows that the thick and thin stratigraphic sections of the Mesabi Biwabik series, one at the east end and the other at the center of the

* Grout and Schwartz (1938, p. 17) noted one occurrence of spots in the Rove slate (equivalent to the Virginia slate) that looked somewhat like greenalite granules, but microscopic examination showed that they were of different origin.
Figure 22. — Photomicrographs of granule textures in Cuyuna iron formation, mostly from the Merritt Mine, depth 200-320 feet; suggesting greenalite or minerals derived from greenalite. (Photographs A and B by G. A. Thiel, C through F by F. F. Grout.)
Figure 23.—Photomicrographs of granule textures in Mesabi iron formation, suggesting greenalite or minerals derived from greenalite. (Photographs by F. F. Grout.)
Mesabi Range, differ about as much as the central Mesabi differs from the Cuyuna.

**The Sequence of Formations in Major and Minor Beds**

A. The series in the two ranges show many analogies, but also local differences. Beginning at the base, underlying the Animikie series north of the Mesabi and east and southeast of the Cuyuna is the Thomson formation, about equivalent to the Knife Lake formation as suggested by Schwartz (1942a, p. 1018). Some of the feeble magnetics in that area (Plate 1) may be equivalent to the Agawa belts in the Knife Lake formation.* They are not all at a definite horizon, and none is known to be more than a few feet thick except at the type locality, Lake Agawa.

B. The Pokegama formation on the Cuyuna is estimated by Wolff as about 350 feet or more in thickness, whereas on the Mesabi it is rarely, if ever, more than 100 feet thick. It underlies the Biwabik iron formation at most places in both districts.

C. The Lower Cherty member on the Cuyuna is 100 to 250 feet thick—perhaps a little thicker than at the west end of the Mesabi. The detailed sequence inside the Lower Cherty member reported by Wolff (see page 57) is almost identical on the Mesabi and the Cuyuna. This sequence is well exposed on both ranges, and includes so many of the same peculiarities that nearly everyone who examines the two will approve correlation. Several mines in the Lower Cherty member on the Cuyuna show lenses of manganiferous iron ore, as has been indicated earlier, and at least one mine in the Lower Cherty beds on the Mesabi—the Alpena Mine—north of Virginia (Wolff, 1951, p. 15) had a manganiferous lens.

D. The Lower Slaty member of the Cuyuna, from 700 to 750 feet thick, is much thicker than the Mesabi maximum. The slaty-looking rocks are still iron-bearing, most of them carrying 20 to 30 per cent iron (see assays of Merritt drill cores, pages 44-45). No single Cuyuna drill hole or exposure has given a measurement of the total. Even on the Mesabi Range, the thickness of the Lower Slaty member ranges from 10 to 230 feet (Gruner, 1946).

E. The Upper Cherty members with “black ores” of manganese and iron are much alike in the two ranges (Wolff, 1951, p. 8). The total thickness of the lower three members of the Cuyuna Biwabik, 880 to 1165 feet, is only a little greater than the total of the three on the Mesabi.

F. The Upper Slaty member on the Cuyuna, estimated at 1700 to 2300 feet thick or more, is in marked contrast with the maximum of 263 feet on the western Mesabi Range. No single drill hole or exposure has given a measurement of the Cuyuna total. However, it has been suggested that there may be an unconformity between the Biwabik and Virginia

formations (Wolff, 1917), and the Upper Slaty beds may have been locally eroded where they prove to be thin. At the top, and near the center of the Cuyuna Upper Slaty member, there are manganiferous ores (see tabulation on pp. 56f.) and the Leonidas Mine on the Mesabi produced manganiferous ore from corresponding beds (Wolff, 1951, p. 10).

G. South of the Mesabi Range several drill holes have been put down through hundreds of feet of the Virginia slate and into the Biwabik formation below. The Virginia slate thus obtained in cores resembles the slaty material south of (above) the Biwabik of the Cuyuna district, except possibly in color. The colored samples of Cuyuna slates were from shallow holes, and the colors may have resulted from local oxidation. Further studies should be made to see if deep cores of lean Virginia slate are brightly colored. Samples of one of the deep Mesabi holes are stored at the University of Minnesota, in the collection of the Geological Survey. They represent about 1700 feet across the beds and are available for the inspection of anyone who would like to compare the slates of the two areas.

The Cuyuna South Range iron-bearing member of the Virginia formation, lying high above Biwabik series, has not been traced to the Mesabi area, but relatively little exploration has been undertaken in the area 5 to 20 miles south of the Mesabi Range mines. This thin iron-bearing member in the slates is not considered as a serious difficulty in correlation.

Question may be raised whether cherty zones 100 feet thick may still be considered major members of a formation when the whole formation increases from 320 feet on the East Mesabi to 3000 feet on the Cuyuna. It is not wholly a matter of thickness; the sequences in detail, textures, colors, assays, and many other features serve to establish them as major members. In both ranges, cherts normally yield blue hard ores; these contrast with the softer, more yellowish brown ores from the slaty members, and with the red “paint rock” from the lean “intermediate slate.”

**KEY BEDS**

Besides the items listed under recognizable groups and sequences, there are several smaller key beds.

A. Magnetic beds, and lines of maximum magnetic attractions are aids to following the structures in both ranges, as has already been indicated. (Notes on Mesabi magnetics are available in A-2.)

B. Algal structures mark two or three horizons. The base of the Biwabik shows pink cherty structures like a pile of inverted bowls a foot or more wide, both on the Mesabi (Leith, 1903, Plate XIII, B) and on the north wall of the Maroco pit of the Cuyuna. A smaller algal structure resembles a pile of thimbles, open end downward. On the Mesabi they were shown by Leith (1903, Plate XII, A), by Grout and Broderick (1919, Plate VII), and by Gruner (1946, Plates XI and XII). Gruner
(1946, pp. 38–49, 92–93) notes that such a bed lies well up in the Mesabi Upper Cherty member, and a similar thin zone is probable in the Cuyuna chert. These constitute two promising key beds. There may be a third algal bed in the Upper Slaty member on the Cuyuna.

C. Manganiferous iron-formation beds, though not too regular, dominate at certain horizons. On the Cuyuna Range, a notable manganese zone is in the Upper Cherty member (as in the Merritt and Mangan mines) where lenses and shattered zones produce "black ores" that are rich in manganese. Wolff (1951, pp. 8, 9) noted that in 1910 three Mesabi Range mines produced black manganiferous cherty ore from this Upper Cherty member. Other manganiferous ores are characterized by certain manganese ore minerals—manganite, groutite, and others.

D. Oolitic textures appear in the Upper Cherty member of the Mesabi (Leith, Plate XIII, D). Several oolitic cores in the Merritt drilling (see Fig. 15) came from the hard rock where the Upper Cherty member lies on the Lower Slaty member (Figs. 11 and 12). This oolite zone has locally at the base a thin conglomerate of iron-formation pebbles, in both the Cuyuna and Mesabi mines.

E. Graphitic slates may prove to mark certain horizons, such as the Lower Slaty member on the Mesabi Range. The corresponding member on the Cuyuna is several hundred feet thick, but graphitic slates in it make only small and probably lenticular beds. The west end of the Virginia pit has a graphic lens, and other graphitic beds have been recorded but not traced very far.

F. High in the Upper Slaty member in the Cuyuna district are two cherty beds; these are not as massive or thick-bedded as the Upper Cherty member on both ranges. A close study of the Mesabi reveals some minor cherty zones locally a short distance below the Virginia slate (Gruner, 1946, Plate I).

G. The only approach to common mechanical sediment (excluding diagenetic pebbles of iron-bearing precipitates) in the Biwabik formation on the Mesabi is the "intermediate slate," which is 1 to 40 feet thick; it is thin-bedded and slaty in appearance but does not have true clay minerals. The sandy and argillaceous sediments on the Cuyuna, though possibly more than 300 feet thick, lie at the same place in the sequence and are not strongly opposed to correlation. Other mechanical sediments are interfingered in the Cuyuna Biwabik (Fig. 24).

H. High phosphorus occurs in much of the ore shipped from the Cuyuna Range, and not so much from the Mesabi; but Wolff (1919) notes that where phosphorus is high on the Mesabi it is localized at the same horizons as on the Cuyuna—one phosphorus-rich bed in the Upper Slaty member, one in the Upper Cherty member, and one in the Lower Slaty carbonate.

K. The occasional carbonate beds on the Mesabi lie mostly in the Slaty members, which are the source of the abundant green carbonate slates and brown ores of the Cuyuna.
L. The Virginia Mine in Secs. 4 and 5, T. 46 N., R. 29 W., lies in the Lower Slaty member of the Cuyuna Biwabik beds, and the ores are thin-bedded but partly cherty and locally manganiferous. These ores are believed to be equivalent to thin carbonate beds of the Mesabi Lower Slaty member.

M. The carbonate slates, though thicker on the Cuyuna Range than on the Mesabi, show variable thicknesses even on the Mesabi and Gunflint ranges. Very little carbonate is known on the eastern Mesabi Range, but farther west, as at Chisholm, there is, above the Intermediate Slate, a carbonate slate as much as 76 feet thick, with 20 to 30 per cent carbon dioxide. A similar bed occurs near Nashwauk.*

N. Only a few Mesabi Range ore bodies are derived from the Upper Slaty member of the iron formation; but many of the ore bodies of the Cuyuna Range are derived from the much thicker Upper Slaty member, from the Sagamore Mine to Rabbit Lake. This difference in the zones of enriched ores may be part of the reason early geologists failed to recognize the possibility of correlating the formations in the two districts. All these analogous beds furnish a strong basis for correlation, in spite of the much greater thickness of the Upper Slaty member on the Cuyuna than on the Mesabi, and the larger proportion of mechanical sediments in the Cuyuna district.

OTHER BASES OF CORRELATION†

A. Unconformities are agreed upon: below the Pokegama at the base of the Animikie series; and below the Keweenawan, although there are only a few poor exposures. Keweenawan flows were reported (Van Hise and Leith, p. 215) to rest unconformably on tilted Animikie. There is some doubt as to unconformity between the Biwabik and Virginia formations. Possibly the unconformity at about this horizon, south of Lake Superior, will support the suggestion of a similar break in Minnesota. Wolff has felt that there was erosion of the iron formation on the Mesabi Range before the Virginia slate was deposited (1917, p. 165), but Gruner (Grout et al., 1951, p. 1047–1050) finds it uncertain. There are few exposures. This bulletin suggests that a cherty bed in the Biwabik from Ironton northeast (Plate 2) may have been eroded so that the Virginia formation transgresses both ends of the chert. The evidence is based wholly on drill cores. Perhaps the best evidence is that the separation of underlying Pokegama and overlying Virginia formations is very small near the southwest end of the Mesabi. David White (1954, Plate 1, sheet 4) shows a very small slaty member and two cherty members, pinching out from about 500 feet of chert to less than 50 feet as traced west 16 miles.

B. The origin of most of the Cuyuna rocks older than Keweenawan is sedimentary, with local intrusives. The sediments are partly mechanical

* Gruner, Personal communication: and data from University of Minnesota, Mines Experiment Station, 1942.
† As listed above, on page 96.
deposits in a shallow sea, but the iron-rich beds were probably chemical sediments in all the districts. In the Minnesota districts chemical precipitates appear to be more abundant than the sands and clays. The interfingering suggested below (pages 110-11, and Figure 24) shows that difficulties must be expected in correlations. Alterations have already been described in Chapter 3.

DIFFICULTIES IN CORRELATION OF MESABI AND CUYUNA RANGES

1. The base of the Virginia slate has, at places on the Mesabi Range, up to 10 feet of cherty limestone, which is not recognized in the Cuyuna drilling even though there may be several drill holes that have explored that basal contact. There are so many carbonate slates in the Cuyuna (Biwabik) formation that the limestone horizon may not have been recognized.

2. There are in the Cuyuna (Biwabik) iron formation some quartzite lenses in the slaty divisions (well shown in the University drilling under the North Hillcrest pit). This has led many to suspect that all quartzites in the district are lenses without much continuity, but the continuity of the Pokegama quartzite is very certain.

3. Metamorphism and deformation are much greater on the Cuyuna than on the Mesabi. Secondary slaty cleavage is almost unknown on the Mesabi, but very common (Fig. 8) on the Cuyuna; locally there are schists near the granites. The greater deformation and recrystallization on the Cuyuna seem clearly related to nearby Keweenawan intrusives.

4. Magnetic belts are common in the central Mesabi district and in much of the Cuyuna district, but cannot be well traced from one to the other. Some probably pinch out, others are offset by faults separating two parts of an original belt, and still others had originally only a little magnetite at scattered places along a magnetite horizon. Western Mesabi granule-textured cherts are commonly almost white, and hard to correlate.

5. The Cuyuna formations are more manganiferous than those of the Mesabi; but the good “black ore” horizon, such as the Upper Cherty member in the Merritt Mine with high manganese and some rhodochrosite veins, is analogous to the Upper Cherty manganiferous ores and rhodochrosite in the Leonidas Mine at Eveleth, and in the Lone Jack and Moose Mines at Virginia (Wolff, 1951, pp. 8 and 23). On the Mesabi Range, the Leonidas Mine produced from the Upper Slaty beds, ore with 7 per cent manganese, equivalent to the manganiferous slaty ores on the Cuyuna (Wolff, 1951, p. 10).

6. The South Range iron-bearing member of the Virginia formation on the Cuyuna Range is not known on the Mesabi Range, but a similar formation is reported in “Upper Huronian” slates in Michigan, probably equivalent to Animikie.

7. The Cuyuna slates are thicker and carry more mechanical sediment
than the Mesabi slates. This may well be attributed to formation near shore, and to interfingering.

8. The ages of the granites near Minnesota ore districts are not yet well settled, but the work of ascertaining their ages is in progress. The St. Cloud red granite, which was carefully studied by Woyski (1949, p. 1005), seems to be Keweenawan. That large mass and its outliers may have recrystallized the Animikie rocks of the Cuyuna. Thiél (1947) found small granitic dikes cutting Cuyuna ores. Probably Keweenawan granites lie close below the metamorphosed Cuyuna iron-bearing beds.

These differences between the Biwabik formation in the Cuyuna district and in the Mesabi district are no harder to accept than the differences between East Mesabi and Central Mesabi. As stated above, however, there are some really sandy beds in the Cuyuna Biwabik series. They can be explained by the supposition that the Cuyuna sediments are thicker and sandier because deposited nearer to a shore with rough topography. It is commonly understood that at several horizons in the Mesabi Biwabik there are pebbly beds, but these should apparently be considered intraformational conglomerates and not contributions of eroded surface rock fragments to a sea-bottom on which iron formation was being precipitated.

CORRELATION DIAGRAM OF NORTH CUYUNA, MESABI & GOGEBIC RANGE IRON-FORMATIONS *

The accompanying correlation diagram (Plate 6) shows the similarity of subdivisions on the three iron ranges. More striking than the similarity of members is the similarity of the minor subdivisions.

The black low-phosphorus siliceous manganiferous iron ores of the North Cuyuna have their counterpart in some manganiferous ores in the Upper Cherty member of the east-central part of the Mesabi. In fact, occasional high-manganese samples occur in this subdivision on the Mesabi Range, from T. 57 N., R. 21 W. eastward, and the writer has seen rhodochrosite crystals in the Upper Cherty taconite wall of the Fayal open pit, Sec. 5, T. 57 N., R. 17 W. near Eveleth.

The detailed subdivision of the Cuyuna Lower Slaty member was made possible by the Merritt drill hole (see pages 44–45), and by drilling in Sec. 1, T. 138 N., R. 26 W. in 1952 by one of the large mining companies, cores and records of which were available to the writer.

The detailed subdivisions of Mesabi and Gogebic ranges, and their equivalence, are shown on the correlation diagram prepared by the writer from his own detailed examination of drill cores and mine workings many years ago; the Cuyuna correlation was added during the past ten years.

Certain Gogebic beds, correlated in Plate 6 with the Lower Slaty member of other ranges, include some cherty beds, named "Norrie cherts" by Hotchkiss (1919), and by Aldrich (1929, pp. 100, 159, 160). Most of

* This section of two pages has been contributed by J. F. Wolff, Sr. Joint authorship is resumed in the next section, where the regional picture is discussed.
the Norrie cherts are thin-bedded and may well be the equivalent of thin-bedded cherts in the Virginia Mine on the Cuyuna Range. The color and weathering of the cherts also suggest that correlation.

Attention should be called to the beds near the contact of the Ironwood and Tyler formations on the Gogebic Range. It might seem that the lower beds of Tyler, which carry some magnetite, should be correlated with the Upper Slaty beds of the Mesabi; but the main unconformity near these beds is above the slates (here called "Pabst"), and below a conglomerate, carrying some magnetite, at the base of the Tyler series.*

Before the basal conglomerate of the lower Tyler was deposited, the Ironwood (Gogebic) iron formation (750 feet thick) and the underlying Palms formation (350 feet thick) were locally eroded from the east end (and in part from the west end) of the Gogebic; and the bottom member of the Tyler Slate formation was deposited on the underlying granite (Leith, Lund, and Leith, pp. 10 and 14). That erosion period must have been long. There may have been a thick series of iron-bearing sediments above the Pabst slates on the Gogebic, comparable to the thick Upper Slaty member of the North Cuyuna. Regardless of thicknesses, there is clear evidence that on the Gogebic Range the top of the Ironwood formation was locally deeply eroded before the Tyler slate was deposited.

The proof of tremendous erosion south of Lake Superior after the deposition of the Ironwood suggests that some erosion of the top of the Biwabik should be sought, and should be expected, northwest of Lake Superior. The result of that search was the evidence shown on Plate 2, that there is a probably unconformable contact between the top of the North Cuyuna Upper Slaty member and the overlying Virginia formation. (See page 74.)

The 707 feet of ferruginous basal Tyler formation shown on Plate 6 obviously was deposited after the great local erosion of the Gogebic iron formation. Therefore it does not seem at all probable that the basal Tyler and Cuyuna Upper Slaty formations were contemporaneous. The only logical conclusion is that the greater part of the North Cuyuna thick Upper Slaty member has no known counterpart among the iron formation subdivisions of the Lake Superior iron districts, except perhaps the top part of the 3000-foot Marquette Negaunee iron formation.

The 232 feet of cherty formation in the bottom part of the Gogebic Range Tyler formation is a very lean chert with some one-inch hematite bands, but it has not produced any ore in the few places where it has been encountered. It can hardly be the stratigraphic equivalent of the Bijiki schist high in the Michigamme slate of the Marquette Range. It is possible that the occurrence of this Gogebic lower Tyler iron formation is unique and has no counterpart in the other districts.

* Aldrich (1929, p. 100) refers to Hotchkiss as using the term "Pabst" for a conglomerate; but Aldrich had "not had any opportunity to examine this horizon." Possibly Hotchkiss believed that both the slates and overlying conglomerate were part of one Pabst formation.
THE REGIONAL PICTURE

Regional studies around Lake Superior were well summarized by Leith, Lund, and Leith (1935, pp. 10–15 and Table). The table on page 108 has been abstracted from their work, with slight modifications, to show the four districts involved in the correlations here discussed. Several dolomite formations occurring unconformably below the important iron formations are recorded in the Cuyuna, Gogebic, Marquette and other districts. Certain details in the sequence of beds, such as Cherty and Slaty members, and the algal structure at the base of the Biwabik formation on the Mesabi and Cuyuna (see page 95), appear also on the Gogebic Range, perhaps modified in details. (Plate 6.)

The Cuyuna South Range member of the Virginia formation has had little attention since it is thin and not generally manganiferous, but it may aid in the correlation of the thick slates in Minnesota with those in Michigan. Both lie hundreds of feet above the larger iron formations that are equivalent to the Biwabik formation.

The Pokegama formation is considerably thicker on the Cuyuna Range than on the Mesabi, but the greater thickness and local quartzose slates of the Cuyuna correlate well with the thickness and character of the Palms quartzite on the Gogebic Range, and the Ajibik on the Marquette.

Slaty beds in the iron formation of the Gogebic Range correlate well with those of the Mesabi, but the fairly thick slaty members on the Gogebic are said (Aldrich, 1929, p. 160) to be more carbonate than slate in thin beds. This correlates especially well with the Cuyuna North Range, where there is a good deal of carbonate in the slaty members and some carbonate even in the cherty members.

Gruner (1946, p. 63, and Tables 10 and II) compared the formations of the Mesabi and Cuyuna with those of the Gogebic and Marquette, by average chemical compositions. It is clear, however, that his average Cuyuna formation composition is based on 4 samples selected from North Range (Biwabik) formation and 1 from South Range (from 13 tabulated by Harder and Johnston, 1918, p. 120).

It is now generally recognized that the Marquette and some other ranges south of Lake Superior (Leith, Lund, and Leith, 1935, p. 10, and table following) show a thick slaty formation, enclosing a thin iron-bearing member, with both lying unconformably above the formations correlated with the Biwabik on the Mesabi Range. Concerning the possible correlation of the Cuyuna and Mesabi Ranges those authors say (1935, p. 15) there are “so many exceptions and qualifications, it fails to be convincing.” It seems likely this trouble results from including in the Cuyuna, two iron formations: (1) North Range, equivalent to the Mesabi Biwabik, and (2) South Range, equivalent to the Marquette Bijiki. The Marquette range, according to these authors, shows satisfactory correlation of the Negaunee iron formation with the Minnesota Biwabik iron formation, but the series overlying the Negaunee is even
## Precambrian Formations of Some Lake Superior Districts
(Modified from Leith, Lund, and Leith, 1935)

<table>
<thead>
<tr>
<th>Mesabi District</th>
<th>Cuyuna District</th>
<th>Gogebic District</th>
<th>Marquette District</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LATER PRECAMBRIAN — KEWEENAWAN SERIES</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrusives, flows and sediments</td>
<td>Intrusives, granites, flows and sediments</td>
<td>Intrusives, granites, flows and sediments</td>
<td>Intrusives</td>
</tr>
<tr>
<td>(Unconformity?)</td>
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<td>(Unconformity?)</td>
</tr>
</tbody>
</table>

| **LATER PRECAMBRIAN — UPPER ANIMIKIE SERIES** | | | |
| Virginia slate, 2000± feet thick | Virginia formation, 3000± feet thick (Includes one iron-bearing bed, 100 to 200 feet thick, high in the series.) | Tyler slate, 7000 to 10,000 feet, includes near the base these items: carbonate slate and chert, graywacke, quartz slate, magnetite slate, conglomerate, quartzite | Michigan slate series, Upper slates, 500 feet Bijiki iron formation, 0 to 500 feet Lower slates, 1000 feet (Unconformity?) Clarksburg volcanics, 0 to 1000 feet Goodrich quartzite, 0 to 1500 feet |
| (Unconformity?) | (Unconformity?) | (Unconformity?) | (Unconformity?) |

| **MEDIAL PRECAMBRIAN — LOWER ANIMIKIE SERIES** | | | |
| Biwabik iron formation, 300 to 800 feet thick | Biwabik iron formation, 2000 to 3500 feet thick (Flows and intrusives) | Ironwood iron formation, 600 to 1000 feet | Negaunee iron formation, 2000 feet Siamo slate, 600 to 1000 feet |
| Pokegama quartzite, 1 to 100 feet thick | Pokegama quartzite, 50 to 400 feet thick | Palms quartzite, 400 feet | Ajibik quartzite, 700 feet |
| (Unconformity?) | (Unconformity?) | (Unconformity?) | (Unconformity?) |
| Algoman granite | Algoman granite | Algoman granite? | Algoman granite |
| Intrusive contact | Intrusive contact | | Intrusive contact |

| **MEDIAL PRECAMBRIAN — PRE-ANIMIKIE SERIES** | | | |
| Knife Lake formation, 2000± feet | Schists and dolomite | Quartzite and dolomite, 150 to 300 feet | Weve slate, 100 to 1000 feet Kona dolomite, 200 to 700 feet Mesnard quartzite, 150 to 700 feet |
| (Unconformity?) | (Unconformity?) | (Unconformity?) | (Unconformity?) |

| **EARLIER PRECAMBRIAN** | | | |
| Older schists and granites | Granite of uncertain age, older schists and gneisses | Granites and gneisses | Granite, gneiss, and schist |

* See map, please those in Lower Unconformity, aligned...
more complex than the Tyler slate on the Gogebic Range. Unconformably above the Negaunee lies the Michigamme slate with the Greenwood iron-bearing series at the base, and a thin Bijiki iron-bearing member in its midst. These have not yet been correlated in all details with the Minnesota ranges. It is believed that the Marquette Bijiki is equivalent to the South Range member of the Cuyuna. It has no known equivalent in the Mesabi and Gogebic ranges.

The Marquette Greenwood formation series (see table on page 108) is probably correlated with the Gogebic iron-bearing conglomerate bed at the base of the Tyler formation (Plate 6). There is little on the Mesabi Range that can be correlated with the Greenwood formation and the base of the Tyler; but Wolff notes that at the top of the Mesabi series there is an "impure limestone and chert bed with occasional pebbles." These may be equivalent to the Pabst and the Greenwood.

The great thickness of the Upper Slaty member mapped on the Cuyuna Range may be questioned: Is the upper part of the series definitely correlated with Mesabi Biwabik? Or could it be a part of the basal beds of the overlying slates, comparable with the Greenwood series on the Marquette? These questions cannot be answered very definitely, but the writers emphasize that up to 1954 no break has been discovered in the Cuyuna Biwabik series below the Virginia formation.

It may be enlightening to arrange the districts in a series showing increasing subdivisions of the main Animikie beds above the basal quartzites as follows:

1. The Mesabi Biwabik iron formation shows two cherty and two slaty members underlying the thick Virginia slate.
2. The Gogebic Ironwood iron formation shows three cherty and three slaty members (the third chert and slate named as one, the Anvil member) underlying the thick Tyler slate, which includes, as its lower 700 feet, some cherty and ferruginous beds.
3. The Cuyuna Biwabik iron formation shows two cherty and two slaty members (the thick Upper Slaty member complicated by two thin-bedded cherts), underlying very thick Virginia formation, in the midst of which is a 200-foot bed of iron formation.
4. The chief Marquette iron formation, the thick Negaunee (without any certain regularity in the alternation of cherty and slaty divisions) does show slaty, cherty, and jaspery beds disturbed by intrusives; above them are the Greenwood and Bijiki iron formations, in two series, associated with quartzite, intrusives and thick Michigamme slates. Plate 6 and the table on page 108 attempt to show these relations.

The Lower Slaty belt on the Cuyuna may be equivalent to the triple group—Yale, Norrie, and Pence members of the Gogebic series—even though the Norrie is said to have two or more layers of thick-bedded chert.

The post-Animikie unconformity is probably best known south of Lake Superior (Van Hise and Leith, 1911, pp. 234 and 378) where Keweenawan rests on thick Tyler slates; but the unconformity transgresses locally
Figure 24.—Stratigraphic interfingering suggested for the Lake Superior iron ranges. (Read Ajibik for Abijik.)
through those slates into the underlying iron formation that is equivalent to the Ironwood and Negaunee formations.

TRANSITIONAL SEDIMENTS IN LAKE SUPERIOR IRON RANGES

Sediments are commonly transitional, along and across the sedimentary bedding. Many beds are transgressive or regressive. At places a formation may grade, without visible contacts, from one mineralogic facies to another deposited at the same time. At other places a tongue of one facies may project into a larger body of another facies formed at the same time. If such developments are repeated the beds are said to be "interfingered." It is here suggested that mechanical sediments may finger into precipitated iron formation, making time planes hard to determine.

Moore, and McKee (1949, pp. 1-48) are not wholly agreed as to the usage of the term "facies," but generally agree on the essential interpretation of the sedimentary structures. It is quite probable that even in the Precambrian, the sediments interfinger differently at different places, instead of grading from one mineral composition to another along or across the beds. Figure 24 serves to show on a small scale how the ideas of facies and interfingering may apply to the Lake Superior iron formation, but it is presented as a suggestion for future research rather than as a finished determination of facts. (Fig. 24 is a rough diagram by F. F. Grout.)

Aldrich (1929, pp. 93, 101, 159, 165) may have had some such relation in mind when he wrote that "whereas the clastics came in to intercalate with chert and carbonate" in one place, "the same beds of chert and carbonate . . . might be absolutely lacking in clastics" at another place. He finds evidence that "clastics came into the basin before iron formation had finished."

James (1954, pp. 240-243, and 279) refers to iron-formation facies and describes interfingerling in the Lake Superior region. With James's definition of iron formation it is hard to tell where iron formation begins and ends.

The interfingerling suggested by Figure 24 may be further cited in explanation of the difference in thickness of members from the Mesabi to the Cuyuna. White (1954, p. 45; Plate 1, sheet 3) traces the sequence of members on the Mesabi to the west end of the range — that nearest to the Cuyuna — and finds that there above the main iron formation, in the overlying mechanical sediments, a tongue (or finger) of iron formation pinches out to the east. It is likely that in the Cuyuna Range there are many such fingers.

This is a problem for future study in Lake Superior iron ranges. After the iron formation was largely completed there was enough change in conditions so that later sediments are dominantly slates.

SUMMARY STATEMENT

Van Hise and Leith (1911, pp. 506-8) said: "In character and size the iron-bearing formations are unique as chemical sediments and differ from
other chemical sediments derived by normal weathering processes. Some unusual and additional factor seems to be required to explain them.

"All the Lake Superior iron-bearing formations are more or less closely related in time and place to basalt flows, usually rich in iron at present and giving evidence of having exuded iron salts at the time of their consolidation.

"The [Mesabi Biwabik] formation of the Animikie group on the north shore of Lake Superior is not associated with basic greenstones of known contemporaneous development, but . . . there is little doubt of its direct continuity with the rocks of the Cuyuna district and the . . . Huronian of the south shore which are associated with basic volcanic rocks.

"The deposition of the Lower Huronian was not accompanied by basic flows and it does not contain a well-developed iron-bearing formation. The Paleozoic of the Lake Superior region lacks basic igneous rocks and also lacks iron-bearing formations like those of the pre-Cambrian."

Most of the objections to the suggested correlation are not serious. Van Hise and Leith (1911, pp. 611-14) explain the complexity of Lake Superior iron ores by reference to conditions of near-shore deposition of clastic sediments, whereas offshore deposits may have been more uniform precipitates.

Leith, in his first monograph on the Mesabi (1903, p. 203), suggested the correlation of the Animikie through the (Cuyuna) Dam Lake quartzite over to Wisconsin. It would seem that the differences in the two ranges are exactly those to be expected if the Cuyuna Range was nearer than the Mesabi Range to a land area where rocks were eroded locally to supply mechanical sediments to a broad sea in which iron minerals were being widely precipitated. The contemporary igneous rocks of the Cuyuna might suggest (1) ferruginous emanations to the sea water, (2) a rough topography such that local embayments may have received much sand and clay, to alternate with the ferruginous precipitate, and (3) ores that would be hydrous (from aqueous precipitation) and high in phosphorus, as are most slaty ores. This would make most of the "difficulties" in correlation, as set forth above, really favorable to the correlation.

The most significant basis for correlation of the North American iron-bearing rocks is the granule texture (Fig. 22) commonly attributed to greenalite, or some similar silicates, believed to be the result of precipitation in a shallow sea. Grout et al. (1951, p. 1065) state: "Such a texture resulting from a supposed precipitation of one or more minerals has no theoretical value—if it could develop in one geologic period, it might equally well result from similar processes in some other periods . . . . In this particular example, however, there is a further line of evidence. The similarity of the granule textures in the iron formations in several districts around Lake Superior was noted very early and suggested a correlation. After close study and observation over a period of 100 years, it can be said that such textures have not been found in two formations of
distinctly different periods in any district. It is on the basis of such experience . . . that the texture in iron formations becomes of great value in correlation."

Such granule textures are known from the Cuyuna North Range to the new Labrador mines, and from Hudson Bay to northern Michigan. The authors of this bulletin think that when carefully and conservatively studied the correlation of the formations of the North Cuyuna district with those of the Mesabi district may well be considered satisfactory.
7. MANGANESE ON THE CUYUNA RANGE FOR EMERGENCY USE

By Frank F. Grout

INTRODUCTION

Steel can hardly be made without manganese. Although only about thirteen pounds are needed for a ton of steel, that much serves to remove sulphur and oxygen from the steel, and to increase its strength and toughness. No other metal serves these two purposes as well as manganese, and if there were another it would probably be more expensive.

The United States has hundreds of small deposits of manganese ore, but the demand is so great that we produce only 5 to 10 per cent of what is required for steel production. Ninety per cent of our manganese is imported. The large producers are the U.S.S.R., Brazil, Africa, and India: ten or twelve other foreign countries produce standard ores in smaller amounts. The amount of manganese imported from Russia, which has about half the world's productive capacity, dropped from 427,000 tons in 1945 to 81,000 tons in 1949. This was in no way related to any exhaustion of supply, but is directly related to Soviet planning. It was accompanied by boasts that Russia had more submarines than all other countries, and might control the shipping lanes. Industry and government in this country have long realized that another war, in which we might lose nearly all imports from across the sea, would place a heavy or even impossible burden on all industries requiring manganese for the making of steel.

Imports of manganese ore into the United States fluctuate rapidly from year to year. Melcher (A-3, 1950, pp. 759 and 769) gives a table and diagram of imports of metallic manganese and manganese ore, from which trends can be seen. Roughly, imports of ore were about 500,000 tons in 1918, 600,000 tons in 1935, and 1,800,000 tons in 1950. We use nearly a million tons of manganese metal each year, but this dropped off a little after the war.

A few points in the history of the steel production since 1917 are significant. Steel producers in the 1917-18 war years were much agitated over reduced supplies of manganese, but at the close of the war imports were resumed. Again in World War II, manganese imports were much reduced by a submarine campaign. A few suggestions were made about using our own manganese in America, but interest faded when Japan gave up the war. More recently the Korean War caused similar reactions. A world metallurgical congress in October 1951, reported that the free
nations possess “a comfortable margin in all strategic minerals except manganese.” * Manganese was the “number one strategic mineral.”

When the “Armistice” was signed on July 27, 1953, the tone of public reports changed for the third time. The Defense Minerals Procurement Agency (DMPA) had virtually suspended all controls on manganese ore before June 1953, as reported by Mining Engineering (Vol. 5, p. 557), which also reported (p. 251) that “stockpiles have been met for [four minerals] while those for . . . manganese have not.”

Thus we have now three times experienced a war emergency in the sinking of manganese imports, a commotion and duplication of efforts to produce manganese enough to survive, and a relaxation and almost total neglect of effort to safeguard ourselves from another such emergency.

The purpose of this chapter is to urge that several studies be vigorously prosecuted to make sure we can use our resources in emergencies, even if the emergency methods of production and beneficiation are more costly than normal imports.

Some quotations from the technical press may serve to show the sequence of opinions and activities of the last ten years. Literally hundreds of deposits in North America were hastily prospected and many suggestions were made for beneficiation of some low-grade deposits. A few of them deserved further study, but interest faded when war ended.

QUOTATIONS ON MANGANESE

Victory, March 10, 1942, announced (p. 17): “New plants to boost output of manganese . . . from 40,000 to 600,000 tons a year . . . . The United States has never been more than a negligible producer of manganese because deposits in this country are low grade . . . . Three large projects will produce more than two-thirds of the expanded domestic output—in the Cuyuna Range of Minnesota, the Missouri River area in South Dakota, and in the vicinity of Boulder Dam in Nevada.

“The Cuyuna Range, largest of the three projects, has presented the most difficult extraction problem . . . . More than a million tons of ore a year will be treated at a Government-built plant to be erected in the area.

“Seven smaller plants . . . are to be built to treat production from small mines.”

Grout (1942) estimated that from the lean Cuyuna formations (not commercial, but available) of manganiferous carbonate slates carrying about 5 per cent manganese, 250 million tons of manganese might be produced.

Emmons and Grout (1943, p. 59) found that “enormous reserves assaying 3 to 8 percent manganese . . . can be steam shoveled from open pits,” on the Cuyuna Range.

M. G. Huntington (A-5, p. 370) said of Chamberlain, South Dakota

* Italics here, and in all the following quotations in this chapter, are mine.
that "to dig enough nodules ... to provide ... 600,000 tons (per year) pure manganese ... we must mine South Dakota at a rate of 450,000 tons daily. This is about 4.5 times the mining at Bingham, Utah, copper operation [the largest of the western copper porphyry open pits]."

Moon (1950, p. 3) reported: "In the light of experience during the War ... the consensus of informed authoritative opinion is that ordinary prudence demands the accumulation of stockpiles ... for use in emergency. It is agreed generally also that such stockpiles must be built up chiefly by importation, before an emergency arises ... to supply our needs for two years. They consider two sources of supply in a war emergency: (1) primary stock piles, mostly of imported ores, and (2) supplementary domestic production. Domestic sources ... would become vital if war continued several years and if foreign supplies should be cut off." One of his conclusions about manganese (p. 27) is that "the large tonnages in South Dakota ... can scarcely be considered available even in a National emergency."

Walter Lewis (1951, p. 33) says "there is probably no technical difficulty that the Government and private industry cannot overcome in obtaining a constant supply of ore from the currently leading suppliers of manganese ore as long as the United States is at peace and the sea lanes remain clear. In time of war, however, the guarding and convoying of ships over these great sea distances would indeed be an almost unsurmountable task for the U.S. Armed Forces."

By October 1951 (Chemical and Engineering News, Vol. 20, p. 4591) a world Metallurgical Congress reported that "the free nations possess a comfortable margin in all strategic materials except manganese, for which production is about equally divided between the free nations and those under Communist control."

In April 1952 (Mining Engineering, Vol. 4, p. 351) in a summary of expansion in U.S. mining, the writer sounds pleased to discover that the production of manganese was "up 50,000 tons." Since consumption was about a million tons this was not very "significant."

In March 1953 Mining Engineering (Vol. 5, p. 251) said: "Objective stockpile goals have been met for [4 items] while those for ... manganese have not, according to a report by the Munitions Board."

In June 1953 (Mining Engineering, Vol. 5, p. 557), Defense Minerals Procurement Agency virtually suspended all allocation controls on manganese ore. After June 1, the only provision left in effect authorized DMPA to issue special directives covering manganese ore deliveries.

On July 27, 1953, the Korean armistice was signed.
In September 1953 Chemical and Engineering News (Vol. 31, p. 3948) said: "After seven years, the five-year program to build up stockpiles of strategic and critical materials is 79% complete. With the bitter experiences of World War II fresh in mind, Congress in 1946 . . . passed the . . . Stockpiling Act (Public Law 520, 79th Congress). The original objective was to complete the stockpile in five years. This has now been discarded. Among the 18 changes made this year were those relating to manganese."

In February 1954 (Mining Engineering, Vol. 6, p. 144) "Trends" said: "During the hearings [of a subcommittee on Minerals, etc. of the Committee on Interior and Insular Affairs] several military strategists stated disbelief in the possibility of keeping long sea lanes open during time of war."

In April 1954, Chemical and Engineering News (Vol. 32, pp. 1576 and 1578) said: "The Government . . . has decided to obtain quantities of strategic and critical minerals now while supply lines are intact." Office of Defense Mobilization (ODM) has already directed Department of Interior's Defense Minerals Exploration Administration (DMEA) to add 19 minerals to its assistance list. For such minerals the government shares a certain percentage of exploration costs—usually 50 or 75 per cent. DMEA shares 75 per cent of cost (of 24 minerals) including manganese.

In August 1954, Mining Engineering (Vol. 6, p. 771) reports on India: "... most of the manganese and iron mines in the Singhum district closed. The slump is blamed on the entry of the . . . Russians into the world manganese market."

In 1954 Chemical and Engineering News said "Manganese—Off the Critical List" (Vol. 32, pp. 4421–22), and continued as follows: "Raw material . . . is low grade ore from . . . Maine, running about 10 to 12% manganese. New method . . . by E. S. Nossen Laboratories utilizes a nitric acid . . . ."

SOME DETAILS OF MINNESOTA AND OTHER SUPPLIES

The one place in which new and important deposits of manganese ore would be of most value would be in the United States itself. The search has been general for a hundred years, but production has been only about 5 per cent of domestic requirements. No optimistic headlines should divert us from preparing to get along without imports, if it should ever become necessary.

It is obvious that if all supplies of metallurgical grade manganese ore were produced within the borders of the United States, it would be necessary to put into production one or more of the larger deposits, in order to replace approximately 1,500,000 tons of ore that must now be imported.
Soon after the first World War (Mineral Resources, 1919, p. 96), H. A. C. Jenison remarked about manganese ores, crediting Harder and Hewett, that “the greatest reserves of low-grade siliceous ore occur in Arizona and . . . Montana, but only a small part . . . could be successfully concentrated. . . . Three-fourths of the reserves of low-grade ferruginous manganese ores appear to be in the Cuyuna Range, Minnesota . . . they must be considered the most valuable source of manganese ore in the country.” This bulletin continues to support such remarks.

The first Minnesota agitation about manganese (1940-41) was based on the idea that Minnesota mines could produce more manganese-rich ores (perhaps 30 per cent manganese) to concentrate to ferro-grade, in place of imports. Such a plan is probably unwise, because the Cuyuna normally mines and ships ores which carry from 5 to 15 per cent manganese, and serve the iron industry a very useful purpose; they should not be curtailed or restricted. The total tonnage of such manganiferous iron ores supplies only a small fraction, if any, of the manganese needed for steel. The large tonnages of manganiferous iron formation, here suggested for emergency use, carry about 5 per cent manganese — some in carbonate slate, some partly oxidized — and need special metallurgical treatment to make ferro-grade concentrates.

Two other factors may to some extent modify the situation based on ore and lean formations carrying manganese. First, there are deposits in Mexico and Canada that might provide some good ores for our steel plants without the danger of submarine sinkings of a cargo. They are not yet very thoroughly explored. Second, there are annually large dumps of manganiferous slag which have been considered waste, but which carry from 10 to 15 per cent manganese. Experiments to date indicate that recovery of manganese from slag will be expensive — involving a clinkering, a smelting, and a converter treatment, and probably a final smelting to ferromanganese, besides grindings and magnetic or other separations. It still remains probable that the Cuyuna supply is the most favorable of all United States supplies for emergencies.

Certain special grades of manganese in small tonnages have been produced in the United States, but the large demand for material needed in making steel has never been filled by ores produced in this country. There are scores of deposits, but only a few could produce a million tons of metallic manganese. Probably no more than half a dozen sources could produce a million tons of manganese metal per year, over a period of ten years, even with government aid and a high price.

Forbes (1952) in a special report, Materials Survey — Manganese, gives a “Digest of United States Situation” in Chapter I, and states (pp. 5–6): “Records of the Federal Geological Survey and Federal Bureau of Mines show that over 99 per cent of known United States manganese-metal resources are to be found in 12 deposits; the balance is distributed among more than 1000 small showings.” Furthermore, about 93 per cent of the known manganese resources of the United States are in four localities:
the Cuyuna range, Minnesota; the Chamberlain area, South Dakota; the Artillery Mountains, Arizona; and Aroostook County, Maine. Reclamation of manganese now wasted in open-hearth slag dumps offers a fifth source of large supplies.

This bulletin maintains that the Cuyuna supplies of emergency manganese are as good as any in the country, and perhaps are best of all. The several beds of manganiferous material on the Cuyuna Range can be classified roughly as follows:

I. Manganiferous iron ore. (From 2 to 10 per cent manganese.) Commercial.
   A.1. Slaty carbonate, oxidized and enriched; combined metals = 45+%
   B.1. Cherty, leached and enriched, "Black ore"; combined metals = 50+%
   A.2. Slaty carbonate, oxidized; combined metals = 30–40%
       (some can be milled to 45% combined metals)
   B.2. Cherty black ore; combined metals = 30–40%
       (some can be milled to 45% combined metals)

II. Manganiferous iron formation. (Part slaty and part cherty, from 2 to 10+ per cent manganese and from 10 to 25 per cent iron.) Not now commercial.

This noncommercial material is the largest supply of manganese for emergency use. Lewis (1951, pp. 37–42), using all the data for the Cuyuna Range, made an engineer's estimate of 500 million tons of noncommercial supplies of manganiferous iron formation. This is being increased by con-

### Table: Large Manganese Deposits of the United States
(By Walter Lewis, 1951, with slight changes.)

<table>
<thead>
<tr>
<th>District</th>
<th>Ore, in Tons</th>
<th>Average Grade, in Percentage of Mn.</th>
<th>Metallic Manganese in Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minnesota. Cuyuna</td>
<td>500,000,000 3</td>
<td>2–10</td>
<td>10,000,000–25,000,000</td>
</tr>
<tr>
<td>South Dakota. Chamberlain</td>
<td>77,000,000 2</td>
<td>15</td>
<td>12,000,000 2</td>
</tr>
<tr>
<td>Maine. Aroostook</td>
<td>200,000,000–300,000,000 3</td>
<td>4±</td>
<td>10,000,000 2</td>
</tr>
<tr>
<td></td>
<td>15,000,000 4</td>
<td>4±</td>
<td>600,000 4</td>
</tr>
<tr>
<td>Arizona. Artillery Peak</td>
<td>195,000,000 5</td>
<td>4±</td>
<td>7,500,000 5</td>
</tr>
<tr>
<td></td>
<td>15,000,000 6</td>
<td>6.5</td>
<td>975,000 6</td>
</tr>
<tr>
<td>A group of 7 others (some crude estimates)*</td>
<td>46,025,000</td>
<td>3–25</td>
<td>3,969,000</td>
</tr>
</tbody>
</table>

* The last group includes North and South Carolina; Leadville, Colorado; Three Kids, Nevada; Batesville, Arkansas; Pioche, Nevada; and Phillipsburg, Montana. (Butte, Montana supplies a by-product of high-grade manganese from ores of other metals; no large increase in production can be expected.)

1 Mostly open-pit ore, unoxidized or lean oxidized carbonate. Includes only the formation available in open-pit mines to a depth of 150 feet.

2 Includes only nodules beneath strippable cover; contained in 2,000,000,000 tons of shale averaging 1.5 per cent manganese.

3 Includes the entire Maple-Hovey ore body to a depth of 1400 feet.

4 Includes open-pit ore only to a depth of 200 feet.

5 All types of ore.

6 Hard ore only.

7 From U.S.G.S.
continued exploration. Lewis summarizes (p. 41): "In arriving at... reserves for the Cuyuna, the outlying deposits... have been included... any material that would come under the class of measured, indicated, and inferred reserves... Regardless of whether agreement can be reached on the total reserve and tons of contained manganese, the Cuyuna Range low-grade deposits compare favorably with those of the other... three [Aroostook, Chamberlain and Artillery Peak]."

There have been several misunderstandings as to the sizes of these large reserves. Lewis' table is based on careful study, and deserves general consideration. Further explorations may revise details but the general picture is clear. (See Appendix A, pp. 123–25.) Green carbonate slates in large tonnages are now exposed in open pits, at the Sagamore, Arko, Alstead to Louise, Hopkins and Mahnomen mines. Drilling shows several bodies that could be stripped without much loss of time. Several large bodies of green carbonate slate have never been assayed for manganese.

This situation seems to demand further plans and action. Popular feeling reacts quickly and somewhat superficially to the war emergencies, and relaxes even more quickly to an armistice. The years since 1910 have shown three such cycles. The lesson should now be well learned, and the United States ought not to relax so completely as before, until metallurgists know how to get along without manganese imports from overseas. The Government should definitely stimulate researches on methods, carried at least as far as large pilot plant tests, to prove that American manganese deposits (including low-grade Cuyuna deposits) can supply our steel mills ferromanganese in almost any desired tonnages.

If the tests show, as is probable, that making ferromanganese from Cuyuna formation is more expensive than imports in normal times, no large plants need be built; but a stock pile of good commercial ore should be kept large enough to serve industry for a year or more in an emergency such as war. In anticipation of such an emergency it is only good sense (1) to prove that the methods that would have to be used will work well in large scale plants, and (2) to select places where the ore can be obtained, perhaps stripping some large open pits, and (3) to design a tentative plant for large production in some well selected place (a) near the ore, (b) near transportation, and (c) near possible town sites.

If several sources of manganese in large amounts, and several methods of making ferromanganese from lean ores (or slags), result in manganese at similar costs, it may be wise to conduct such researches in more than one district, and use more than one metallurgical process, to see if good products are obtained. Certainly the Cuyuna Range seems to have so many features in its favor that it should not be neglected.
APPENDIXES, REFERENCES, AND INDEX
NOTES AND REFERENCES ON THE METALLURGY OF MANGANESE

The deposits in the United States that carry manganese in sufficient quantity to be considered as a partial substitute for imports have been listed in Chapter 7. None of these is wholly satisfactory. There are no large rich commercial manganese ores in the United States. In an emergency, it is likely that (1) several small rich deposits will add perhaps 10 per cent of our needs and (2) several large lean deposits may be driven into production by the demands of the steel industry. References are given below to several researches on the methods proposed and partially tested, for production of manganese and ferromanganese.

Manganese is strategic because it is essential to the nation's defense industry, and critical because it is in short supply domestically. To bring us greater self-sufficiency, the U.S. Bureau of Mines is giving top priority to finding ways of using our vast reserves of low-grade manganese materials.

Pilot plant tests prove that many domestic manganese deposits can be upgraded enough to be suitable for steel-making, but the cost of treatment may be two to four times the price of imported high-grade ores. Continued research may reduce these high costs, and the Bureau of Mines is actively testing out the metallurgical methods.

The low-grade manganese deposits of the United States (listed on page 119) include twelve large sources, four larger than the rest; and we must add the artificial deposits of manganiferous slags, of which large tonnages may be available. Pilot plants have been operated at four places by the U.S. Bureau of Mines, using ores from the four abundant supplies; and another plant, with cooperation of the Bureau and the American Iron and Steel Institute, has proved that manganese can be recovered from open-hearth slag.

Recent summaries of progress are in the Materials Survey—Manganese (1952), prepared for the National Security Resources Board, with the cooperation of the U.S. Bureau of Mines and the U.S. Geological Survey; and in Facts about Manganese, issued by the U.S. Department of the Interior, Bureau of Mines, July 1953 (both papers presented by J. J. Forbes, director of the Bureau of Mines).* In the résumé of the sources listed in Chapter 7—Dakota, Cuyuna, Boulder City group, Aroostook (and the manganese slags at Pittsburgh)—it is clear that metallurgical studies have been made of each of the five. Some are still in progress.

1. The Dakota region has shales carrying 1½ per cent manganese. Too much tonnage would have to be handled to give a real contribution to our needs; several times as much rock would have to be mined as in the greatest of the porphyry coppers of western states. If the Dakota work was restricted to the nodules (Zinner and Grosh, 1949) there might be a product carrying 15–20 per cent manganese, and considerable lime, which could be used; but such a product would still be a long way from being ferromanganese. Lovell Moon (1950) says that “the large tonnage of manganese near Chamberlain, South Dakota... can scarcely be considered available even in a national emergency.”

2. Various deposits near Boulder City, Nevada, have been explored more carefully than before, and the pilot plant methods of metallurgical treatment show that some high-grade products can be made. In the tests, it has been found that some early estimates of tonnages and grades were more optimistic than production. No doubt in an emergency there could be substantial production, at an increased cost, from the ore at Artillery Peak.

3. At College Park, Maryland, and at Pittsburgh, a practical method of recovery of manganese from the silicate ores in Aroostook County, Maine, has been sought. The studies are said (Forbes, 1953, pp. 17–19) to be moving by steps from the laboratory to the pilot-plant stage.

4. Slag studies were reported by Joseph, Barrett, and Wood (1930). Later studies on slag dumps had the benefit of some government loans, and some cooperation of government with private industry. The latest report is by R. C. Buehl, M. B. Royer, and J. P. Riott (1953). The work, done at the Bureau of Mines at Pittsburgh, “demonstrated that open-hearth slags can ... yield synthetic high-grade ferromanganese ore.” The process

*References are to works listed, in chronological order, at the end of this Appendix.
involves two stages: first, a blast furnace reduction to spiegelisen containing 12 to 24 per cent manganese; and second, a selective oxidation of manganese from this spiegel in a basic converter to produce a slag containing 55 to 60 per cent manganese. Some of the by-products may also be of value. The authors believe that "the pilot plant tests indicate that about half the manganese requirements of the country could be supplied from open hearth slag." The two or possibly three furnace treatments, and the addition of fluxing materials, indicate that costs are high for producing this manganese-rich slag. Still another process is needed to make the slag into ferromanganese such as is asked by the steel-makers. For studies of slag see Ruppert (1952) and Kootz et al. (1952); and Chemical and Engineering News (Vol. 32 [1954], p. 1126).

5. The Cuyuna manganese situation has been left to the last because it seems to have several advantages over the rest. These are as follows:

A. The deposits are located in a mining district where beneficiation has long been a familiar process, with a variety of methods.

B. The district has good shipping facilities, and transportation is not too expensive to bring in supplies and to ship the product to steel mills.

C. Mining conditions are good. Open pits will serve to produce the manganiferous material for many years. Many mines that are already open have the supplies of carbonate slate and lean oxidized ore; these are exposed and easily accessible in the sides and bottoms of the pits. The belts of workable formation are about 300 feet thick and are locally repeated across the width of an open pit. Belts with steep dips can be followed several miles. There will be enough for many years before mining reaches depths greater than 150 feet.

D. The available material is estimated at 500,000,000 tons (see page 119). There is probably more in some adjoining areas, but the adjoining deposits are not yet well mapped; and surely there is more at depths greater than 150 feet (not used in calculation of tonnage). Drilling was suggested by the engineers of Division V, U.S. Bureau of Mines (Forbes, 1952, p. 20) to check old estimates.

E. The grade of Cuyuna material (see Appendix B) ranges from 2 to 15 per cent manganese, and much can be produced carrying more than 5 per cent manganese, besides 20 to 30 per cent iron. This applies to the enormous tonnages of manganiferous carbonate slate. There are also, especially near the "shipping ores," some partially enriched cherty or slaty formations, not quite rich enough to ship, or to concentrate to shipping grade at a profit. Many of these carry more than 5 per cent manganese.

F. Laboratory and Pilot Plant tests seem favorable. The problem (Forbes, 1953, p. 17) is to obtain an acceptable manganese product and an acceptable iron concentrate, so that the two may share in the cost. The iron ore, especially if it still carries a little manganese, is readily marketed on the Cuyuna.

G. The Cuyuna Range has an advantage in some nearby pyrite deposits (see pp. 86-87) that are well-explored and capable of supplying sulphur, if it is desired for processing the lean manganiferous material. (See under "References" following these Appendixes: Pennington and Davis, 1953; Schwartzt, 1951; Thiel, 1924b; and Winchell, 1907.)

Chemical and Engineering News (Vol. 31 [1953], pp. 677-78) says: "Iron sulphide deposits in Aitkin and Carlton counties, Minnesota, may provide the state with a sulfur industry and also may prove to be the missing link in the development of Cuyuna Range manganese . . . Flotation tests were conducted by bureau metallurgists under the direction of Carl E. Wood in laboratories on the University of Minnesota campus.

The report indicates that an . . . important result of the tests is the possible use of the iron sulphide deposits in the development of a Minnesota manganese industry . . . Using sulfur dioxide gas, the bureau is currently conducting pilot plant tests in the recovery of manganese from Cuyuna carbonate slate ore in a sulphatizing furnace. This will be followed by the leaching step in a flotation mill to be installed in the bureau's manganese pilot plant at Fort Snelling, Minnesota.

If the use of sulfur dioxide gas in the process under investigation is successful, as laboratory tests have indicated, the Cuyuna Range manganese-bearing iron ores in Crow Wing and Aitkin counties may be developed eventually in conjunction with the iron sulphide deposits in Aitkin and Carlton counties.

The Cuyuna Range has about 500 million tons of low-grade iron material containing from 10 to 25 million tons of manganese, the report states. Of the total manganese used by the steel industry today, the bureau report estimates that only about 10% is furnished by domestic producers. It is more than likely that a sulphatizing roast such as that proposed would make sulphate from both the carbones and oxides of manganese.
This rather comprehensive series of tests of the methods for producing usable high-manganese products from American manganese reserves will no doubt result in sufficient production to prove that, in emergency, it would not take long to produce large tonnages in the United States. A stockpile of imported ferrograde ore, to supply the steel mills for a year, would probably be enough to permit the country to establish its own manganese production in an emergency, without further imports. Then one deposit, or several of the best deposits here noted, should become the basis of commercial expansion, with Government subsidy if needed, to meet any wartime or other emergency. The testing and selection of methods should not be postponed until the emergency arrives. (See Chapter 7.)

SELECTED REFERENCES ON MANGANESE METALLURGY

1918. Edmund Newton, Manganiferous iron ores of the Cuyuna: Minnesota Mines Experiment Station Bull. 5.
1941. Ted Counselman, Sintering tests of Cuyuna ore. Mimeographed and issued at the Duluth meeting of the Minnesota section, AIME, in April. (Manganese had an increased percentage in sinter; silica was increased also.)
1948. Hearings on strategic and critical minerals before the Subcommittee on Mines and Mining, House of Representatives, 80th Congress, second session. (Pages 218-19 note a conflict between the mining-geologic needs for ammonium sulphate and the Department of Agriculture's needs for the ammonium salts as fertilizer. It should be possible now to supply both needs.)
1952. R. S. Dean, Manganese extraction by carbamate solutions: Min. Eng. 4: 55-60.
APPENDIX B

CHEMICAL TESTS, SHIPMENTS, AND RESERVES

| Table A. Manganese, Iron, and Carbon Dioxide in “Carbonate-Slate” of the Cuyuna District, Minnesota |
| (Samples mostly by Minnesota Geological Survey; preliminary assays by Minnesota Mines Experiment Station, 1941.)* |

<table>
<thead>
<tr>
<th>Samples</th>
<th>Per Cent of Mn</th>
<th>Per Cent of Fe</th>
<th>Per Cent of CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagamore open pit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 feet, in south wall</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4009</td>
<td>4.33</td>
<td>28.55</td>
<td>16.14</td>
</tr>
<tr>
<td>4010</td>
<td>4.26</td>
<td>27.15</td>
<td>14.84</td>
</tr>
<tr>
<td>4011</td>
<td>5.18</td>
<td>23.83</td>
<td>14.98</td>
</tr>
<tr>
<td>4012</td>
<td>5.39</td>
<td>25.06</td>
<td>5.35</td>
</tr>
<tr>
<td>Anticline north of main pit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4013</td>
<td>7.89</td>
<td>27.08</td>
<td>19.30</td>
</tr>
<tr>
<td>4014</td>
<td>5.78</td>
<td>23.05</td>
<td>14.48</td>
</tr>
<tr>
<td>West wall of pit, opened 1941</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4015</td>
<td>3.21</td>
<td>21.61</td>
<td>3.39</td>
</tr>
<tr>
<td>Arko open pit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top to bottom of exposure in north wall; one of the slaty members</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4001</td>
<td>8.19</td>
<td>19.88</td>
<td>9.32</td>
</tr>
<tr>
<td>4002</td>
<td>9.77</td>
<td>15.63</td>
<td>18.91</td>
</tr>
<tr>
<td>4003</td>
<td>7.21</td>
<td>31.49</td>
<td>13.19</td>
</tr>
<tr>
<td>4004</td>
<td>8.23</td>
<td>32.26</td>
<td>16.91</td>
</tr>
<tr>
<td>4005</td>
<td>7.59</td>
<td>23.47</td>
<td>15.96</td>
</tr>
<tr>
<td>4006</td>
<td>7.51</td>
<td>28.24</td>
<td>12.94</td>
</tr>
<tr>
<td>North Hillcrest open pit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4019, lower 10 feet flat</td>
<td>6.69</td>
<td>24.68</td>
<td>18.68</td>
</tr>
<tr>
<td>4020, upper 15 feet folded</td>
<td>6.87</td>
<td>24.76</td>
<td>19.72</td>
</tr>
<tr>
<td>East Mahnomen open pit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4021, east end, south wall, 10 feet</td>
<td>4.44</td>
<td>29.48</td>
<td>10.91</td>
</tr>
<tr>
<td>4022, east end, syncline, upper 20 feet</td>
<td>3.19</td>
<td>36.97</td>
<td>8.36</td>
</tr>
<tr>
<td>4023, east end, syncline, lower 20 feet</td>
<td>3.60</td>
<td>36.82</td>
<td></td>
</tr>
<tr>
<td>Wearn Mine (Portsmouth)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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* See Chapter 4, Part I.
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Table B. Commercial Assays,* Cuyuna Carbonate Slate and Chert Samples. (The Pontiac Property includes two claims: Clark and Joan No. 3.)

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<th>Per Cent of Mn</th>
<th>Per Cent of SiO₂</th>
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* Cargo analyses of ore shipped are published annually by the Lake Superior Iron Ore Association, Cleveland, Ohio. Much of the ore shipped is beneficiated, and many cargoes consist of mixed ores from different mines.
MORE COMPLETE ANALYSES OF FORMATION

Assays of Iron Formation by Mr. Howard Evans, from the Research Laboratory of the Oliver Iron Mining Company, Reported in 1952

PORTSMOUTH OPEN PIT

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<th></th>
<th>S.E. Bank</th>
<th>W. Bank</th>
<th>N. Bank</th>
<th>Arko Pit*</th>
<th>North</th>
<th>Mahnomen</th>
<th>Sagamore †</th>
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</table>

* If ignited the Arko sample would have 18% Mn and 22% Fe. Combined metals = 40%.
† If ignited the Sagamore sample would have 10.1% Mn and 30.7% Fe. Combined metals = 40.5%.

OLDER ANALYSES, UNIVERSITY SCHOOL OF MINES EXPERIMENT STATION

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1. Trench, north part of Sagamore pit
2. North wall, Arko pit, 1941
3. Cross cut, Merritt Mine, 178-foot level
4. Kennedy Mine
5. Kennedy Mine
6. Mangan No. 2 Mine (South Mahnomen)

* If ignited No. 2 would have 9.3% Mn and 32% Fe. Combined metals = 41.3%.
† If ignited No. 3 would have 10.5% Mn and 25.8% Fe. Combined metals = 36.3%.
### Table C. Selected Cargo Analyses of North Cuyuna Range Ores

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<td>1918</td>
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<tr>
<td>Sagamore</td>
<td>42.06</td>
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</tr>
<tr>
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TABLE C — Continued

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<th>Phos.</th>
<th>Silica</th>
<th>Mn.</th>
<th>Alum.</th>
<th>Lime</th>
<th>Mg.</th>
<th>Sulph.</th>
<th>Ignition Loss</th>
<th>Moisture</th>
<th>Iron</th>
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<td></td>
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<td>5.74</td>
<td>.97</td>
<td>.27</td>
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1945

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<th>Alum.</th>
<th>Lime</th>
<th>Mg.</th>
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<th>Ignition Loss</th>
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<th>Iron</th>
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<td>5.74</td>
<td>.83</td>
<td>.012</td>
<td>10.09</td>
<td>12.84</td>
<td>46.53†</td>
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<td>Mahnomen</td>
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<td>4.68</td>
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<td>.19</td>
<td>.013</td>
<td>8.09</td>
<td>16.91</td>
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<td>6.55</td>
<td>7.33</td>
<td>3.90</td>
<td>.83</td>
<td>.23</td>
<td>.012</td>
<td>10.09</td>
<td>12.84</td>
<td>46.53†</td>
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ANNUAL AVERAGES

<table>
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<th>Silica</th>
<th>Mn.</th>
<th>Alum.</th>
<th>Lime</th>
<th>Mg.</th>
<th>Sulph.</th>
<th>Ignition Loss</th>
<th>Moisture</th>
<th>Iron</th>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Non-Bessemer</td>
<td>55.86</td>
<td>.260</td>
<td>8.20</td>
<td>.80</td>
<td>1.68</td>
<td>7.85</td>
<td>11.03</td>
<td>48.70</td>
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<tr>
<td>Manganiferous ‡</td>
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<td>10.64</td>
<td>7.85</td>
<td>11.58</td>
<td>47.61†</td>
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<td></td>
<td></td>
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<tr>
<td>1945</td>
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<td>Non-Bessemer</td>
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<td>9.28</td>
<td>.96</td>
<td>1.66</td>
<td>6.03</td>
<td>12.19</td>
<td>48.20</td>
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<tr>
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<td>47.30</td>
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<td>9.89</td>
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<td>13.08</td>
<td>46.45†</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>1950</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Non-Bessemer</td>
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<td>10.74</td>
<td>49.29</td>
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<td>.227</td>
<td>12.59</td>
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<td>16.64</td>
<td>46.69†</td>
<td></td>
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</tr>
</tbody>
</table>

* Gain by ignition
† Combined iron and manganese
‡ Manganiferous Ores averaged 86.1 per cent of total shipments
## TABLE D. ANNUAL SHIPMENTS AND ESTIMATED ORE-RESERVES OF THE CUYUNA DISTRICT, MINNESOTA, IN GROSS TONS *

<table>
<thead>
<tr>
<th>Years</th>
<th>Annual Shipments</th>
<th>Estimated Reserves May 1st</th>
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<tbody>
<tr>
<td>1911</td>
<td>147,431</td>
<td></td>
</tr>
<tr>
<td>1912</td>
<td>305,111</td>
<td></td>
</tr>
<tr>
<td>1913</td>
<td>733,091</td>
<td></td>
</tr>
<tr>
<td>1914</td>
<td>859,404</td>
<td>30,357,000</td>
</tr>
<tr>
<td>1915</td>
<td>1,136,113</td>
<td>72,405,000</td>
</tr>
<tr>
<td>1916</td>
<td>1,716,218</td>
<td>77,926,000</td>
</tr>
<tr>
<td>1917</td>
<td>2,428,884</td>
<td>70,160,000</td>
</tr>
<tr>
<td>1918</td>
<td>2,478,800</td>
<td>63,209,000</td>
</tr>
<tr>
<td>1919</td>
<td>1,861,165</td>
<td>59,393,000</td>
</tr>
<tr>
<td>1920</td>
<td>2,191,528</td>
<td>24,820,000†</td>
</tr>
<tr>
<td>10-year total</td>
<td>13,851,675</td>
<td></td>
</tr>
<tr>
<td>1921</td>
<td>489,500</td>
<td>25,081,000</td>
</tr>
<tr>
<td>1922</td>
<td>1,496,356</td>
<td>29,485,000</td>
</tr>
<tr>
<td>1923</td>
<td>2,220,733</td>
<td>43,041,000†</td>
</tr>
<tr>
<td>1924</td>
<td>1,469,054</td>
<td>46,121,000</td>
</tr>
<tr>
<td>1925</td>
<td>1,514,853</td>
<td>51,091,000</td>
</tr>
<tr>
<td>1926</td>
<td>2,082,689</td>
<td>53,209,000</td>
</tr>
<tr>
<td>1927</td>
<td>1,981,501</td>
<td>49,653,000</td>
</tr>
<tr>
<td>1928</td>
<td>2,097,716</td>
<td>53,209,000</td>
</tr>
<tr>
<td>1929</td>
<td>2,596,186</td>
<td>48,265,000</td>
</tr>
<tr>
<td>1930</td>
<td>1,929,189</td>
<td>66,549,000†</td>
</tr>
<tr>
<td>10-year total</td>
<td>17,876,977</td>
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</tr>
<tr>
<td>1931</td>
<td>898,090</td>
<td>66,757,000</td>
</tr>
<tr>
<td>1932</td>
<td>98,737</td>
<td>69,700,000</td>
</tr>
<tr>
<td>1933</td>
<td>741,139</td>
<td>70,025,000</td>
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<tr>
<td>1934</td>
<td>532,571</td>
<td>47,554,000†</td>
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<tr>
<td>1935</td>
<td>798,481</td>
<td>47,869,000</td>
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<tr>
<td>1936</td>
<td>1,305,439</td>
<td>63,227,000†</td>
</tr>
<tr>
<td>1937</td>
<td>1,775,445</td>
<td>62,275,000</td>
</tr>
<tr>
<td>1938</td>
<td>581,823</td>
<td>60,775,000</td>
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<tr>
<td>1939</td>
<td>1,290,673</td>
<td>62,076,000</td>
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<td>1940</td>
<td>1,734,176</td>
<td>65,431,000</td>
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<tr>
<td>10-year total</td>
<td>9,756,574</td>
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<td>1941</td>
<td>2,441,042</td>
<td>65,505,000</td>
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<td>1942</td>
<td>3,035,532</td>
<td>64,760,000</td>
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<td>1943</td>
<td>3,065,555</td>
<td>63,880,000</td>
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<tr>
<td>1944</td>
<td>2,538,492</td>
<td>62,384,000</td>
</tr>
<tr>
<td>1945</td>
<td>3,016,899</td>
<td>59,738,000</td>
</tr>
<tr>
<td>1946</td>
<td>2,858,516</td>
<td>59,299,000</td>
</tr>
<tr>
<td>1947</td>
<td>2,860,437</td>
<td>56,089,000</td>
</tr>
<tr>
<td>1948</td>
<td>3,149,442</td>
<td>38,430,000†</td>
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<tr>
<td>1949</td>
<td>2,730,012</td>
<td>37,719,000</td>
</tr>
<tr>
<td>1950</td>
<td>3,224,557</td>
<td>43,415,000</td>
</tr>
<tr>
<td>10-year total</td>
<td>28,414,484</td>
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<tr>
<td>1951</td>
<td>3,513,827</td>
<td>41,870,000</td>
</tr>
<tr>
<td>1952</td>
<td>3,133,211</td>
<td>44,808,000</td>
</tr>
<tr>
<td>1953</td>
<td>3,700,496</td>
<td>60,372,000†</td>
</tr>
<tr>
<td>43-year total</td>
<td>80,252,244</td>
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</table>

* Data from Minnesota Department of Taxation (and School of Mines, University of Minnesota).

† Most of the abrupt declines in reserves are based on rulings that certain low-grade ores should not be taxed. Similarly, abrupt increases are based on rulings that low-grade ores must be taxed.
APPENDIX C

COPY OF A UNIVERSITY PROJECT, SEPT. 16, 1941

Application for a Grant for Research from the funds of the Graduate School, University of Minnesota, by Frank F. Grout (professor of geology).

Project: The core drilling of some holes to explore the geology and manganese resources of the Cuyuna Range.

The Relation of Cuyuna Manganese to National Defense

The principal use of manganese is in making steel. It is very necessary to de-sulphurize and de-oxidize the steel to which it is added, because sulphur tends to make steel brittle when it is as hot as it must be when "rolled" into plates or rails. No satisfactory substitute has been found for manganese in de-sulphurizing, and for a number of years about 14 pounds of manganese metal have been consumed for each ton of steel produced in the United States. Manganese also improves the steel in toughness and resistance to abrasion.

Normally a million tons of high-grade ore (over 45 per cent manganese) are needed each year and when the demand for steel is high the tonnage of manganese ore needed increases also. The production of manganese in the whole United States is perhaps 5 to 10 per cent of the demand in normal times, and most of it is from the Cuyuna Range. Manganese imports supply 90 per cent of the demand in normal times, so that manganese is a "strategic mineral." The resources of the Cuyuna Range may prove a large factor in National Defense.

Outline of Problem

1. The sequence of rock formations bearing iron and manganese on the Cuyuna Range is not well known, chiefly because the rocks are buried under 50 feet or more of sand and gravel. Drilling at selected places might show several things. The information would be a general guide to exploration for ores in the region of Lake Superior. At present there is much disagreement as to the relation of the well-explored Mesabi Range to the slightly explored Cuyuna Range. If the Cuyuna series of rocks is analogous to the Mesabi series, the two ranges may be of the same age and no other important iron-bearing series is to be expected. On the other hand, if the sequence of rocks is very different, it seems likely that they were formed at different times, and the continuation of the Mesabi rocks with their dominantly important ores should be sought on one side or the other of the Cuyuna Range. The experts at present disagree. Some believe the Cuyuna rocks are older, others believe them younger, and still others believe they are of the same age. Cores taken from a hole drilled through the formation might bring most of the geologists who have studied the series into agreement. To be sure much drilling has been done, but it has not been planned with this problem in mind; its only purpose was to find ore near the surface, and drilling was discontinued as soon as the rock formations were encountered.

2. Emergency manganese supplies. The Cuyuna Range has a larger proportion of manganese than any other iron range in the Lake Superior region. In normal times the country is dependent on imports from Russia, Brazil, and India, but so little is now available from those sources that an intensive search is in progress for deposits in and near the United States. The deposits of the Cuyuna Range are a large part of the total of available manganese in the country. They have not been largely mined because the main production has been "manganiferous iron" ore containing 7 to 15 per cent manganese, rather than "manganese ore" with more than 45 per cent manganese, such as has been imported.

The National Defense Commission and United States Geological Survey have indicated to the State Geological Survey that they wish accurate data on tonnage and grade of manganese deposits; and further, that they would be interested in the nature of the "carbonate-slate" formation below the known ore deposits. This is commonly believed to be the original rock from which the Cuyuna manganiferous ores have been formed by weathering, and it occurs in tonnages far greater than those of any manganiferous ore deposit in the country; but at most places it contains only from 4 to 8 per cent manganese.
Several of the Survey staff members have this summer given these problems their attention and a large collection of the records of drilling and chemical tests is on file. The estimates of tonnage of ores (and associated rock too lean to be ore) are well advanced.

On the problem of the nature and volume of the several original rocks, the progress has not been satisfactory. About 100 samples of "carbonate-slate" have been tested for manganese and other constituents at the laboratories on the range and at the Mines Experiment Station; but the thickness of the bed and its relation to other parts of the iron-bearing formation are not clearly shown in the mines now open, or in the drill cores that are available. We do not know whether our samples represent a formation that is only 50 feet thick, or one that is several hundred feet thick; nor whether all the "carbonate-slate" is in one bed or in several beds alternating with other iron-bearing rocks. Commercial drilling has usually stopped as soon as the drill reached low grade material.

3. Plan of procedure. Several practical men have offered cooperation in selecting desirable places for drilling, viz., Mr. J. F. Wolff of the Oliver Iron Mining Company of Duluth, who mapped the geology of the district several years ago; Mr. Perry Harrison, Crosby, Minnesota, who is the most extensive operator of mines on the range; Mr. A. Emil Matson, Cooley, Minnesota, Engineer for Butler Brothers of St. Paul, who operate one of the underground mines of the range; and Mr. Carl Zapfe, Brainerd, Minnesota, who has managed ore properties on the range for the Northern Pacific since about 1906.

With the advice of these men, drills might be started at two or three places, with a strong probability that the results will be significant not only in a scientific way but in a way to assist in National Defense. My present opinion is that the most promising locations are along the west side of the state-owned Northland Mine property in Sec. 20, T. 47 N., R. 98 W., and in the Arko Mine property in Sec. 9, T. 46 N., R. 29 W. Other promising places lie in the properties of Butler Brothers in Sec. 33, T. 47 N., R. 29 W.

As soon as results are obtained from the early part of the drilling they may furnish a guide to the geologists and operators in management of further drilling or, if the results are unexpectedly bad, they may dictate a shift to the other location.

4. Budget. About 95% of the expense will be for drilling. This can be handled by competitive bids. I know of three who might bid:

1. The Longyear Company, Minneapolis, Minnesota
2. The Duluth Diamond Drilling Company, Duluth, Minnesota
3. R. M. Adams, Fidelity Building, Duluth, Minnesota

I understood Mr. Adams to say he now has drills on the range.

The usual costs of such a program are $8.50 to $9.50 per foot.

The hole at the Arko Mine property would be the simplest — a vertical hole, starting in the carbonate-slate to find how deep it goes and what lies below. It might happen that the information would be satisfactory by the time drilling reached 300 to 400 feet.

The other holes planned are "angle holes," and should go 1000 feet or more if the location proves favorable. If unfavorable, the facts should be apparent before drilling goes more than 200 to 300 feet. In summary of the estimated budget:

Near Arko Mine, 300 feet at $8.00 .......................... $900
Near Northland Mine (State-owned), 1000 feet at $3.00 .......................... 3000
Near Merritt Mine, 1000 feet at $8.00 .......................... 8000
Allow for shift if choice of area is not favorable .......................... 1100

$8000

I shall be glad to give time to watch the results of drilling and prepare the results for publication. There may be some small expense in handling samples or in surveys to locate the drill accurately.

Other members of the Geological Survey staff are interested and available for consultation.

I believe the Mines Experiment Station will assay the cores that are of interest. The managers of companies on whose land the work is to be done all speak as if they will be glad to cooperate in making their records available, facilitating the placing of drills, and giving permission to do the work.

5. Publication. The information expected may well be published by the University as a matter of interest to many men in iron and steel work. It is of a sort commonly desired by two journals, (1) Economic Geology, (2) Mining and Metallurgy.

Respectfully submitted
FRANK F. GROUT
October 14, 1941

Professor F.F. Grout
P 205

Dear Professor Grout:

I am glad to inform you that your project for a study of the "Geology and Manganese Resources of the Cuyuna Range" has been approved, with a grant of $8,000 from the general research fund. You will, I think, be pleased to know that this project was enthusiastically approved by President Coffey, who told me that he was for it 100 per cent, and urged that it be set in motion.

I sincerely hope that the enterprise will yield important information, and work out successfully, as in fact I have confidence that it will.

The budget number for the project is 230-3201-2429. You will of course want to be in close touch with the business administration of the university in handling problems involving contracts and other business aspects of the work.

Sincerely yours,

Theodore C. Blegen, Dean
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