1960


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GEOLOGY AND ORE DEPOSITS OF THE SOUDAN MINE
ST. LOUIS COUNTY, MINNESOTA

A thesis submitted to the Graduate School of the University of Wisconsin in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

by

Frederick Lindsley Klinger

Degree to be awarded
January 19--
June 1960
August 19--
To Professors: Tyler Cameron Emmons

This thesis having been approved in respect to form and mechanical execution is referred to you for judgment upon its substantial merit.

Approved as satisfying in substance the doctoral thesis requirement of the University of Wisconsin.

Date of Examination, Feb 4, 1960
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INTRODUCTION

Iron ore deposits in several of the districts in the Lake Superior region occur in close association with volcanic rocks and ancient sediments which are believed to be of Keewatin or early Precambrian age. These associated rocks may include flows, intrusives and pyroclastic material of basic to acidic composition and sedimentary rocks of both clastic and chemical origin. Most of these rocks are found in steeply dipping attitudes and they are often slightly metamorphosed. The iron deposits which occur in host rocks and environments of this type are generally known as "Keewatin type" ores in contrast to the deposits found in the iron formations of the well known Huronian sedimentary sequence.

The Keewatin iron deposits consist of steeply dipping, relatively narrow bodies of lenticular or tabular shape which occur along one or more stratigraphic horizons parallel to the structure of the enclosing rocks. The iron minerals in these deposits may consist of oxides, sulphides or carbonates. The ore is massive and often contains relict structures and textures which suggest that the ore formed by replacement of the rocks within which it occurs.

Well known deposits of the Keewatin type in the Lake Superior region occur in the Michipicoten District of southern Ontario, at Steep Rock Lake in western Ontario, and in the Soudan Mine in northeastern Minnesota.

In the Michipicoten district, an iron formation which mainly consists of a "banded silica" member occurs within a group of Keewatin volcanics and clastic sediments. Lenticular bodies of massive siderite
and pyrite occur along the contact between the siliceous horizon and an underlying group of acid volcanics. The iron ore bodies lie parallel to the dip of the enclosing rocks but contain remnants of volcanic material suggesting that they were formed by replacement.

At Steep Rock the country rocks consist of a basal limestone overlain by a series of volcanic rocks and clastic sediments. A layer of pyroclastics overlies the limestone. The Steep Rock orebody which consists of massive hematite and goethite occurs between the limestone and the pyroclastics. The orebody is tabular in shape and lies parallel to the dip of the enclosing rocks. Textures in the ore are similar to textures in the adjacent rocks suggesting that the deposit formed by replacement.

The iron deposits in the Soudan Mine are found closely associated with steeply dipping beds of siliceous iron formation enclosed in a group of Keewatin volcanic rocks. The orebodies are lenticular or tabular in shape and lie parallel to the structure of the enclosing rocks. The ore consists of massive hematite which contains internal structures similar to the structure in the adjacent siliceous iron formation, once again suggesting an origin by replacement.

In their character and mode of occurrence, the ores found in Keewatin-type rocks are different from the ores usually found in the Huronian iron formations of the Lake Superior region. The bulk of the Huronian deposits, as typified by the soft ores of the Marquette, Gogebic and Mesabi districts, appear to be residual accumulations of earthy iron oxide formed by the leaching of silica from iron formation. The ores found in Keewatin-type rocks, however, are typically hard and massive. They include deposits of massive iron carbonate and iron
sulphide as well as deposits of iron oxide. In general, the concentration of iron does not appear to have been caused merely by removal of other constituents but by an addition of iron which was sufficient to cause volume-for-volume replacement of rocks in which the deposits occur. The host rocks are not necessarily iron-rich types. It should be noted that certain "hard-ore" deposits found in Huronian rocks, such as occur at the contact between the Goodrich quartzite and Negaunee iron formation in the Marquette district of Michigan, resemble the Keewatin type occurrences.

The concentration of the soft ore found in Huronian iron formations has been explained by a theory of leaching and residual accumulation which has found wide acceptance, although the progressive stages of the process are subjects of some debate.

The concentration of Keewatin-type ores, however, is not adequately explained by this process. The differences in character of the ore and in mode of occurrence between the Huronian and Keewatin types of deposits suggest that they have originated in different ways. The origin of the Keewatin ores is not clear. Successive studies of the deposits at Michipicoten and at Steep Rock have resulted in differing hypotheses as to the manner in which these deposits have formed.

The Michipicoten ores were considered by Collins and Quirke (1926) to represent hot spring deposits formed in permeable volcanic rocks by solutions of volcanic origin. Both the ore deposits and associated rocks were formed during the same period of volcanism. A similar view has recently been presented by Goodwin¹. On the other hand,

¹Goodwin, A. M.; paper presented at the Institute of Lake Superior Geology; Duluth, Minn.; April 1958.
Moore (1946) and Kidder and McCartney (1948) think the ore was deposited after deformation of associated rocks by hydrothermal solutions rising from (Algoman) granitic intrusives.

The Steep Rock deposit is considered by Roberts and Bartley (1943; 1948) to have been deposited by hydrothermal solutions which followed a brecciated zone between the limestone bed and the pyroclastic; the ore being formed after deformation of the associated rocks. On the other hand, Jolliffe (1955) suggests that the ore was formed by lateritic weathering of ferruginous limestone.

The origin of the ore at Michipicoten and at Steep Rock is thus in doubt. The deposits of both districts have been classed as epigenetic and of hydrothermal origin, formed after the deformation of the rocks in which they occur. A syngenetic origin has also been postulated in each case, but with the difference that at Steep Rock the ore may be a residual accumulation whereas the Michipicoten ores may be chemical deposits related to hot spring activity.

The Soudan deposits were originally thought to have been formed by downward-moving meteoric waters (Smyth and Finlay, 1895; Clements, 1903). These waters dissolved iron carbonate from the iron formation and carried ferrous iron downward into structural troughs formed between iron formation and impervious greenstone. In the troughs, the ferrous solutions mingled with meteoric waters carrying free oxygen, and deposits of hematite were formed.

As mining operations in the ores progressed, relationships were revealed which suggested that their origin may be hydrothermal and in some way related to the presence of intrusive rocks (J. F. Wolff and C. J. Muller; Gruner, 1926; 1930; Reid and Hustad, 1950; Schwartz
and Reid, 1955). The nature of the ore occurrence at Soudan, however, has been defined only in general terms. Although various aspects of these ores have been described, no comprehensive study of the geology of the mine and its ore deposits has been published since the ores were first described by Clements in 1903.

Statement of Problem

The present state of knowledge concerning the Keewatin-type iron ores has proved inadequate to provide a satisfactory basis for explaining the origin of these deposits. Further information in the form of detailed investigations of such deposits is required before some of the conflicting hypotheses listed above can be resolved. Since the Soudan Mine is a well known example of this type of ore occurrence, a detailed description of the Soudan deposits would have an important bearing on the problem. The present study was therefore undertaken with the purpose of clarifying the nature of the ore occurrence and applying the results of this investigation to the problem of origin.

Methods of Investigation

Surface geologic mapping of the mine area, including the open pits, was done on a scale of 1 inch equals 100 feet, using a solar compass and metal tape. Section corners were used for control, with traverses being tied into base-lines run between corners. The accuracy of surface control was checked against large-scale aerial photographs.

The geology of underground workings was mapped on a scale of 1 inch equals 60 feet, using the mine maps as a base. Measurements were made by taping from the numbered tags of mine survey points.
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The geology of underground workings was mapped on a scale of 1 inch equals 60 feet, using the mine maps as a base. Measurements were made by taping from the numbered tags of mine survey points.
The geology of the 10th, 12th, 17th and 19th levels was mapped in detail, along with portions of other levels.

The mapping was supplemented by detailed lithologic studies of core from numerous exploration drill holes, some 300 of which were available. Chemical data from many ore holes was obtained from analysis records, and partial analyses of rock samples were furnished by the Oliver Iron Mining Division district laboratories at Ely and Eveleth. Many petrographic thin sections and some polished surfaces were studied for additional information.

Acknowledgements

The writer is indebted to the Oliver Iron Mining Division for its support of this project, and to many people in the geological, engineering, and operations departments for their help in various parts of the work.

The cooperation of Mr. Earl Holmes, superintendent of the mine, and of Mr. John Lamprecht, mine engineer, did much to make the work go forward smoothly. The analysis of many rock samples was made possible by Mr. Iver Lerohl and Mr. W. J. Trudgeon, chief chemists at the Eveleth and Ely laboratories, respectively. The personal assistance given by R. L. Bleifuss, H. B. Miles, R. D. Lopez, W. M. Holway, H. E. Bakkila, and C. L. Iverson is gratefully acknowledged.

The work was done under the general supervision of R. W. Marsden and I. L. Reid of the geological department, and the writer is indebted to them for aid in completion of the work as well as for helpful discussion of its various phases.
X-ray and chemical data were contributed by Dr. S. W. Bailey of the University of Wisconsin and by Dr. S. S. Goldich of the University of Minnesota. Helpful discussions in the field were provided by Drs. G. M. Schwartz, S. S. Goldich, and S. A. Tyler.

The writer was assisted in field work by Martin Lesser, Barry Erickson, and William E. Crain. Thanks are due them for their willing work and extra time.

Historical Note

The Soudan Mine is owned and operated by the Oliver Iron Mining Division of the United States Steel Corporation. It is located in St. Louis County, Minnesota, in the western part of the iron mining district known as the Vermilion Range. The mine is located near State Highway 169, two miles east of Tower and twenty miles west of Ely, Minnesota.

The Soudan Mine is the oldest producing iron mine in the state, having shipped its first ore in July, 1884. It has been in almost continuous operation for 75 years, and has produced nearly 15,000,000 tons of high-grade hematite ore. The mine has provided the major support for the communities of Tower and Soudan since their settlement.

Discovery of hematite ore in the Soudan area was incidental to a search for gold in the 1860's. Although no gold deposits of any consequence were found, the indications of massive hematite deposits on the south shore of Lake Vermilion aroused some interest. The existence of massive hematite was verified in 1866 by H. H. Eames for the

Minnesota Geological Survey, but it was not until 1875 that serious exploration and development of the deposits was begun under the direction of George R. Stuntz. Deposits were developed both on Soudan Hill and on Lee Hill between Soudan and Tower. Although operations have been continuous since 1884 at Soudan, those at the Lee Mine were discontinued in 1892.

The deposits were first mined in open pits, with depths up to 150 feet being reached. The narrowness of the orebodies, and their steep dips were not conducive to open pit mining so underground operations were soon started. Although at least twelve shafts were sunk in the mine area to develop certain orebodies, only one is in operation at the present time, hoisting ore and servicing all operating levels. A second shaft is used for ventilation and as an emergency escapeway.

Mining operations at the present time extend to a depth of nearly 2,500 feet. The ore is mined by a horizontal cut-and-fill method. The ore, jasper and greenstone country rock are relatively strong; the main use of timber is in cribbing for manways and ore-chutes from the stopes. Drifts and crosscuts usually require no support.

The product is entirely of "lump" grade, being a massive blue-gray hematite which is exceptionally hard. Its relatively high purity and dense structure make it a premium-type ore. The ore is used for carbon control in the making of open-hearth steel.
GENERAL GEOLOGY

The rocks of the Soudan area consist of three main units: the Ely greenstone, made up largely of chloritic schists of volcanic origin; the Soudan iron formation, locally called "jasper," which occurs as a group of lenticular beds within the greenstone; and the Knife Lake sediments which consist of slate, graywacke, arkose and conglomerate.

Soudan Hill, on which the mine is located, is made up of greenstone and iron formation. The hill is part of a ridge-making belt of these rocks, about half a mile wide, which trends northeastward along the south shore of Lake Vermilion. The depressions which flank this ridge on the north and south are occupied by sediments correlated by Clements (1903) with the Knife Lake group.

The distribution of the main rock units is shown on the accompanying geologic map (see Figure 1).

The structure of the Knife Lake sediments is essentially parallel to the structure of the greenstone and iron formation. Bedding and cleavage in these rock units is usually found to strike E-W to N. 80° E. and dips 75°-85° N. The axial planes of folds also conform to this structure, although the direction and angle of pitch of the folds is variable. The parallelism between the structures found in the Knife Lake rocks and those found in the greenstone and iron formation, as shown in the Soudan area, reflects the pattern found elsewhere in the Vermilion district and is probably its most outstanding geologic feature.

The apparent conformity of structure between the Knife Lake rocks and the greenstone-iron formation group suggests that the main
FIG. 1

GENERALIZED GEOLOGIC MAP
SOUDAN MINE AREA

SCALE
0 500 1000 FEET

LEGEND

Soudan iron-formation, with banded structure
Jim, Jb Jasper; massive to poorly banded with relatively low iron content
Jrb Jaspilite; well-banded, with relatively high iron content
Ely greenstone, with lenses of iron-formation
Css Siliceous and/or sericitic schists
Cs Chlorite-schist and massive greenstone
Strike and dip of schistosity
Strike and dip of bedding
Graded bedding, showing tops of beds
Observed fold, showing pitch
Possible fold
Observed geologic contact
Probable contact
Inferred contact
Fault
rock units form a continuous stratigraphic sequence. However, relationships found in the eastern part of the Vermilion district suggest that the Knife Lake sediments are separated from the greenstone and iron formation by a structural and erosional unconformity and that the Knife Lake sediments are the younger group. Since the two groups are separated from later Precambrian (Animikie) formations by a major unconformity, they are both of early Precambrian age. The Minnesota Survey has thus designated the greenstone and iron formation as Earlier Precambrian, or Keewatin; and has assigned the Knife Lake group to the Medial Precambrian. The positions of these rocks in the Precambrian column of Minnesota are shown in Table I.

The main structural feature in the Keewatin rocks of the Soudan mine appears to be a tightly-compressed synclinal fold which plunges westward. The angle of pitch of this structure varies from nearly horizontal to vertical, and the keel of the fold is so greatly attenuated that its eastern extension resembles an undeformed sedimentary bed. Although it is possible to consider this structure as a synclinal fold, its correct interpretation is uncertain.

In general, the structural relationships between iron formation and greenstone are complex and are usually difficult to interpret. They may be of sedimentary, intrusive, or deformational origin, but distinguishing criteria cannot often be found.

A noteworthy feature of the area is the relative abundance of folded structures found in the iron formation and in the finer-grained sediments of the Knife Lake group, as contrasted with the scarcity of similar structures in the greenstone. This is probably due to genetic differences between the rock types, as well as to the scarcity of recognizable and persistent lithologic units within the greenstone.
### TABLE I

**PRECAMBRIAN COLUMN OF MINNESOTA**

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<th>Division</th>
<th>Group</th>
<th>Formations and Members</th>
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<tr>
<td></td>
<td><strong>Upper</strong></td>
<td>(Sandstones; other seds.</td>
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<tr>
<td></td>
<td></td>
<td>(Intrusives, acid &amp; basic</td>
</tr>
<tr>
<td></td>
<td><strong>Middle</strong></td>
<td>(Flows, tuffs, seds.</td>
</tr>
<tr>
<td>Keweenawan</td>
<td><strong>Lower</strong></td>
<td>(Congl. &amp; sandstones</td>
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<td></td>
<td></td>
<td>___________<strong><strong>--Unconformity, may be great on Cuyuna Range--</strong></strong>____</td>
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<tr>
<td>Later</td>
<td></td>
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<tr>
<td></td>
<td><strong>Animikie</strong></td>
<td>(Virginia Slate = Rove</td>
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<tr>
<td></td>
<td></td>
<td>(Biwabik Iron Fmn. = Gunflint</td>
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<td></td>
<td></td>
<td>(Pokegama Quartzite</td>
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<td></td>
<td></td>
<td>___________<strong><strong>--Unconformity, great on Mesabi and Gunflint Ranges--</strong></strong>____</td>
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<td></td>
<td></td>
<td>Algoman intrusives, orogeny, and erosion</td>
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<td></td>
<td></td>
<td>Central and S.W. Minn. granites?</td>
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<tr>
<td></td>
<td><strong>Medial</strong></td>
<td>____________________________</td>
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<tr>
<td></td>
<td><strong>Knife Lake</strong></td>
<td>(Slate,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(graywacke</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(iron-bearing beds</td>
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<tr>
<td></td>
<td></td>
<td>(conglomerate</td>
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<tr>
<td></td>
<td></td>
<td>(tuffs, lavas, and intrusives</td>
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<tr>
<td></td>
<td><strong>Earlier</strong></td>
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<td></td>
<td><strong>Keewatin volcanics (Ely greenstone)</strong> and Soudan iron fmn. member (No Coutchiching recognized in Minnesota)</td>
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The extent and character of faulting in the area is largely unknown, but may be better defined by areal studies of a broader nature. The mine area is cut by a vertical cross-fault which strikes N. 30° W. The horizontal displacement along this fault is about 130 feet; the vertical displacement is unknown but possibly is large. Longitudinal or strike-faults occur in the mine but the displacements along them are unknown. In general, displacements along faults do not appear to be large, but accurate measurements are prevented by the scarcity of reference horizons.

The iron formation of the area occurs in several distinctive varieties. These consist of barren gray chert, a massive jasper, or a well-banded "jaspilite" consisting of alternating layers of jasper and iron oxide. The chert and massive jasper tend to occur in relatively small, lenticular bodies which are marginal to the main belts of iron formation (see Figure 1). The jaspilite is typically found in thicker, more persistent beds and makes up the bulk of the iron formation in this area. The ore deposits are usually associated with the jaspilite type.
The first recorded geological observations in the western part of the Vermilion district were made by Dr. J. G. Norwood in 1848 and published in 1852. Dr. Norwood's traverse evidently crossed Lake Vermilion just west of Tower, for he missed the outcrops of iron formation and described only slates and micaceous schists on the south shore of the lake.

Little or no geological work was done in the Vermilion district until after the Soudan ore deposits were developed in the late 1870's, and most of it followed discovery of the Ely ores in 1883. This discovery, which emphasized the economic potential of the region, stimulated considerable work between 1883 and 1900, largely by geologists of the Minnesota and United States geological surveys. Most of this work was concerned with the eastern part of the district, where there is more variety in the rock types and their relationships are better exposed. The geologists working in the area included N. H. Winchell, A. Winchell, H. V. Winchell, A. H. Chester, A. C. Lawson, C. R. Van Hise, R. D. Irving, U. S. Grant, Bailey Willis, W. S. Bayley, W. M. Chauvenet, and W. N. Merriam.

In 1886, Bailey Willis published a report on the Soudan area. He described east-west anticlinal ridges of jasper, with intervening synclinal valleys of younger and softer rocks, and noted the steep to vertical dip of the iron-bearing series. He suggested the following stratigraphic succession:

**Top** - Black fissile slate; Compact quartz-dioritic rock (metamorphosed sediment); Conglomerate (sandstone pebbles and traces of black slate); Grayish white or black sugary quartzite with magnetite grains; Chloritic schist; White, gray, brown or red jasper, containing layers of hard blue specular ore; **Bottom** - Thinly laminated light gray chloritic schist.
This sequence was apparently constructed on the basis of traverses made in the Tower area. The upper three units were later included in the Knife Lake group.

In 1895, H. L. Smyth and J. R. Finlay described the geology and ore deposits of the Tower-Soudan area. According to them, the rocks are divided into two sedimentary formations, the older a fragmental slate, and the younger the jasper or iron formation. These formations are cut by a complex of basic to acidic intrusives, the older of which are the greenstones. The general structure is described as a complex of eastward-pitching folds. The authors noticed that ore deposition seemed to be guided by schist-jasper contacts, whether such contacts were discordant or concordant to the jasper.

They described the occurrence of ore in jasper along the hanging-wall of a cross-cutting dike, in which the banding of the jasper follows through, undistorted, into the ore. They concluded that the ore was formed in pitching troughs having impervious bottoms, by downward-moving waters which removed the silica and replaced it by iron oxide; according to the theory advanced by Van Hise for other deposits of the Lake Superior region.

In 1897, J. H. Eby and C. P. Berkey described the occurrence of native copper, chalcopyrite, and secondary cuprite, malachite and azurite in an orebody at Soudan.

In 1899 and 1900, the general geology of Minnesota was summarized by N. H. Winchell and others of the Minnesota Survey. Winchell grouped the greenstone, iron formation, and the slate and conglomerate of the Tower-Soudan area, together as "Lower Keewatin." The clastic sediments were regarded as the younger rocks.
In 1903, a comprehensive report on the Vermilion district was published by the U. S. Geological Survey as Monograph No. 45. It was based on field work done, from 1897 to 1900, by J. M. Clements, W. S. Bayley, and C. K. Leith. This volume is still the basic reference work for the area.

Clements placed the greenstone as the oldest rock in the district. He described it as an igneous complex of volcanic flows and intrusives, of intermediate to basic composition. He placed the Soudan iron formation in the upper part of the greenstone, with occasional patches of clastic sediment lying between the iron formation and greenstone. The slate and conglomerate of the Soudan area, previously included by Winchell in his "Lower Keewatin" group, were correlated by Clements with the Knife Lake sediments. Clements held that the Knife Lake sediments belong to a distinctly later group of rocks, separated from the greenstone and iron formation by a major unconformity. This unconformity was caused by the Laurentian orogeny and granitic (Saganaga) intrusions. Following accumulation of the Knife Lake sediments, a second period of orogeny occurred, during which the Keewatin and Knife Lake rocks were compressed into their present folds, and were intruded by Algoman (Giants Range) granite. The Algoman orogeny is the last major event recorded in the rocks of the Soudan area, with the exception of scattered basic dikes which Clements describes as similar to those cutting the Duluth gabbro.

Following the theories of Van Hise, Clements regarded the Soudan formation as originally a cherty iron carbonate, and the ore deposits as formed by downward-percolating surface waters.
In 1923, G. M. Schwartz published important petrographic and chemical data on the greenstone as part of a study of the intrusive effects of granite and gabbro. The average greenstone sample is shown to be of basic composition.

In 1926, J. W. Gruner proposed that the Soudan ores were formed by hydrothermal solutions, as opposed to the theory of Van Hise. He also suggested that the oxidation was of hydrothermal origin. At about the same time, similar ideas on the origin of the Ely and Soudan ores were held by J. F. Wolff and C. J. Muller, geologists for the Oliver Iron Mining Company. They regarded the ore as formed by hydrothermal solutions related to intrusives which cut the iron formation.

In 1930, Gruner followed up his ideas on the hydrothermal origin of the Vermilion ores. He published experimental data which indicated hot water as an efficient solvent of silica, and also that hot water can oxidize ferrous minerals provided that hydrogen, released in the reaction, can escape. He regarded the Vermilion ores as formed by hydrothermal solutions, whose source was Keweenawan basic intrusives. Iron was probably introduced in the form of iron chlorides.

In 1930, a petrographic study of some of the mine rocks was made by R. G. Kendall. He noted the abundance of sericite, and remarked that acidic to intermediate rock types, although subordinate to basic types, may be more abundant in the Soudan Mine than was formerly thought.

In 1941, Gruner published results of detailed work on the stratigraphy and structure of the Knife Lake rocks. Although his work was on the Knife Lake type-area, some fifty miles east of Soudan, in the eastern part of the district, the results are applicable to the
Soudan exposures. He noted that longitudinal faults are common in the Knife Lake rocks, but may be unnoticed without detailed mapping.

In 1950, I. L. Reid and J. B. Hustad published additional information on the mine geology, in particular the association of ore with narrowed parts of jasper bodies.

In 1951, F. F. Grout and others of the Minnesota Geological Survey reviewed the Precambrian stratigraphy of the state. In the discussion, it is stated that no sediments older than the Ely greenstone are recognized in Minnesota. This is in reference to the "Coutchiching" rocks which occur in the areas of Rainy Lake and Burntside Lake. These rocks were earlier mapped as older than the greenstone, by A. C. Lawson in 1887 and again in 1913, and have been the subject of considerable controversy.

In 1951, William Liddicoat, while investigating the structure in the western part of the mine, noted that some varieties of the greenstone in that area appear to be sedimentary.

In 1955, Schwartz and Reid described replacement features and possible wall rock alteration associated with the ore at Soudan. Chemical analyses were given which show relatively high potash, silica, or ferrous iron content of some rocks as compared with analyses of the typical Ely greenstone. They suggest that the sericite schist at Soudan may be related to ore deposition, since such a rock is rare elsewhere in the area, but recognize the possibility that it may represent altered rhyolitic flows or intrusions. A high ferrous iron content was found in some rocks near the ore, and the writers conclude that large amounts of ferrous iron, as well as combined water and some alumina, have been added to the greenstone near the orebodies.
GREENSTONE

Introduction

The principal rock type in the Soudan Mine area is a chloritic schist derived from highly altered flows, intrusives and sediments. Although many relict structures and textures are preserved despite the high degree of alteration and the development of schistosity, positive identification of the original nature of these schistose rocks is often difficult if not impossible. This difficulty has led to the adoption of the blanket designation "greenstone" for these rocks in order to have a descriptive term without genetic significance.

Mineralogy

The essential minerals of the greenstone are chlorite, sericite and quartz. In addition to the abundant chlorite, sericite, and quartz, the rocks of the greenstone contain pyrite, carbonate, and "leucoxene" as common accessory minerals, with apatite, tourmaline, zircon, epidote, zoisite and lantanite sometimes present. Feldspar, biotite, and hornblende occasionally occur but are largely altered to chlorite or sericite. Remnants of chloritoid, largely replaced by chlorite, were found in one specimen. Fine-grained minerals occur which resemble anthophyllite, antigorite, and kaolinite, but the identifications were not positive.

Chlorite

Chlorite is the dominant mineral of the greenstone and is usually present in considerable amounts. The chlorite occurs as disseminated flakes, but more commonly as fine-grained aggregates.
It may be concentrated in bands, patches, or parallel streaks, and is usually associated with sericite or fine-grained quartz. Chlorite is sometimes found as amygdale-fillings, and also occurs as secondary veinlets. It sometimes occurs in pseudomorphic aggregates which resemble lithic fragments and biotite or amphibole crystals.

Several types of chlorite occur. The most abundant type, which shows dark-gray to bluish gray interference colors, has very weak birefringence, and exhibits pleochroism from pale green to yellowish green, is apparently clinochlore. A second type, usually occurring with clinochlore, which shows weaker pleochroism, very low birefringence, and "ultra-blue" interference colors, appears to be penninitite. A third type, sometimes occurring with the others, but also in secondary veinlets, is pleochroic from medium-green to pale yellow, shows relatively strong birefringence and interference colors to light gray or first-order yellow. This chlorite is apparently an iron-rich variety, such as thuringite.

Sericite

Sericite occurs as disseminated flakes and as fine-grained aggregates, and resembles chlorite in its mode of occurrence. It is usually associated with chlorite or quartz. The shape of some aggregates of sericite suggest that it has replaced feldspar crystals as well as rock fragments. It also appears to have replaced chlorite in some basic rocks adjacent to ore.

Quartz

Quartz occurs as fine-grained granular aggregates and also as phenocrysts and detrital grains. The fine grained material ranges from
.001 to .05 millimeter in size, and the grains frequently show "strain shadows." The phenocrysts and detrital grains are usually much larger in size, and some reach 2 millimeters in diameter. Quartz is found in almost all of the rocks and appears to be most abundant in the more sericitic types. The fine-grained variety is the most common type; it may be rather evenly distributed in the rock-matrix, or concentrated in regular bands or lenticular aggregates. Quartz also occurs as veinlets or amygdale-fillings.

Comparison with Ely Greenstone

The greenstones of the Soudan Mine area have been correlated with the Ely greenstone. Typical Ely greenstone as described by Schwartz (1924, p. 28) consists of plagioclase, chlorite, hornblende, epidote, calcite and magnetite with chlorite as the most characteristic mineral. Schwartz considers that this assemblage of calcic and ferruginous minerals was most probably derived from basalt. The typical mineral assemblage of chlorite, sericite and quartz found in the Soudan area contrasts strongly with that of the Ely greenstone with particular reference to the abundance of quartz and sericite and lack of calcic minerals at Soudan. This is particularly true of a belt of quartzose and sericitic rocks which commonly separates the Soudan iron-formation from more basic varieties of the greenstone.

Chemical Composition

The chemical compositions of the Soudan area greenstones are different in several important respects from typical Ely greenstone as well as from other greenstones of the Lake Superior region. Table II shows several published analyses of the Ely greenstone, and analyses of
greenstones from Michigan and Ontario for comparative purposes.

Table III shows some of the chemical features of the Soudan area greenstones.

**TABLE II**

**ANALYSES OF GREENSTONE**

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
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<tbody>
<tr>
<td>SiO₂</td>
<td>51.73</td>
<td>51.95</td>
<td>49.72</td>
<td>49.65</td>
<td>46.28</td>
<td>48.85</td>
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<td>Al₂O₃</td>
<td>15.28</td>
<td>12.58</td>
<td>16.76</td>
<td>16.36</td>
<td>14.24</td>
<td>15.83</td>
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<td>Fe₂O₃</td>
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<td>1.90</td>
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<td>FeO</td>
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<td>10.79</td>
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<tr>
<td>MgO</td>
<td>6.72</td>
<td>8.90</td>
<td>7.62</td>
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<td>5.82</td>
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<td>CaO</td>
<td>9.40</td>
<td>7.00</td>
<td>9.35</td>
<td>9.18</td>
<td>11.28</td>
<td>6.20</td>
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<td>Na₂O</td>
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<td>2.79</td>
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<td>K₂O</td>
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<td>H₂O+</td>
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<td>2.67</td>
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<td>2.39</td>
<td>0.28</td>
<td>3.77</td>
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<tr>
<td>TiO₂</td>
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<td>1.03</td>
<td>0.89</td>
<td>N.D.</td>
<td>1.70</td>
<td>1.28</td>
</tr>
</tbody>
</table>

I¹ Average of 3 phases of greenstone at Ely, Minn. (S. Darling, analyst)

II¹ Ely greenstone from Pine Island, Lake Vermilion (S. Darling, analyst)

III² Ely greenstone from outcrop, Sec. 9-61-14 (Eileen Oslund, analyst)

IV¹ Ely greenstone, Sec. 17-65-5 (Dodge & Sidener, analysts)

V³ Greenstone, Rocky Islet Bay, Rainy Lake, Ontario (M. F. Connor, analyst)

VI⁴ Greenstone, Marquette District, Michigan (G. Steiger, analyst)


³Lawson, A. C.; "The Archean Geology of Rainy Lake Re-studied"; Canada Geol. Survey Memoir 40 (1913); p. 50.

TABLE III
PARTIAL ANALYSES OF GREENSTONE AT SOUDAN

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
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<tr>
<td>SiO₂</td>
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<td>64.38</td>
<td>37.39</td>
<td>44.86</td>
<td>51.39</td>
<td>48.00</td>
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<tr>
<td>Al₂O₃</td>
<td>10.61</td>
<td>15.52</td>
<td>22.06</td>
<td>14.84</td>
<td>15.72</td>
<td>34.68</td>
</tr>
<tr>
<td>Total Fe</td>
<td>3.80</td>
<td>2.79</td>
<td>11.87</td>
<td>8.15</td>
<td>9.38</td>
<td>2.73</td>
</tr>
<tr>
<td>MgO</td>
<td>1.95</td>
<td>1.76</td>
<td>12.42</td>
<td>5.80</td>
<td>8.27</td>
<td>2.25</td>
</tr>
<tr>
<td>CaO</td>
<td>.23</td>
<td>.36</td>
<td>.29</td>
<td>9.18</td>
<td>.49</td>
<td>.30</td>
</tr>
<tr>
<td>TiO₂</td>
<td>.32</td>
<td>.36</td>
<td>.64</td>
<td>.96</td>
<td>.58</td>
<td>N.D.</td>
</tr>
<tr>
<td>Ignition</td>
<td>2.65</td>
<td>2.66</td>
<td>7.80</td>
<td>7.69</td>
<td>5.88</td>
<td>5.25</td>
</tr>
</tbody>
</table>

I Chloritic quartz-sericite schist, 19th Level.
II Chlorite-sericite rock, occurring within I; 19th Level.
III Chlorite-schist; basic flow or sill; 19th Level (734).
IV Massive calcitic greenstone, 19th Level.
V Average of nine samples from basic dikes (12th Level).
VI Sericite schist, 19th Level near No. 8 Shaft.

Analysts: O.I.M. Division, Eastern District Laboratory.

The analyses of Table III partially illustrate the wide range in composition found in the rocks at Soudan. Some of the differences are due to a chemical dissimilarity between original rock types but others are due to the addition or removal of various constituents during rock alteration. The samples of Table III were selected to illustrate this point. Sediments or flows of acid composition are represented by samples I and II; basic igneous rocks by samples III, IV and V; and sample VI is from a zone of sericite schist which appears to have formed by alteration of a chlorite schist.

In two of the three analyses of basic rock shown in Table III, the percentage of lime is very low, and in the other sample it is similar to the quantity found in the Ely greenstone. Whereas most of
the rocks of basic composition at Soudan show a deficiency of lime comparable to the analyses cited, they resemble the Ely greenstone in their proportions of iron and magnesia. These features suggest that lime may have been an important original constituent of these rocks but has been removed, probably by hydrothermal alteration. Hydrothermal alteration may also account for the fact that the proportion of combined water in the Soudan rocks is noticeably higher than in the Ely greenstone.

The titania content of the Soudan rocks is generally low, even in the basic varieties. Although analyses are not numerous, the basic rocks usually contain 0.5-0.7% and the more acidic rocks 0.2-0.5%. The titania content of the basic rocks is lower than would be expected from schist derived from basalt. Samples of basic rock which show more than 0.7% titania contain more lime than the others. It is possible that the same alteration which removed lime also removed titania. It should be noted, however, that the titania content of the Ely greenstone, as shown in Table II, is not appreciably higher than the basic varieties of the Soudan greenstone.

**Lithology**

The greenstones are usually fine-grained and range in color from dark-green to gray or yellowish-gray, depending on the amount of chlorite or sericite present. Although the rocks are schistose, they are not extensively sheared, and many primary textures are preserved. Specimens showing granular, ophitic or diabasic, fragmental, banded, porphyritic, amygdaloidal, and (rarely) spherulitic textures are found. The rock types present include flows, intrusives, and fragmental sediments of both bedded and massive appearance.
There is usually a well-defined schistosity in the greenstone, striking E-W to N. 80° E., and dipping 75-85° N. The strike and dip of the lithic units, and the planar or linear structures within them, is generally parallel to the schistosity although in some places the schistosity may be observed to cut across lithologic boundaries. Amygdules, nodular particles, and lithic fragments are usually somewhat flattened in the plane of schistosity but do not appear otherwise oriented. Although schistosity is a characteristic feature of the greenstone, it appears to be more extensively developed in some rock types than in others. The dense, even-grained rocks, such as flows and intrusives, are relatively massive whereas schistosity is more prominently developed in the sediments and fragmental rocks.

The general shape of lithic units in the greenstone appears to be lenticular. Some units are long and fairly regular, whereas others show abrupt thickening or thinning along strike and dip. Intercalation of some units with others appears to be common. These features result in abrupt changes in lithology along strike and down-dip, and correlation of rock units is further complicated by variable rock-alteration. Some of these relationships are shown on the accompanying map of the 17th level (See Figure 2).

Flows

The presence of flows is largely inferred from amygdaloidal textures. In the absence of this texture, it is usually difficult to distinguish flows from concordant intrusives.

Amygdaloidal textures in the greenstone are fairly common, and they are found in both chloritic and sericitic rocks. The amygdules usually consist of granular quartz, sometimes with calcite, ferruginous
carbonate, or chlorite. They commonly occur in narrow zones, from a few inches to several feet wide, but also are found in irregular, isolated patches. In one instance, three vertically-dipping amygdaloidal zones of regular width were found which resembled sedimentary beds rather than the tops of flows; the zones occurred within a four-foot section of greenstone, were from four to six inches wide, and two of them were spaced only six inches apart.

Individual amygdaloidal zones have been mapped for distances of up to 200 feet but may be much more extensive. Some large bodies of sporadically amygdaloidal greenstone occur which have been traced for distances of at least half a mile in both a horizontal and vertical direction. It is probable that this greenstone is made up of several individual flows.

Although the amygdaloidal zones found in the greenstone probably represent the tops of flows, they have not proved useful in determining the stratigraphic succession of the rocks in which they occur. Chilled borders, "pipe amygdules," or other features which might indicate the bottoms of flows have not been found. In addition, the amygdaloidal zones are not associated with fragmental material or oxidized zones by which the tops of successive flows might be distinguished.

A fine-grained flow of syenitic composition, only two feet thick, was encountered in a drill hole in the southern part of the mine. The rock is light-gray to pinkish in color and consists of numerous small rod-like crystals of feldspar showing flow-structure set in a fine grained matrix. The feldspar appears to be albite, but traces of "quadrille" structure also suggest microcline. Numerous globular structures from one to two millimeters in diameter, which
resemble spherulites, are filled with carbonate and quartz. The flow-structure of the rock bends around the globules.

The ellipsoidal or pillow-structures commonly found in the Ely greenstone appear to be rare in the Soudan Mine area. They have been observed in only two or three places and are some distance from the mine. One of them is illustrated in Figure 3.

The range in thickness of single flows is not known, but judging from the number and frequency of the amygdaloidal zones, most of the flows appear to be thin. Some bodies of amygdaloidal greenstone are several hundred feet thick but these probably represent a composite thickness of several flows.

**Intrusives**

Intrusive rocks in the Soudan area consist of basaltic and lamprophyric dikes and large bodies of chlorite schist which exhibit both crosscutting and concordant relationships with the associated rocks.

It is impossible to estimate the relative proportion of intrusive material in the Soudan Mine area. Distinguishing features are rare and contact relationships often contradictory. Temperature effects such as chilled borders or contact metamorphism of the intruded rocks are rarely present. In addition to the lack of distinct intrusive effects, structures simulating intrusive relationships have been produced by flows. A large body of greenstone northeast of the mine cuts across a mass of siliceous fragmental rock. Inclusions of the siliceous material were found within the greenstone. Despite these intrusive characteristics, later discovery of pillow structures and amygdaloidal zones suggest that the greenstone is a flow.
FIG. 3

ELLIPSOIDAL GREENSTONE
ELLIPSOIDS PARTIALLY SHEATHED IN
GRANULAR CHERT & JASPER
Dikes

A number of chloritized basic dikes were found, mostly in the eastern part of the mine. The dikes may reach ten feet in thickness but most are less than two feet thick. They show a wide range in strike but commonly dip northward at steep to shallow angles. The dikes are mostly fine-grained, have a massive to schistose structure, and are sometimes faulted.

The dikes may be grouped into three types on the basis of differences in structure, texture, and composition.

The dikes of type I are massive to weakly schistose, have a fine-grained granular texture, show no chilled borders, and are from one to two feet thick. They strike N. 30-80° E. and dip 20-50° NW. The dikes are chloritized, but their mineralogy has not been investigated in detail.

Type II is represented by one dike. It has a massive structure, a fine to medium-grained granular texture, and shows prominent chilled borders which have a porphyritic texture. The dike strikes approximately N-S, has a vertical dip and is from six to eight feet thick. A specimen from this dike on the 15th level contains altered calcic plagioclase (andesine-labradorite), chlorite, magnetite, and minor amounts of calcite and "leucoxene." Much of the chlorite is pseudomorphic after hornblende and possibly pyroxene, with abundant magnetite rimming the pseudomorphic aggregates. The rock appears to be diorite or gabbro.

The dikes of type III strike N. 65-80° W. and dip 40-60° NE. They are somewhat schistose, show no chilled borders, and are from one to ten feet thick. These dikes are featured by a prominent micaceous
texture, and appear to be altered biotitic lamprophyres. Most of the dikes are extensively chloritized, but a fresh specimen, obtained from a drill hole, consists of albite, actinolite, biotite, and chlorite, with accessory calcite, epidote, and leucoxene.

Chemical analyses of the different types are shown in Table IV.

TABLE IV
ANALYSES OF DIKE ROCKS

<table>
<thead>
<tr>
<th>Type</th>
<th>Total Fe</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>TiO₂</th>
<th>Ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>9.78</td>
<td>52.15</td>
<td>16.94</td>
<td>.50</td>
<td>6.64</td>
<td>.66</td>
<td>5.19</td>
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<tr>
<td>II</td>
<td>18.54</td>
<td>34.15</td>
<td>15.94</td>
<td>.50</td>
<td>10.03</td>
<td>1.44</td>
<td>7.53</td>
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<tr>
<td>(a)</td>
<td>16.84</td>
<td>35.94</td>
<td>14.55</td>
<td>3.86</td>
<td>8.73</td>
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<td>(b)</td>
<td>9.01</td>
<td>50.63</td>
<td>14.51</td>
<td>.48</td>
<td>9.90</td>
<td>.50</td>
<td>6.78</td>
</tr>
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</table>

I Average of 4 samples, 12th Level.

II Samples from dike on 17th Level.
   (a) chilled border
   (b) interior

III Average of 5 samples, 12th & 10th Levels.

Although the dikes of types I and III are different in texture and structure, the analyses indicate that these dikes are similar in composition. The high iron content of type II appears to be related to secondary magnetite formed by the alteration of ferromagnesian minerals and suggests that the original rock was unusually rich in iron.

Intrusive Chloritic Schists

In a number of places beds of iron formation appear to be separated into groups of parallel lenses by an intrusive body of chloritic schist. The strike and dip of the lenses are parallel to the bedding in the intruded iron formation. The concordant relationship
which suggests a rather passive type of intrusion is illustrated on the 27th level of the mine where a sericitic chlorite-schist cuts across a bed of iron formation in one place but in other places the intrusive is concordant with the bedding (see Figure 18). It is possible that such predominantly concordant intrusives may be quite common but not recognized.

Sediments and Fragmental Rocks of Uncertain Origin

General Description

A group of rock types occur within the greenstone which do not appear to be directly related to igneous sources. Some of these types are clearly recognizable clastic sediments whereas others are of less certain origin. It is possible that this group includes both sediments and varying amounts of pyroclastic material.

The fragmental rocks and sediments range widely in composition but generally are rich in sericite or quartz. They have a massive to well-bedded structure and fine-grained to coarsely fragmental textures. Most of the members of the group are fine-grained although one prominent unit contains many fragments ranging from one inch to two inches in diameter. Individual particles are usually angular and often somewhat flattened in the plane of schistosity.

Description of Individual Units

A conspicuous fragmental or conglomeratic rock occurs on the lower levels in the western part of the Soudan Mine. Numerous angular to lenticular particles of a yellow quartz-sericite rock are embedded in a dark green groundmass of calcareous chlorite schist. The sericitic particles are usually not more than one inch in diameter but may range
up to two inches in the long dimension. Some of these particles contain "eyes" composed of granular quartz. Two rounded pebbles of granitic composition were discovered in this rock unit on the 25th level of the mine. The pebbles consist of a granitoid aggregate of albitic plagioclase and quartz. Although no transitional phases were found, the pebbles may represent the original material from which the sericite-quartz rock was derived.

Fine-grained, thinly banded chloritic and sericitic schists which resemble sediments are found in several places in the greenstones. Rocks of this type are seldom found in beds more than a few feet thick. A regular, well defined banding caused by rhythmic variation in composition or grain size characterizes these beds.

Another distinctive rock found in the greenstone is a chloritic quartz-sericite schist containing angular quartz grains up to two millimeters in size and occasional recognizable rock fragments up to an inch in diameter. In single exposures, the quartz grains often appear to be evenly distributed throughout this rock, but close examination reveals that their distribution is widely variable and that they tend to be concentrated in parallel zones. These zones sometimes show a distinct gradational bedding. The fragmental nature and bedded appearance suggest that the chloritic quartz-sericite schist may be a tuffaceous sediment. It occurs as discontinuous, ragged, elongate bodies scattered along what appears to be a stratigraphic horizon within the greenstone, and is typically found between the iron formation and more basic varieties of greenstone. The occurrence of this work is shown on the map of the 17th Level as "CQSS" (see Figure 2).
Stratigraphic Relationships

The sequence of deposition of most of the rocks of the greenstone has not been adequately determined. Although amygdaloidal zones, "pillow-structures," and examples of graded bedding were observed, none of these structures was found to be reliable in determining the tops and bottoms of beds, because contradictory relationships are usually present. Without this information only very general statements can be made about the stratigraphy of the greenstone.

A zone of siliceous and sericitic schists commonly separates the iron formation from greenstone of basic composition. The fragmental rocks and sediments are usually found near the iron formation in the siliceous and sericitic zone, whereas the flow types occur for the most part in the greenstone of more basic composition.

It is possible that the fragmental rocks and sediments of the siliceous and sericitic zone were deposited prior to the accumulation of the main beds of iron formation. This possibility is discussed in the section on stratigraphy of the iron formation.

Intrusive Age Relationships

Masses of basic greenstone intrude the iron formation and appear to intrude the siliceous schists. The dikes cut the iron formation and the siliceous schists, and dikes of types II and III also cut basic greenstone. Although schistosity is not well developed in these intrusives, it is usually present and is parallel to the schistosity of the surrounding rocks.

These relationships suggest that both the iron formation and the rocks of the greenstone were subjected to a period of intrusion which took place prior to the general development of schistosity.
Metamorphism

In general physical appearance and mineral composition, the greenstones of the Soudan area resemble regionally metamorphosed rocks of low metamorphic rank. Despite the development of schistosity, many primary features such as amygdaloidal or fragmental textures and bedding have been preserved. Preservation of these structures during the alteration of a heterogeneous assemblage of rock types to chlorite, sericite, and quartz suggests that the metamorphism was accomplished by hydrothermal solutions acting under relatively static conditions of stress.
SOUDAN IRON FORMATION

General Statement

The Soudan iron formation is a fine-grained, banded rock, consisting of alternate layers of ferruginous chert and iron minerals. It is usually found within the Ely greenstone and is most abundant in the western part of the Vermilion district. The rock derives its name from typical exposures on Soudan Hill.

Mineralogy

The dominant minerals of the Soudan iron formation are quartz (chert), hematite, and magnetite. Siderite is fairly common to abundant. Pyrite and chlorite occur as accessory minerals and apatite is rarely found.

Quartz

Quartz, in the form of jasper or chert, is the most abundant mineral in the iron formation. It occurs as fine-grained aggregates of irregular grains which range in size from .01 to .05 millimeter. Slightly elongate grains occur in some places which lie in parallel orientation but are not optically oriented. Coarser-grained quartz, sometimes occurring as euhedral crystals, is often found in numerous veinlets which cut across jasper bands.

Hematite

Hematite is the most common iron-bearing mineral of the iron formation in the Soudan area. It occurs as microscopic granules, unoriented flakes, euhedral crystals, and as pseudomorphs after magnetite (martite). Hematite crystals are usually found interstitial to
quartz, magnetite, or martite and are rarely oriented parallel to the bedding of the iron formation.

The hematite of the jasper bands usually occurs as randomly oriented flakes which range up to .01 millimeter in size and as fine-grained aggregates which are found in streaks or scattered patches. The hematite in the oxide bands is usually coarser-grained than in the jasper bands, ranging up to 0.5 millimeter in diameter and occurring as lenticular flakes, euhedral crystals, and frequently as pseudomorphs after magnetite. Euhedral crystals tend to be associated with relatively coarse quartz, and are frequently found in quartz veinlets. Hematite is sometimes found to border ragged crystals or aggregates of siderite and chlorite, suggesting that the hematite developed from the oxidation of these minerals.

Magnetite

Magnetite occurs in the iron formation as bands or disseminations of euhedral crystals. In jasper or chert, magnetite occurs as sparsely disseminated crystals which are usually less than 0.1 millimeter in diameter, whereas in the oxide bands of the iron formation magnetite is more abundant and the crystals reach 0.5 millimeter in size.

Magnetite is most commonly found in partially oxidized portions of the iron formation, where it is usually associated with more or less siderite or ferruginous carbonate. In the less oxidized areas the magnetite is sometimes fresh but is usually partly altered to hematite. The hematite occurs along octahedral planes in the magnetite or at the periphery of magnetite crystals. In the more oxidized areas the magnetite is completely replaced by hematite, and
the resulting pseudomorphs may show the octahedral planes of magnetite or they may consist of a mosaic of broad, unoriented hematite crystals.

**Siderite**

"Siderite" as used in these descriptions refers to a highly ferruginous carbonate. This carbonate probably contains varying amounts of calcium, magnesium, and manganese but the proportions have not been determined. The mineral is tan to yellowish brown in color and exhibits moderate to high relief and strong birefringence. It is usually very fine-grained but has been found in euhedral rhombs up to .25 millimeter in diameter.

Siderite is often found associated with magnetite but may occur as relatively pure layers in chert. It is sometimes found under conditions indicating partial alteration to hematite.

Siderite is usually found in unoxidized or partially oxidized portions of the iron formation, but it rarely occurs in strongly oxidized areas.

**Chlorite**

Chlorite is a fairly common constituent in the oxide bands of the iron formation. Chlorite occurs with siderite and magnetite but appears to be more closely associated with the carbonate. Most of the chlorite appears to be an iron-rich variety. It is dark green and exhibits relatively strong pleochroism and high birefringence under the microscope. Another variety of chlorite which is less birefringent, is found in chloritic chert and occasionally in magnetite-rich bands. Partial alteration of chlorite to hematite has occurred in some areas.
Lithology

The iron formation is usually dense and fine-grained. The rock may be massive, with disseminated iron minerals, or it may show various types of banding in which iron minerals and chert are more or less segregated. Although there are many variations of a minor nature, three principal lithologic types have been distinguished. These are: greenish-white chert, lean jasper, and rich banded jasper or "jaspilite." The basic difference between these three types is mineralogical, although they also show differences in chemical composition, internal structure and mode of occurrence.

The greenish-white chert consists almost entirely of quartz and has a low iron content. Its color is due to accessory chlorite. Pyrite typically occurs in this rock, and is found as small disseminated crystals, sometimes as bands, and is occasionally concentrated at the contacts of chert with greenstone. Siderite may be present, but is usually not seen in hand-specimens. The chert occurs as thin bands, nodules, irregular lenses, and as beds which usually are no more than a few feet thick. Sometimes the chert is irregularly altered to red jasper. The bodies of chert are typically associated with the siliceous and sericitic zones of the greenstone which are marginal to the main belts of iron formation.

The lean jasper is of reddish color and primarily consists of quartz, hematite, and martite or magnetite. Pyrite is a common accessory mineral, usually as disseminated grains, and siderite is often present, sometimes in quantity. The lean jasper usually has a massive to poorly banded internal structure. It occurs as thin lenses and pods but also forms larger, more persistent bodies. It often associated with, and grades into, the greenish-white chert. The lean
jasper makes up most of the smaller bodies of iron formation in the Soudan area. It also tends to occur between the greenish-white chert and jaspilite types of iron formation.

The rich banded jasper, or jaspilite, consists of quartz, hematite, and martite or magnetite, but the minerals are typically segregated into regular, closely spaced bands. Ferruginous carbonate, chlorite and pyrite occur but do not seem to be typical. Carbonate is sometimes abundant and may form conspicuous bands. The main features of the jaspilite, which distinguish it from the greenish-white chert and lean jasper are 1) its well-banded internal structure, 2) greater iron content, and 3) the tendency to form more regular and persistent bodies. It forms a large part of the main belts of iron formation in the area.

Reference to the general geologic map (Figure 1) and to the map of the 17th level (see Figure 2) shows the occurrence of the various types of iron formation. The symbols "Jlm" and "Jb" represent the lean jasper: "Jrb" represent jaspilite.

Table V shows the average chemical composition of different types of iron formation.

<table>
<thead>
<tr>
<th>Type</th>
<th>No. of Samples</th>
<th>Fe</th>
<th>P</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenish-white chert</td>
<td>4</td>
<td>1.82</td>
<td>.020</td>
<td>93.22</td>
<td>.34</td>
<td>.04</td>
</tr>
<tr>
<td>Lean jasper</td>
<td>25</td>
<td>15.27</td>
<td>.041</td>
<td>76.10</td>
<td>.30*</td>
<td>.06</td>
</tr>
<tr>
<td>Sideritic I.F.</td>
<td>5</td>
<td>16.35</td>
<td>.025</td>
<td>64.90</td>
<td>.15</td>
<td>.45</td>
</tr>
<tr>
<td>Jaspilite</td>
<td>11</td>
<td>34.12</td>
<td>.069</td>
<td>50.81</td>
<td>N.D.</td>
<td>.10</td>
</tr>
</tbody>
</table>

*Average of 4 samples only.
The analyses indicate that the iron formation consists essentially of iron and silica, even though the mineralogy of lithologic types may be different. The relatively high manganese content of the sideritic type may indicate that manganese is present in the carbonate.

Stratigraphy

The lithologic types of the iron formation were found to have a rather well defined areal relationship. Mapping of the chert, lean jasper, and jaspilite indicates that these lithic units occur in parallel zones which show a consistent stratigraphic relationship to one another.

The zones of greenish-white chert are usually found along the south side of the main belts of iron formation. Zones of lean jasper lie between the chert occurrences and the main beds of iron formation which consist largely of jaspilite. The lean jasper may occur as separate beds or as transitional zones between the chert and the jaspilite. From south to north, the lithologic sequence is chert, lean jasper, and jaspilite (see Figures 1 and 2). The lithologic change from chert to jaspilite usually takes place within a stratigraphic interval of 200 feet.

Although the lithologic sequence is most commonly found in a vertical stratigraphic arrangement, there is evidence that the sequence takes place laterally as well. The lateral change has been found to occur within a single bed of iron formation. This bed is illustrated in Figure 4. The bed consists of greenish-white chert on the 17th level; lean jasper on the 19th level; greenish-white chert, lean jasper and jaspilite on the 21st level; and jaspilite on the 23rd level.
FIG. 4

17th. LEVEL  
PYRITIC GREENISH CHERT

19th. LEVEL  
LEAN JASPER

21st. LEVEL  
CHERT & LEAN JASPER
BANDED LEAN JASPER

23rd. L.  
JASPILITE

SCALE

(VERTICAL DISTANCE BETWEEN LEVELS 200')

CROSS-SECTION 525 E.
LOOKING EAST
SHOWING RELATIONSHIP OF LITHOLOGIC TYPES OF IRON-FORMATION OCCURRING IN SINGLE BED
The similarity between the lithologic sequence found in both vertical and lateral stratigraphic arrangements strongly suggests that the lithologic units occur as vertical and lateral facies changes within the iron formation. If the lithologic types represent facies changes, then the lithologic sequence indicates a direction of changing conditions in the original environment of deposition. Information on the character of such changes and the direction in which they occurred may be useful in determining the conditions under which the iron formation was formed. This could also lead to the determination of the original surface(s) of deposition and the direction of sedimentary tops.

In the iron formation, the beds of iron oxide or chert do not show variations in texture or composition which would indicate the depositional sequence. The sequence of deposition of the rocks of the greenstone is also uncertain. Without this information, any conclusions regarding the general sequence of deposition of these rocks must necessarily be based on indirect evidence.

If the lithologic sequence is considered, from chert to lean jasper to jaspilite, changes of an orderly nature are evident in the structure, lithology, and composition of these rock units. In the direction of this sequence, there is a progressive increase in the size and continuity of beds, in the development of a regularly-banded internal structure, and in the abundance of iron. These features are most poorly developed in the chert, are moderately developed in the jasper, and reach maximum levels in the jaspilite. These relationships suggest that the nature of the different lithic units may be used to some extent to define the sedimentary conditions under which they were deposited.
The regular banding, greater thickness and persistence of the jaspilite beds is in contrast to the poorly developed banding, smaller size and interrupted character of the beds of chert and lean jasper. These differences suggest that deposition of siliceous sediment was greatly restricted during the accumulation of the chert but was much more extensive where the jaspilite formed. The deposition of large bodies of chert may have been prevented by either chemical or physical factors: chert may have formed at an early stage in the period of siliceous sedimentation, when little silica was available, or it may have accumulated in such an unstable physical environment that only minor deposits could form. The jaspilite appears to have formed in an environment where the availability of silica was great and where physical disturbances were few.

The sedimentary conditions under which iron was deposited may also be inferred from its abundance in the lithologic units. Iron is most abundant in the jaspilite and is moderately abundant in the lean jasper, but is practically absent in the chert. This suggests that the deposition of silica could occur under a variety of environmental conditions but that deposition of iron was more restricted to the jaspilite zone.

The stratigraphic relationships between the lithologic types suggest that environmental changes could occur horizontally as well as vertically within the basin(s) of deposition and that these changes tended to occur in an orderly sequence. Although the lithologic sequence is found to occur as both vertical and lateral facies changes in the iron formation, the vertical stratigraphic arrangement of chert, lean jasper, and jaspilite is more widely developed and is the one most
commonly found. This suggests that the sequence of lithic units is primarily related to time and might be used to indicate the order in which the beds were deposited. If the original surface of deposition were found, to which the lithologic sequence could be referred, the direction of sedimentary tops might be determined.

The original surface of deposition may be indicated by the rocks with which the chert and lean jasper are associated. Deposits of chert and lean jasper are typically found in the zone of siliceous and sericitic rocks which appear to separate the main beds of iron formation from greenstone of basic composition. The siliceous and sericitic rocks appear to consist largely of clastic material and probably include pyroclastic deposits. These rocks appear to be poorly sorted and greatly variable in thickness, are discontinuous along their strike and in places are intercalated with flows. These features suggest that deposition of these rocks was relatively rapid and that they accumulated in a volcanic environment where irregular deposits of poorly sorted clastics could mingle with flows and tuffs. This suggests that these rocks may have formed under surface conditions. Deposits of siliceous sediment occurring with these rocks would be expected to be erratic, as are the deposits of chert and lean jasper.

The chert may represent the first stage in development of the iron formation. If a slow submergence of the area is assumed, with increasing amounts of silica and iron available, the deposition of successive beds of chert, lean jasper, and jaspilite could occur. As submergence increased, the environment of deposition could become more stabilized, allowing thick deposits of jaspilite to accumulate.
Although specific information as to the tops and bottoms of beds is lacking, the relationships described above suggest that the following stratigraphic succession may occur in the greenstones and iron formation at Soudan:

(Top) Basic greenstone?
Jaspilite
Lean jasper
Clastic sediments and chert
(Bottom) Basic greenstone

There are masses of basic greenstone in places along the north side of the iron formation, adjacent to jaspilite. Some of these rocks are probably intrusives, but at least one mass appears to be a flow.

A belt of sediments appears to underlie the greenstone at the base of the above group. This is discussed in the following section on the Knife Lake sediments.

Comparison with Michipicoten District

The stratigraphic sequence as proposed for the Soudan area may be compared to the stratigraphy of the Keewatin rocks of the Michipicoten district in southern Ontario.

At Michipicoten, the iron formation occurs within a group of volcanic rocks of acid to basic composition. Underlying the iron formation is a group of acid volcanics consisting largely of pyroclastic material but including basic to intermediate flows as well as clastic sediments. The iron formation consists of a siliceous member ("banded silica"), a pyrite member, and a siderite member, with the siliceous member composing the bulk of the iron formation. (The pyrite and siderite members are regarded by Collins and Quirke (1926) as integral
part of the iron formation, but are regarded by Moore (1946) and Kidder and McCartney (1948) as later deposits formed by hydrothermal solutions.) Basic greenstone is generally found to overlie the iron formation but clastic sediments are found at this horizon in some areas. The general stratigraphic column is outlined below:

(Top) Basic greenstone
Banded silica member
Pyrite member
Siderite member
(Bottom) Acid volcanics

After Collins and Quirke (1926), p. 52-53

The stratigraphic relationships in the Michipicoten district are similar to those found in the Soudan area, although the respective iron formations show differences in lithology and composition. The zone of sedimentary and tuffaceous rocks found adjacent to the iron formation at Soudan appears to correspond in type with the group of acid volcanics which underlies the Michipicoten iron formation. Also, basic greenstone consisting of flows or intrusives is found to occur above the iron formation in both districts.

The banded silica, pyrite, and siderite members of the iron formation at Michipicoten occur in a consistent stratigraphic arrangement, even though the upper or lower members may not be found in some localities. These features resemble the facies relationships found in the iron formation at Soudan.

Assuming that the stratigraphic columns are correct, the distribution of iron with respect to the stratigraphy of the iron formation at these localities indicates that the deposition of abundant iron occurred at an early stage in the accumulation of iron formation at
Michipicoten, whereas deposition of abundant iron at Soudan was preceded by a period of siliceous sedimentation. This suggests that iron was mainly deposited at Michipicoten under sedimentary conditions which were different from those at Soudan. This possibility is supported by the fact that pyrite or siderite members do not occur in the Soudan iron formation.

Original Character of Iron Formation

Most of the iron formation in the Soudan Mine area is oxidized but the degree of oxidation is widely variable. The relative abundance of hematite, magnetite, and siderite in the iron formation is also variable and this appears to be related to the degree of oxidation. Relationships between these minerals suggest that much of the hematite now present in the iron formation has formed from the oxidation of magnetite and siderite.

Much of the iron formation in the mine area is well oxidized and contains hematite as the principal iron mineral. Oxidized iron formation contains abundant martite, usually associated with flakes or tabular crystals of hematite. Partially oxidized iron formation contains magnetite, siderite and hematite as the principal iron minerals, with accessory chlorite and pyrite. The magnetite is closely associated with siderite and in this variety of iron formation magnetite can be seen in all stages of alteration to hematite. Also, in this type of iron formation siderite and chlorite are found partly altered to hematite. Unoxidized iron formation contains siderite and magnetite as the principal iron minerals, with siderite often occurring alone.
In oxidized iron formation the abundance of martite indicates that magnetite was formerly present. The close association of hematite crystals with the martite is analogous to the occurrence of siderite with magnetite in partially oxidized iron formation, where hematite occurs as an alteration product of both of these minerals. This relationship suggests that both siderite and magnetite may have been present in areas of oxidized iron formation, and that the hematite may be largely of secondary origin.

The close association of magnetite with siderite is a common feature in areas of partially oxidized iron formation. In unoxidized iron formation, siderite often occurs alone but where magnetite occurs it is always associated with siderite. This suggests that magnetite may have formed from siderite and that siderite may be the primary mineral.

Alternate layers of sideritic chert and magnetitic jasper may occur within a single bed of iron formation. One of these occurrences is illustrated in Figure 7(D). The sideritic chert appears to contain no magnetite whereas the jasper contains both siderite and magnetite as well as hematite. The layers of oxidized and unoxidized iron formation are in sharp contact with one another and they appear to be primary deposits. This suggests that both oxidizing and reducing environments occurred during the period of sedimentation.

The primary deposition of magnetite and hematite is possible but the relationship of the minerals suggests that the primary sediment consisted of iron carbonate and silica, with oxidizing conditions developing during sedimentation resulting in the formation of oxides from the carbonates.
Structure

The main belts of iron formation are made up of lenticular bodies rather than continuous beds. The lenticular units are parallel to each other and are separated by greenstone. Contacts between iron formation and greenstone are usually sharply defined, whether the contact surface is straight or highly irregular. The lenses vary in length from a few feet to thousands of feet and are usually less than 70 feet thick. They strike E-W to N. 80° E. and dip approximately 80° N.

Single units of iron formation may occur as long thin lenses, thick pods or as irregular folded masses. Abrupt thickening and thinning is common, and either one or both sides of a body may show deep inward rolls or outward bulges. Two or more beds may coalesce into a single unit or a bed may pinch out entirely and then reappear along the projected strike or dip. Some bodies terminate by gradual thinning whereas others are abruptly "rounded off." Some of these structures may be seen on the general geologic map (Figure 1) and the map of the 17th level (Figure 2); others are shown in the accompanying sketches (see Figures 5, 6, 8 and 11).

Folds in the iron formation may be relatively simple or highly complex. Secondary folds often occur on the crests and limbs of primary folds, and a fold may fade rather rapidly into undeformed beds along the projected pitch. In general, the axial planes of folds in the iron formation are parallel to the strike and dip of the beds, although the pitch of folds is variable and may be inclined toward the east or west.
The most prominent folded structure in the Soudan Mine appears to be an isoclinal, tightly compressed syncline with a westerly pitch. The angle of pitch is highly variable and the crest of the fold is blunt in some places and greatly elongated in others. Along the flanks of the syncline the iron formation often appears to occur as a series of parallel lenses separated by greenstone. Although the synclinal structure is well developed in the lower part of the mine, toward the surface the keel of the fold becomes elongate and it merges into a single belt of iron formation which can be followed eastward for nearly a mile. This belt of iron formation may be seen in the southeastern part of the geologic map (see Figure 1) and the synclinal structure is indicated west of the fault in the central part of the area.

Along the southern border of the southeastern belt of iron formation, the lithologic sequence from south to north is chert, lean jasper, and jaspilite. The chert and lean jasper occur mostly as separate lenses within the siliceous schist. Near the eastern end and on the north side of this belt, the lithologic sequence is reversed. If this belt is an elongate synclinal fold and the stratigraphic sequence in the iron formation is correctly inferred, the lithologic sequence should be reversed on either side of the jaspilite, and this relationship is found. Along the south side of the next belt of iron formation to the north, the sequence from south to north is chert, lean jasper, and jaspilite, suggesting that in this belt the tops of the beds face north. The areal relationships suggest that this belt lies on the north limb of an anticlinal fold, the south limb of which is a part of the synclinal structure as well. It is
thus possible to consider the two belts of iron formation as contiguous, and in the northern belt the tops of beds should face north, as they apparently do. These relationships suggest that the iron formation in the Soudan area occurs as a series of elongate, complex folds of variable pitch which are developed in a single belt of iron formation.

The structural complexity of the iron formation may be better understood from a description of the banded structures found in single beds. The internal structure of bodies of iron formation is shown by the bands of chert and iron minerals. The banded structure generally conforms to the gross structure of the unit. Irregularities in the contacts of a unit are usually reflected in minute detail by the banding; this has been found in the most complexly distorted bodies of iron formation (see Figure 8). In folded beds, the folds in the banding may occur on both the limbs and crests and in each case the axial planes of the folds in the banding are parallel to the axial plane of the larger fold. Even where greatly folded the bands remain sharply defined although some thickening and thinning occurs in the crests and limbs of the folds. The iron formation appears to have been deformed in a plastic condition, but the internal structure is remarkably well preserved.

Some of the structures described above are illustrated in Figure 7. In this figure, the straight bands in sketches (A) and (C) are parallel to the contacts of a folded bed and the minor folds are parallel to the axial plane of the larger fold. The structure of the bands in (B) appears to be caused by compaction. Sketch (D) shows the conformity of internal structure to irregularities in the larger bed.
SKETCH OF OUTCROP SHOWING RELATIONS BETWEEN BODIES OF IMPURE CHERT AND CHLORITIC SCHIST

LOOKING WEST

FIG 5

DETAIL OF CONTACT BETWEEN LENS OF BANDED JASPER AND CHLORITE SCHIST

FIG 6

Legend:

- Dark-gray to greenish-gray granular chert
- Dark-green chlorite-schist
- Gray-green chlorite-sericite schist, siliceous & pyritic

Legend:

- Red, white & black banded jasper & chert (j, jasper; c, chert)
- Dark-green chlorite schist
- Gray chert

Scale 0 - 5 FEET
FIG. 7

Distortion of Jasper bands by Greenstone (Surface — 500' West of Butte Shaft)

Banding in Jaspilite 27th L. West Drift

Chlorite Sch.

Jasper

Banded Chalcedony

Sideritic Chert

Banded Jasper

Jasper

Jasper

Gash veins

Sideritic Chert (Pyritic)

Jasper

Banded Sideritic Chert (Pyritic)

Jasper

INTERNAL STRUCTURES OF IRON FORMATION
Detailed Sketch of Outcrop

Showing Complex Relations between Jasper and Schist
The complexity of structures found in the iron formation is probably due to the plastic manner in which these beds were deformed. Although the folds are isoclinal, the nature of folding appears to have been erratic. These features, together with the apparent lack of folds in the greenstone, suggest that these rocks may not be strongly folded.

The structural features of the iron formation may be due to the deformation of unconsolidated sediment. Considering the close association of the iron formation with volcanic rocks and the frequent occurrence of greenstone within bodies of iron formation, many of the complex structures may be of primary origin. They may have been caused by irregularities in the surface of deposition, slumpage of sediment along primary slopes, compaction by overlying material, and possibly by intercalation or intrusion by lava flows.

The distinction between primary and secondary structural features is usually prevented by the general parallelism between bedding, amygdaloidal zones, intrusive contacts and the axial planes of folds. These relationships make interpretations of structure uncertain.

Despite the complexity of structure in the iron formation and the lack of visible folds in the greenstone, the correlations possible between the broader structural and lithologic features of the iron formation suggest that large isoclinal folds are actually present, but relationships are probably complicated by the presence of many structural features of a primary nature.
Metamorphism

There are few metamorphic effects visible in the iron formation, except for the oxidation of magnetite, siderite, and chlorite.

The chert consists of a fine-grained aggregate of quartz which shows a uniform range in grain size of .01-.05 millimeter. The quartz of the jaspilite appears to be slightly coarser grained, with a grain size of .02-.06 millimeter. There is sometimes a preferred orientation of the quartz grains parallel to banded structures, with a maximum ratio of length to width of 2 : 1. In oxidized iron formation, the periphery of individual quartz grains may be clear, whereas the centers are clouded by granules of hematite, suggesting that secondary enlargement of the quartz grains has occurred. In a few places the texture of the iron formation appears to be coarsened by recrystallization, with the chert showing a sugary texture and containing magnetite crystals up to one millimeter in diameter.

Although chlorite of different types occurs, it rarely shows any relationships which would suggest that it formed by a reaction between ferrous minerals and chert. No iron silicates other than chlorite have been found, although actinolite, garnet, and possibly other minerals occur in the iron formation elsewhere in the Vermilion district.
KNIFE LAKE GROUP

General Description

The greenstone and associated iron formation of Soudan Hill is flanked on the north and south by belts of fine to coarse-grained sedimentary rocks. These rocks were correlated with the Knife Lake sediments by Clements (1903), who considered them to unconformably overlie the Keewatin greenstone and iron formation.

Rocks of the Northern Belt

The sediments to the north crop out along the shore of Lake Vermilion and on islands in the lake. In this vicinity they consist mainly of slate and conglomeratic rocks. They strike approximately east-west and dip vertically to steeply northward. Minor folds observed in the slates plunge 90° to steeply westward.

The slate is a fine-grained banded to massive rock, colored various shades of gray. It consists of quartz, chlorite, sericite, and carbonate. The bands in the slate are usually less than one inch in thickness, and sometimes show a poorly-defined graded bedding.

The conglomeratic rocks are gray to light gray in color and are somewhat bleached on weathered surfaces. Outcrops nearest to Soudan Hill show a fine to medium-grained fragmental texture, and consist of quartz, sodic plagioclase, calcite, sericite, and minor amounts of chlorite. The grains of quartz and feldspar are angular. One small fragment of basic porphyry was found. Other outcrops of conglomerate contain abundant rounded pebbles and boulders of acid porphyry in a groundmass which appears to consist of the same material.
Most of the conglomerate contains very little chloritic material. In the exposures examined, few fragments of chloritic schist were found, and fragments of iron formation are almost as rare. The fragments of iron formation are about one inch in diameter and consist of a gray, very siliceous rock which has a poorly defined banding. No fragments of jaspilite or ore were found.

The conglomerate of this area was correlated by Clements (1903) with the "Ogishke" conglomerate, which he considered to be the basal unit of the Knife Lake sediments. More recently, Gruner (1941) showed that conglomerate of the "Ogishke" type is not always basal but occurs at several horizons within the Knife Lake group. Similar relationships are suggested in the lake area north of Soudan, where several zones of conglomerate occur in the slate in Stuntz Bay.

Rocks of the Southern Belt

The southern belt of sediments is about 600 feet wide and crops out along the south slope of Soudan Hill. The rocks consist of interbedded graywackes and banded slate which strike approximately east-west with a dip of 70-80° northward. Minor folds in the slate are found to strike east-west and plunge 65° eastward.

The slate is a dark gray banded rock similar to the slate of the northern sediments. The bands are often composed of feldspathic material and angular quartz grains. The slate consists mostly of fine-grained quartz, calcitic carbonate, sericite, and chlorite, with accessory zircon, tourmaline, and some carbonaceous material.

The graywacke is a light-to-dark gray rock which exhibits a reddish-brown cast on weathered surfaces. It is featured by abundant
angular quartz grains which range up to several millimeters in size. Feldspathic material appears to be abundant but is largely altered to sericite. Some of the partially altered grains appear to be sodic plagioclase. The graywacke consists mostly of sericite, quartz, and calcite, with accessory zircon, tourmaline, and apatite. Very little chlorite is present.

Conglomerate, although abundant in the northern sediments, appears to be absent in the southern occurrences.

Relation to the Iron Formation and Greenstone

The Knife Lake sediments of the northern and southern belts are similar in general appearance although conglomerate has not been found in the southern zone. The dip and strike of the beds in both belts are essentially parallel although minor folds show different directions of pitch. In one outcrop in the southern belt, graded bedding indicates that the tops of the beds face north. This relationship suggests that the southern belt of sediments underlies the greenstone. If both belts of sediments belong to the Knife Lake group and no strike faults exist, then the Soudan greenstones and iron formation are intercalated with the slates and graywackes of the Knife Lake group. This possibility is not in accord with the Precambrian stratigraphy of this area as outlined by the Minnesota Geological Survey (Grout, et al, 1951). The resolution of this conflict has regional geologic significance.

A number of drill holes put down in the southern part of the mine appear to have a bearing on the problem of the relationship of the Knife Lake sediments to the iron formation and greenstone. The rocks encountered in these drill holes are described in the following paragraphs.
Drilling on the 18th level showed that the iron formation in the southwest part of the mine lies in apparent conformable contact with several hundred feet of clastic sediments on the south. These sediments change from a sericitic graywacke to a dark, locally carbonaceous slate as the iron formation is approached. Thin cherty beds appear in the slate just before the iron formation and schist is encountered. The diminishing grain size of the sediments suggests that the tops of the beds are to the north and that the sediments underlie the iron formation.

In the same section of the mine but on the 27th level, a hole drilled south passed through an alternating sequence of iron formation and greenstone before encountering black slate and sericitic graywacke. These sediments occur within 25 feet of the southernmost bed of iron formation. Fifteen feet of slate was encountered which graded southward into 30 feet of graywacke. The grain size of the graywacke shows a rather distinct coarsening to the south, suggesting that the tops of the beds face north and that the sediments underlie the iron formation and greenstone. The bedding in the graywacke makes a slight angle (5-10°) with the apparent trend of the iron formation. A parallel hole 400 feet to the west of the one just described, encountered graywacke immediately south of the last occurrence of chert and jasper. This graywacke did not show gradational bedding. In both holes the contacts between sericitic schists and sediments were not clearly defined but appeared gradational.

A hole drilled southward from the 12th level, in the eastern part of the mine, encountered 30 feet of graywacke which appeared to lie within greenstone. The graywacke was encountered near the
projected greenstone/Knife Lake contact, and resembled rocks found near this contact on the surface.

The relationships described above suggest that the sediments underlie the greenstone and that the two rock groups are essentially conformable. This possibility is supported by other observations which are described below.

No fragments of greenstone or of iron formation have been found within the southern sediments, even where a relatively coarse-grained graywacke adjoins the greenstone.

The stratigraphic relationships in this area, as proposed by the Minnesota Geological Survey (Grout, et al, 1951), specify that a major unconformity occurs between the greenstone and the adjoining sediments. If this relationship exists, then the greenstone must have been deformed by at least two orogenies (Saganaga and Algoman) whereas the sediments were deformed only by one. It seems highly unlikely that the greenstone has been so affected, since primary textures and structures are often preserved in detail and are not visibly folded. These features add further support to the possibility that the sediments and greenstone are conformable and are not widely different in age.

Certain relationships are found which suggest that the sediments and greenstone may be separated by a slight unconformity, or that some faulting has occurred along the contact between these rock groups. Plotting of the contact between the sediments and greenstones indicates that the contact dips 70-75° N., whereas the normal dip of the greenstone and iron formation is 80° N. The approximate contact between the sediments and the greenstones may be observed in a small
pit southwest of the mine. Fine-grained banded sediments occur on the south wall of the pit, and greenstone schists and ore on the north. The contact occurs as a sheared zone in the eastern end of the pit, and dips approximately 80° N. The two groups of rocks here appear to be in faulted contact but are not extensively sheared. Penetration of the same contact by underground drilling also shows that rocks on either side of the contact are not shattered or extensively sheared.

Although it is possible that a slight unconformity exists between the sediments and greenstone, and that some movement has taken place along the contact, neither of these features would appear to indicate that a major disconformity occurs between the sediments and greenstone. Since gradational bedding in the sediments suggests that they underlie the greenstone, a slight unconformity could be interpreted as further evidence that the sediments are the older rock group. Also, if the sediments and greenstone are in essentially conformable contact, a certain amount of movement would be expected to occur between them since the contact would represent a natural surface of discontinuity between two physically different groups of rocks. Any pressure exerted on the area would tend to be relieved by movement along this surface, and shearing would be expected to be localized here.

The evidence indicates that the apparent parallelism of structure, shown between the southern belt of sediments and the greenstone, is due to actual structural conformity between these rock groups. The evidence further indicates that the sediments are stratigraphically below the greenstone and that no major disconformity is present.
If the southern belt of sediments belongs to the Knife Lake group, then the greenstones and iron formation are intercalated with the Knife Lake sediments. This may help to explain the general structural parallelism shown between the sedimentary belts and the greenstone in the Soudan area, as well as in other parts of the Vermilion district.
ORE DEPOSITS

The ore deposits of the Soudan Mine consist of steeply dipping, lenticular bodies of high grade iron ore. The ore is a bluish gray, fine grained variety of hematite which is generally massive in appearance but may contain internal structures such as banding or brecciated textures which appear to be inherited from rocks which the ore has replaced.

The orebodies in the Soudan Mine are rather small when compared with other iron ore deposits of the Lake Superior region. As mined, the orebodies are about 20 to 40 feet thick, 100 to 600 feet long, and are usually extensive down dip. The largest dimensions encountered so far are widths of 100 feet, a length of 1,000 feet and depths of at least 2,500 feet. In general, the size and persistence of orebodies appears to be related to the continuity of the beds of iron formation in which they occur.

The shapes of the orebodies are also influenced by the shape of the iron formation bodies in which they occur. Orebodies which occur in folded or faulted iron formation inherit much of the contortion and discontinuity of the host rock. Most of the orebodies are tabular, elongate lenses which may have regular, sinuous or highly irregular contacts with the adjacent rocks. Both contacts may be with iron formation although commonly one or both walls are schist. In general, the contacts with schist are regular and well defined whereas the contacts with iron formation tend to be irregular and somewhat gradational.
Mineralogy

The dominant ore mineral is hematite, with quartz, chlorite, and apatite as common accessory minerals. Pyrite and chalcopyrite less frequently occur but are sometimes abundant. Kaolinite is rare, and single occurrences of goethite and siderite have been found. A number of copper minerals, including bornite, chalcocite (?), cuprite, native copper, azurite, malachite, and brochantite (?) occur in one orebody but are unusual.

Hematite

Hematite usually occurs as a very fine-grained aggregate of randomly oriented lenticular flakes which average from .01 - .05 millimeter in size. Small vugs in the ore are often crusted with druses of euhedral hematite crystals which range in size up to .05 millimeter. Coarse aggregates of micaceous hematite occur near faults, in brecciated ore, and occasionally in schist adjacent to ore. The size of hematite flakes in these occurrences may reach two centimeters. The coarser aggregates of hematite appear to be secondary.

Flakes of hematite of all sizes and modes of occurrence appear to be weakly magnetic when tested with a hand magnet. This might be due to submicroscopic magnetite, although none has been found.

Hematite pseudomorphs after magnetite (martite) often occur in the ore. Although the external form of the magnetite crystals is well-preserved, the internal arrangement of hematite crystals may preserve the octahedral partings of magnetite, or the hematite may occur as a mosaic of irregular grains. The specimens showing the octahedral pattern appear to be porous with the hematite crystals
forming a meshwork. The "martite" crystals are usually grouped in parallel bands. The ore usually shows two types of bands; both types are fine grained, but differ in appearance and texture. One type appears to be very dense and is relatively lustrous. This type contains numerous pseudomorphs of hematite after magnetite, and is similar to the magnetitic bands of iron formation. This type will be referred to as "pseudomorph-bands" in the following pages. The second type of band is of duller luster and consists of fine-grained hematite occurring as randomly-oriented flakes without associated martite. These bands, which will be referred to as "replacement bands," are often porous, and are characterized by secondary minerals such as quartz and chlorite.

Quartz

Quartz occurs with the ore as small disseminated grains, as coarse crystalline aggregates interstitial to ore bands, as well-formed crystals lining vugs, and as remnants of jasper in the ore. Where coarsely crystalline, the quartz is frequently associated with powdery aggregates of dark green chlorite. Coarsely crystalline quartz frequently occurs where jaspilite grades into ore. It may form in vugs, or occurs as bands which can be traced into bands of jasper. Quartz crystals in vugs may contain finely divided iron oxide, crystalline hematite, or chlorite, or they may contain no visible impurities. The crystals are sometimes coated by pyrite or by chlorite.

Chlorite

Chlorite occurs in the ore as dark green, fine-grained powdery aggregates of micaceous plates. It tends to occur in vugs along
"replacement bands" of the ore as finely crystalline aggregates of powdery consistency. In the vugs it often coats the surface of quartz crystals, and sometimes is enclosed in the quartz. A sample of chlorite from a vug was analyzed by Dr. S. S. Goldich at the University of Minnesota. The analysis is recorded in Table VI below.

**TABLE VI**

ANALYSIS OF CHLORITE FROM VUG IN ORE
Shaft Vein Orebody, 80' above 25th Level

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>SiO₂</td>
<td>23.99</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>23.33</td>
</tr>
<tr>
<td>TiO₂</td>
<td>tr</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.48</td>
</tr>
<tr>
<td>FeO</td>
<td>36.62</td>
</tr>
<tr>
<td>MnO</td>
<td>.20</td>
</tr>
<tr>
<td>MgO</td>
<td>2.57</td>
</tr>
<tr>
<td>CaO</td>
<td>.26</td>
</tr>
<tr>
<td>H₂O+</td>
<td>10.47</td>
</tr>
<tr>
<td>H₂O-</td>
<td>.06</td>
</tr>
<tr>
<td>Total</td>
<td>99.98</td>
</tr>
</tbody>
</table>

The chlorite is very rich in iron with a composition close to that given for thuringite by Dana and Ford¹, although the alumina content is slightly less. Some ferric iron may substitute for Al³⁺ in the crystal lattice.

Aggregates of chlorite are found in the ore and in the iron formation near ore. Chlorite occurs in small vugs which seem to be localized in the jasper bands of the iron formation and in the "replacement bands" of ore.

Apatite

Apatite occurs in the ore as fine-grained aggregates and single crystals up to two millimeters in diameter, but is usually very fine-grained and difficult to recognize in hand specimen. It usually occurs with chlorite (thuringite?) in ore, and sometimes with kaolinite. Apatite appears to be a common accessory of the ore and probably accounts for the relatively high phosphorus content.

Pyrite

Pyrite occasionally occurs in the ore as disseminated euhedral crystals. It is not common in the ore, but may be locally abundant. Where found, it seems to occur mostly near the limits of an orebody, but it is sometimes present in vugs in the ore. Some of the quartz crystals lining vugs are partially coated with pyrite. Pyrite is often associated with aggregates of chlorite and quartz in veinlets and vugs in the iron formation. It is also associated with chalcopyrite.

Chalcopyrite

Chalcopyrite occurs as irregular grains or small masses in the ore or in the iron formation adjacent to ore. The mineral is rarely found in the schist. Chalcopyrite is often associated with quartz and sometimes with other sulphides and chlorite, but it may also occur as isolated grains. Chalcopyrite is usually found near the periphery of orebodies.

Textural relationships between ore and chalcopyrite indicate that chalcopyrite is the later mineral. It occurs in fracture-fillings in both ore and adjacent iron formation, in secondary
cavities parallel to ore bands, and in one case an ore breccia was cemented by chalcopyrite.

**Other Minerals**

A very fine-grained soft white mineral occurs along some fractures in ore as a constituent of some vugs, and in secondary veinlets in iron formation near ore. One specimen of this mineral, occurring in small cavities in massive ore, was identified as kaolinite from x-ray analysis by Dr. S. W. Bailey at the University of Wisconsin.

A group of copper minerals occurs in a part of an orebody in the western section of the mine. These include chalcopyrite, bornite, and native copper, and probably chalcocite and cuprite. Eby and Berkey (1897) described malachite, azurite, cuprite, and native copper occurring in the same orebody on an upper level. A mineral resembling brochantite apparently came from the same orebody.

Specimens of other minerals, including dolomite, siderite, aragonite, goethite, and possibly marcasite have been seen but these appear to be rare. The specimens are large and were mostly found in vugs in the ore.

**Paragenesis**

The fine-grained hematite of the iron ore occurs as pseudomorphs after magnetite and as randomly oriented flakes. No evidence was found which indicates a difference in age of these types, although the ore textures suggest that the hematite has replaced different materials.
Secondary veinlets of coarse specular hematite were found in one orebody to cut the denser ore. Fine-grained hematite occurs as fracture fillings in brecciated chloritic and sericitic schist along a fault zone in another orebody. The hematite of the fracture-fillings does not occur as veinlets in adjacent ore but is coarser-grained and may represent a second generation of hematite.

Chlorite and quartz appear to be of slightly later age since they line small vugs in the ore. These minerals are intimately intergrown with fine-grained hematite in many instances, however, and the relationships are difficult to evaluate. Veinlets of chlorite and quartz, with other minerals, cut the iron formation in the vicinity of ore but are not seen to cut the ore itself. Chlorite veinlets often cut schists of various composition which occur adjacent to ore.

Pyrite occurs in the ore as disseminated crystals as well as fracture-fillings. Chalcopyrite occurs as fracture-fillings and in one instance occurs as the matrix of ore fragments. These sulphides appear to have formed in the ore as secondary minerals. In one specimen of chalcopyrite which fills cavities in ore, pyrite, bornite, and chalcocite (?) were found. The paragenetic sequence appears to be pyrite, chalcopyrite, and bornite and chalcocite (?) in the order of deposition.

Native copper occurs as coatings on joint planes in the ore, as fracture-fillings, and occasionally as vug linings. It is later in age than the ore.

Chemical Composition of Ore

The average composition of the iron ore in various orebodies, calculated from exploration drill core analyses, ranges from 63 to
66% Fe, 2 to 8% SiO₂, 0.4 to 2.0% Al₂O₃, and 0.0 to 0.25% P. The manganese content is rather constant, between 0.06 and 0.09%. Sulphur is absent or in negligible amounts, and a few samples of ore from surface exposures showed a titanium content of 0.12% or less.

A comparison between the compositions of iron ore and iron formation, aside from the obvious differences in iron and silica, indicates that the average content, in weight percent, of alumina and phosphorus is higher in the ore than in the iron formation. The difference in alumina is evidently due to chlorite, which is a common mineral in the ore but is relatively scarce in the iron formation. The difference in phosphorus is probably related to the abundance of apatite.

Except for the occasional inclusion of schist material in ore, there appears to be little or no relationship between the composition of an orebody and the composition of its adjacent schist. Locally, some ore appears to have formed by alterations in schist; this is referred to in the description of wall rock alteration.

**Mineral or Chemical Zoning**

The distribution of mineral and chemical impurities in the ore appears to be variable but irregular. Examination of drill core and plotting of analyses from drill holes across different parts of orebodies does not show consistent results. One hole may show increasing amounts of alumina, phosphorus, or silica between the foot- or hanging-wall of an orebody, but an adjacent hole may show the variations to be reversed. In general, the mineralogical or chemical character of the ore does not appear to change with depth.
Localization of Ore

Lithic Controls

All of the orebodies occur within beds of iron formation or can be reasonably interpreted on the basis of inclusions and relict structures as having replaced pre-existing beds of iron formation. The jaspilite variety of iron formation appears to be the principal host for commercial bodies of iron ore. There is no direct relationship between ore occurrence and internal features of the jaspilite such as mineralogic variations or degree of banding.

The schist adjacent to ore may be an altered flow, intrusive, pyroclastic or sediment. Certain types are characteristic of orebodies in different parts of the mine but with the possible exception of intrusives, no one type is common to all orebodies. For a given orebody, the hanging wall and footwall schists may be similar or they may be of different types.

Where ore occurs along a contact between jasper and schist, the ore may thicken toward the jasper but is limited by the schist. The maximum thickness of ore is thus limited by the thickness of the body of iron formation in which it occurs. As the ore tends to occur in narrowed portions of a jasper body, recurrent thickening and thinning of the jasper may cause intermittent occurrence of ore along the strike or dip. Where ore is followed into thickened portions of a jasper body, its occurrence tends to become irregular. Some of the relationships are illustrated in Figures 9, 11, 12-B, and 16.

Structural Controls

Orebodies tend to occur at the contact between iron formation and schist. Orebodies may pinch and swell along the strike and
FIG. 9

CROSS-SECTION, SANDBERGER PIT
LOOKING EAST
SHOWING OCCURRENCE OF
ORE IN STEEPLY-DIPPING LENS OF JASPER

FIG. 10

CROSS-SECTION, EAST END NO. 7-NO. 8 PIT
LOOKING EAST
SHOWING STEEPLY-DIPPING LENS OF ORE

- MASSIVE, WELL-JOINTED, FINE GRAINED GRANULAR ORE
- CHLORITIZED ROCK
- SERICITIC AND CHLORITIC SCHIST
ISOMETRIC BLOCK DIAGRAM OF
SHAFT VEIN - 651 OREBODIES
LOOKING SOUTHEAST
SHOWING RELATION OF ORE OCCURRENCE
TO STRUCTURE OF IRON FORMATION

FIG. II

100'  100'  100'

Ore

SCALE
DIAGRAMMATIC SKETCH OF OREBODIES OCCURRING IN JASPILITE
Based on Geology of 27th level (Montana area) as shown in drift & stopes

- Jaspilite, showing banding
- Ore, showing banding
- Greenstone

MINIATURE OREBODY DEVELOPED ON POD OF JASPILITE
19th Level 250' East of No. 8 shaft

- Jaspilite, showing banding
- Ore
- Sericite schist
dip but the persistent portion of the ore lense follows the contact. This control is also evident in the localization of orebodies in "pinched" structures of iron formation where two schist-iron formation contacts approach one another. These thinned sections of iron formation appear to be the principal structural control on the location of orebodies. Such thinning may be due to deformation, injection of intrusives, or possibly to differences in original sedimentation.

The only apparent control on ore occurrence exerted by folding appears to be in the development of pinched structures in the iron formation during deformation. No consistent relationship of ore to specific parts of folds has been recognized. Ore occurs in the crests, troughs and limbs of folds as well as in iron formation which appears to be undeformed.

Faulting may have some influence on the localization of ore but the areas where the effects of faulting can be recognized are areas where the development of ore is small or predates the period of faulting. Pre-ore faulting may have localized some ore deposition since there are examples of fracture-fillings and breccia cementation by ore near a fault on the 27th level of the mine (see Figure 14). There are also places near No. 8 shaft between the 12th and 22nd levels where hematite replaces small amounts of schist in the vicinity of a longitudinal fault zone. Other occurrences of ore along faults are probably due to post-ore movement. They appear to be "drag ore," or parts of a pre-existing orebody which have been faulted into contact with barren rock. In general, the ore does not appear to be localized by faults although some ore has formed in shattered jasper.
**Possible Intrusive Controls**

There is a close association between ore occurrence and the presence of micaceous-textured lamprophyric dikes in the northern and eastern parts of the mine on the upper levels. A prominent exposure of one of the dikes on the 12th level is illustrated in Figure 15. This dike appears to form the footwall of a small orebody near the eastern limit of the mine workings. The same dike occurs on the 10th level (8th L. Alaska), where a larger orebody has been mined out. The western part of this orebody apparently rested on the dike.

In the northern part of the 12th level, about half a mile northwest of the dike shown in Figure 15, two small dikes of the micaceous variety occur. The dikes intersect a bed of jaspilite, and a small orebody occurs near the point of intersection. In the jaspilite near this orebody there are two thin concordant stringers of micaceous-textured rock which resemble the dike material. Although the exposures do not show a positive connection of the stringers with the dikes, they are less than 20 feet above the intersection of the dike with the jaspilite and the texture is so similar that there is little reason to doubt their connection. Ore occurs along the contacts of these stringers, and the relationship is shown in Figure 13. The width of the ore on either side of a stringer is about the same, and is also about the same width as the stringer itself. Where the two stringers become closer together, the ore selvages also approach each other and finally merge into a solid band of ore. Drill core and surface exposures show that rocks of the lamprophyric type occur near ore in other areas although not with such a clear relationship between ore and dike rock.
Certain orebodies, which occur in the main belt of iron formation in the eastern part of the mine, are bordered by a fine-grained, massive, granular-textured greenstone. These orebodies occur in a zone in which the iron formation is apparently divided into several parallel lenses by the greenstone. Although the lenses of jaspilite are parallel to each other, their continuity down dip and along strike is interrupted, and it is possible that the greenstone is intrusive. Some of the relationships may be seen along the north side of the orebodies illustrated in Figures 16 and 17. The greenstone appears to intrude the ore, but it is also possible that the ore has been localized in structures resulting from intrusion.

A body of schist shows an intrusive relationship with banded jasper near No. 8 shaft on the 27th level. Ore occurs in places along the contacts between jasper and schist (see Figure 18). Most of the ore occurs in the jasper, but in several places where the adjacent schist is heavily chloritized part of the ore has replaced the chloritized schist.

Wall Rock Alteration

The schistose greenstones which form the wall rocks of ore may be sericitized, chloritized, or altered to red-brown "paint rock". One or more types of rock alteration may occur adjacent to a given orebody, but no one type seems typical of all orebodies. Also, different types of rock alteration are often superimposed on each other.

Iron formation, adjacent to ore, frequently shows recrystallization of jasper to coarse quartz. Small vugs are often found which
SELVAGES OF BANDED ORE ADJACENT TO GREENSTONE STRINGERS IN BANDED JASPER - 12th. LEVEL 824 STOPE
(GREENSTONE MAY BE INTRUSIVE)

CHLORITE SCHIST
MICACEOUS CHLORITE SCHIST
ORE BANDED JASPER

LOOKING EAST

DIAGRAMMATIC SKETCH DRIFT FACE - 27th. LEVEL SHOWING VEIN OF ORE CUTTING BANDED JASPER
WIDTH OF FACE 9 FEET

GREENSTONE ORE JASPER
DETAIL MAP, EAST END 12th LEVEL
SHOWING OCCURRENCE OF ORE ALONG HANGING WALL OF DIKE
(No. 707 STOPE)

LEGEND

- - - - - Ore
- - - - - Micaceous dike rock
- - - - - Iron formation
s - - - - - Chloritic and sericitic schists

SCALE
0 60 120 FEET
FIG 16

LOOKING EAST

3 VERTICAL CROSS-SECTIONS OF ALASKA OREBODY SHOWING OCCURRENCE OF ORE IN STEEPLY-DIPPING LENS OF IRON FORMATION

SCALE IN FEET

<table>
<thead>
<tr>
<th></th>
<th>Ore</th>
<th>Jasper</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td></td>
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</tbody>
</table>

HORIZONTAL & VERTICAL FROM ENG DEPT MAPS

SUPERIOR DATUM
INTERFINGERING OF SCHIST WITH ORE
AS SHOWN BY SERIES OF STOPE MAPS (No. 3 Orebody)

ELEVATIONS IN FEET

From Eng. Dept. Maps
PLAN OF DRIFT AT No. 8 SHAFT, 27th. LEVEL
SHOWING
RELATION OF JASPER AND ORE TO INTRUSIVE GREENSTONE

- JASPER, Showing banding & breccia
- ORE
- CHLORITE - SERICITE SCHIST
usually contain quartz crystals and aggregates of chlorite. In the vicinity of ore, the iron formation is frequently cut by small veinlets and fractures which may contain quartz, chlorite, chalcopyrite or hematite, and sometimes kaolinite or ferruginous carbonate. Occasionally, chert appears to be partially replaced by chlorite.

The association of sericitized and chloritized schists and "paint rock" with the orebodies at Soudan was the subject of a recent paper by Schwartz and Reid (1955). The authors compared the composition of these schists with Ely greenstone and suggested that the differences found were related to the ore-forming process. They noted a relatively high potash content of some rocks, a high ferrous iron content in others, and oxidation of a chloritic schist to "paint rock." They also mentioned the possibility that the sericite schist is derived from originally acidic rocks.

**Sericitized Rock**

Narrow zones of a yellow to yellowish-green sericite rock occur adjacent to ore and to some iron formation near ore. The yellowish rock is usually a schist, but may be dense and massive. The schist gradually loses its yellowish color and grades into dark green chloritic schist away from the contact with ore or with iron formation. The width of the sericitized zone is usually a few feet, but ranges from a fraction of an inch up to 30 or 40 feet. The association of the sericite schist with ore and its gradation into chloritic schist away from ore suggest that the schist may be related in some way to the ore forming process. The absence of sericite schist adjacent to other orebodies, however, suggests that the occurrence is incidental, rather than related to, the presence of ore.
The sericite schist occurs largely in an area where original rock textures and structures have been largely obliterated, and where the effects of strike-faulting and cross-faulting may be extensive.

The siliceous and sericitic rocks of tuffaceous and sedimentary origin, which are found to be associated with the iron formation, often form the footwall of orebodies but the sericite content of these rocks is independent of the occurrence of ore. Also, the hangingwall rocks of the same orebodies may consist of massive chlorite schist which shows no sericitic alteration adjacent to the ore.

Chloritized Rock

The alteration of chloritic and sericitic schist to a dark green, fine grained massive chlorite rock has been observed in certain places adjacent to ore and iron formation. The chlorite rock ranges in thickness from one inch to several feet and the thickness seems greater adjacent to ore than to iron formation. The chloritized rock is sometimes partially replaced by fine grained hematite. Specific occurrences of the chlorite rock are illustrated in Figs. 9 and 10, and three chemical analyses are given in Table VII, which is shown on the following page.

Schwartz and Reid (1955) presented several analyses of chloritic wall rocks of ore and three of these analyses are shown in Table VIII. The analyses indicate that some wall rocks of ore are unusually rich in ferrous iron.
TABLE VII
ANALYSES OF CHLORITE ROCK

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>22.85</td>
<td>22.15</td>
<td>36.30</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>24.20</td>
<td>20.43</td>
<td>14.73</td>
</tr>
<tr>
<td>Total Fe</td>
<td>31.02</td>
<td>29.81</td>
<td>24.59</td>
</tr>
</tbody>
</table>

1. Chloritized wall rock of 2' ore lens. Surface pit west of stockpile ground.
2. Chloritized wall rock of 6" ore lens. Small pit west of No. 1 shaft.

W. J. Trudgeon, analyst

Note the approximate equivalence of silica and alumina in Nos. 1 and 2, which resembles the chlorite analysis in Table V.

TABLE VIII
IRON CONTENT OF CHLORITIC WALL ROCKS

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe₂O₃</td>
<td>5.6</td>
<td>12.5</td>
<td>2.5</td>
</tr>
<tr>
<td>FeO</td>
<td>26.3</td>
<td>24.7</td>
<td>12.1</td>
</tr>
</tbody>
</table>

1. North wall rock, Montana orebody, 22nd level.
2. North wall rock, No. 8 orebody, 20th level.
3. South wall rock, 734 orebody, 19th level.

(Analyses by S. S. Goldich)

In the wall rocks represented by samples 1 and 2, the chlorite content appears to decrease away from the ore, whereas in the wall rock represented by sample 3 the chlorite content does not appear to change.
The chloritized rock shown in Figure 10 may represent altered sericitic schist. A drill hole 100 feet away encountered alternating layers of jasper and sericitic schist at the projected contact of the layers of ore, schist, and chlorite rock shown in the figure. Elsewhere, chlorite rock may represent alteration of either sericitic or chloritic schist.

Scattered veinlets of chlorite have been found in all types of wall rocks. These veinlets seem to be restricted to the vicinity of ore, and to this extent, the development of chlorite is closely associated with the occurrence of ore. Whereas chlorite-rock or chlorite schist may occur adjacent to ore, these rocks are not associated with all orebodies. The relatively high chlorite content may be due to local introduction of iron, or to the removal of other constituents such as lime, silica, magnesia, or alkalies.

"Paint Rock"

"Paint rock" is a local term applied to a schistose rock which has a dark red or reddish-brown color. The color is due to finely-divided ferric oxide resulting from rock alteration. The alteration appear to have occurred in two ways: 1) by oxidation of chloritic material; and 2) by introduction of ferric oxide. The alteration has affected both the chlorite and sericite schists.

Paint-rock alteration is most frequently found in the schists adjacent to orebodies, and adjacent to iron formation in the vicinity of orebodies. Although frequently found, its occurrence may be irregular or very limited, and it is not present near some orebodies.
Some areas of paint-rock appear to be associated with faults, particularly in the areas where faults intersect orebodies. In one of these areas, large amounts of ferric oxide have apparently been introduced into the schist and in some places the schist is largely replaced by hematite.

In the central part of the mine, near No. 8 shaft, sericite schist appears to be converted to paint-rock in several places. In one instance paint-rock is developed along cross-fractures and schistosity planes, apparently entering the schist from these surfaces. On 19th level, a yellow to greenish-yellow sericite schist appears to have been impregnated by iron oxide and is converted to paint-rock. Analyses of the schist and paint-rock are shown in Table IX.

### TABLE IX

**ANALYSES OF A SERICITE SCHIST AND ADJACENT "PAINT ROCK"**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Total Fe</th>
<th>P</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>MnO</th>
<th>CaO</th>
<th>MgO</th>
<th>Ign.</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-1</td>
<td>2.73</td>
<td>0.080</td>
<td>48.00</td>
<td>34.68</td>
<td>0.03</td>
<td>0.30</td>
<td>0.25</td>
<td>5.25</td>
</tr>
<tr>
<td>19-2</td>
<td>40.91</td>
<td>0.080</td>
<td>16.65</td>
<td>18.05</td>
<td>0.11</td>
<td>0.30</td>
<td>1.19</td>
<td>4.20</td>
</tr>
</tbody>
</table>

19-1 Sericite schist, 19th Level, near No. 8 shaft  
19-2 "Paint rock," 6 feet north of 19-1  

(Analyses by O.I.M. Eastern District Laboratory)

The replacement of schist by ferric oxide may take place gradually over several feet. A zone of ore or near-ore may grade laterally into unaltered chloritic or sericitic schist. The ore appears to retain some of the schistosity of the original rock and is rather soft. These features are not shown by ore which has replaced iron formation. Table X shows the changes in composition across a
zone of paint-rock in sericitic schist which was penetrated by a
drill hole on the 10th level (D.H. 875).

**TABLE X**

**PARTIAL ANALYSES FROM A ZONE OF PAINT ROCK**
**IN SERICITIC SCHIST**

<table>
<thead>
<tr>
<th>Footage</th>
<th>Total</th>
<th>Fe</th>
<th>P</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.5'</td>
<td>9.43</td>
<td>.025</td>
<td>57.60</td>
<td>21.52</td>
<td></td>
</tr>
<tr>
<td>63'</td>
<td>33.29</td>
<td>.065</td>
<td>25.40</td>
<td>18.51</td>
<td></td>
</tr>
<tr>
<td>65'</td>
<td>54.87</td>
<td>.101</td>
<td>10.90</td>
<td>7.56</td>
<td></td>
</tr>
<tr>
<td>67'</td>
<td>65.13</td>
<td>.128</td>
<td>3.70</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td>69'</td>
<td>62.40</td>
<td>.274</td>
<td>4.55</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>70'</td>
<td>25.74</td>
<td>.053</td>
<td>28.80</td>
<td>24.07</td>
<td></td>
</tr>
<tr>
<td>73'</td>
<td>5.47</td>
<td>.019</td>
<td>57.10</td>
<td>23.40</td>
<td></td>
</tr>
</tbody>
</table>

(W. J. Trudgeon, analyst)

60.5' Yellowish-green chlorite-quartz-sericite-schist. Has slight reddish cast.

63' Paint-rock. May have increased chlorite content from 63.5'.

65' Paint-rock, nearly ore.

67' Ore, appears to be replacement of schist.

69' " " " " " " " "

70' Paint-rock, similar to 63'.

73' Yellow-green schist, similar to 60.5'.

**Schwartz and Reid (1955) presented analyses of a sample**
**of paint-rock and of the adjoining chlorite-sericite schist. Their**
**samples were taken from the same area of the mine as the schist**
"paint rock" **samples described above. Their analyses, given in**
**Table XI, suggest that oxidation of chlorite has produced much of**
**the ferric iron in the "paint rock."**
TABLE XI
ANALYSES OF A CHLORITE-SERICITE SCHIST
AND ADJACENT "PAINT ROCK"

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>31.85</td>
<td>25.29</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>27.93</td>
<td>19.61</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.15</td>
<td>38.61</td>
</tr>
<tr>
<td>FeO</td>
<td>23.38</td>
<td>6.44</td>
</tr>
<tr>
<td>MgO</td>
<td>1.33</td>
<td>.40</td>
</tr>
<tr>
<td>CaO</td>
<td>.04</td>
<td>.29</td>
</tr>
<tr>
<td>Na₂O</td>
<td>.43</td>
<td>.42</td>
</tr>
<tr>
<td>K₂O</td>
<td>3.26</td>
<td>3.74</td>
</tr>
<tr>
<td>H₂O+</td>
<td>8.12</td>
<td>3.80</td>
</tr>
<tr>
<td>H₂O⁻</td>
<td>.48</td>
<td>.70</td>
</tr>
<tr>
<td>TiO₂</td>
<td>.84</td>
<td>.08</td>
</tr>
<tr>
<td>CO₂</td>
<td>.04</td>
<td>.68</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>.08</td>
<td>.19</td>
</tr>
<tr>
<td>MnO</td>
<td>.08</td>
<td>.02</td>
</tr>
</tbody>
</table>

1. D.H. 799, 19th level, composite of 90.5'-92'.
   Yellowish-green chlorite-sericite schist.
   H. Baadsgaard, analyst.

2. D.H. 799, composite of 88'-90.5'. "Paint rock."
   H. Baadsgaard, analyst.

In the part of the mine where the samples of Tables IX, X, and IX were taken, the "paint rock" usually appears to be formed by introduction of ferric oxide into sericite schist, rather than by oxidation of chlorite schist.

Relation of Wall Rock Alteration to Ore Occurrence

The different types of wall rock alteration found with the ore appear to have one common characteristic: each type is found to occur with certain orebodies but none seems characteristic of all orebodies. The rock alterations are variable and one type may be superimposed on another, but none appears to be directly related to the occurrence of ore.
Age of the Ore

Clements (1903, p. 233) described the massive, non-schistose structure of the Soudan ore and concluded that the ore was formed subsequent to the last intensive deformation of the associated rocks; i.e., after the folding of the Knife Lake sediments.

Gruner (1926, p. 642) described the occurrence of large vugs at the border of a Soudan orebody and concluded that no deformation of the rocks has occurred since the ore was formed. The walls of the vugs were soft "paint rock" on one side and ore and jasper on the other, and were lined with large crystals of quartz, hematite, and other minerals. Since the vugs were intact, and were believed to have formed at the same time as the ore, Gruner considered that any subsequent deformation should have shattered them or squeezed the soft schist into them.

The present work supports the conclusion that the ore deposits at Soudan have not been strongly deformed, although some later faulting has occurred. The ore is not schistose or brecciated, vugs are intact, and ore/greenstone contacts are not extensively sheared. Also, the meshwork structure of hematite pseudomorphs after magnetite in the ore has not been destroyed. These relatively fragile structures have been found intact in the main orebodies as well as in an ore lens only two feet thick.

A second generation of hematite appears to post-date structural movements which occurred after the main ore-forming period. These movements, and the later hematite, are both later in time than a sericite rock which has been dated at 1.67 billion years by the $A^{40}/K^{40}$ method. A sample of sericitized rock from the western part of
the mine, dated by the same method, yielded an age of 2.54 billion years. These measurements suggest that more than one age of sericite is present and that at least some hematite is younger than 1.67 billion years. This age would correspond to the post-Huronian-pre-Keweenawan period according to Goldich. The evidence suggests that the geologic history of the ore at Soudan is more complex than has been previously recognized.

**Origin**

The structural and textural relationships between ore and iron formation suggest that the ore occurs as replacement deposits of hematite within the iron formation, particularly the jaspilite type. The orebodies occur in the iron formation and their dimensions are controlled by its structure. The banded structure of ore is conformable to, and continuous with, the banded structure of iron formation. The texture, width, and spacing of martitic bands ("pseudomorph bands") in the iron formation are similar to those found in the ore. Brecciated iron formation is found adjacent to ore which shows a relict breccia-texture, and the volume of iron formation appears to be largely preserved by the ore.

The concentrations of hematite do not appear to be related to the present erosional surface or to a former surface. Weathering of exposed iron formation is only superficial, and the orebodies are not overlain by "leached cappings" of iron formation. Although there

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1S. S. Goldich, personal communication.
are zones in the jaspilite from which iron might have been removed, these zones may occur above, below, or laterally with reference to orebodies. There is little evidence which could be interpreted as "slump structure" resulting from reduction in volume of the iron formation by leaching of silica. These features, together with the persistence of ore with depth, and its relatively constant composition through a vertical interval of 2,500 feet, suggest that the ore was not formed by supergene processes.

The possibility that the orebodies are syngenetic with the iron formation, as primary beds of iron carbonate or iron oxide, appears to be discounted by the abrupt nature of the ore-iron formation contact which often cuts across the bedding of the iron formation at nearly right angles. In addition, the preservation in ore of the textures and banded structures of iron formation indicates that the ore replaced a bedded rock and is thus of secondary origin.

The possibility must be considered that the hematite orebodies represent oxidized replacement deposits of siderite. Some orebodies appear to be constricted extensions of lenticular bodies of iron formation, and these occurrences suggest that the volume of ore may be less than the volume of iron formation which has been replaced. Also, the frequent occurrence of ore in "pinched" or narrowed structures suggests that these structures are possibly caused by reductions in volume related to the ore-forming process. Such volume changes suggest that siderite may have been the original mineral replacing the iron formation, with later oxidation to hematite and compaction to form the present structure. The possible
occurrence of siderite as the original ore mineral at Soudan might be analogous to the primary replacement deposits of siderite in the Keewatin-type iron formation of the Michipicoten district.

Specimens of coarse siderite veined by hematite have come from one orebody (No. 8) at Soudan. There are secondary veinlets of siderite in the iron formation, particularly where siderite occurs in bands with magnetite and occasionally coarse hematite is found in the siderite of the veinlets. A few thin sections suggest replacement of chert by siderite. Although gradations from hematite ore into siderite have not been observed, such occurrences would probably be uncommon because oxidation is extensive in the iron formation in the vicinity of ore.

If the ore deposits have formed by the alteration of bodies of siderite, a reduction in volume or an increase in porosity might be expected, due to the loss of carbon dioxide. The preservation of textures and structures of the iron formation by the ore do not seem to indicate that a significant reduction in volume has occurred. The "pseudomorph bands" of the ore are usually not broken or collapsed, and the spacing between them does not appear different from the spacing of similar bands in adjacent iron formation. These bands should show evidence of collapse or should be pressed closer together if a decrease in volume has occurred, since the volume change would principally occur along the "replacement bands" of the ore. In ore which has replaced brecciated iron formation, relict breccia fragments remain sharply angular and show no evidence of compaction. Although vugs often occur at the boundary between ore and iron formation, they usually appear to have formed by the removal of chert from bands of the iron formation and not by compaction of ore.
If a decrease in volume has not occurred, an increase in porosity might be expected. Determinations of the specific gravity of ore show a consistently high density, usually between 4.8 and 5.1 gm./cc. Determinations of micro-porosity (pores less than 14 microns diameter) show less than 2% pore space and this is confirmed by the high density. The micro-porosity of iron formation either adjacent to ore or distant from ore appears to be no different from that found in the ore.

The high density, low porosity, and volume-for-volume replacement features shown by the ore do not seem to be compatible with an oxidized deposit of siderite. Although the gross shape of orebodies often suggests that a decrease in volume has occurred, there are also cases where the walls of a bed of iron formation remain nearly parallel even where the full width of the bed is occupied by ore. These examples, though few, support the volume-for-volume replacement relationship suggested in smaller specimens. Considering the variable structure of bodies of iron formation, it often seems likely that the narrowed structures occupied by ore are actual structural thinnings of the iron formation and are not caused by volume changes in the ore. These relationships suggest that the ore was formed as replacement deposits of hematite.

Addition of iron was necessary to form the replacement deposits. There is no evidence that the greenstone contributed a quantity of iron sufficient to form an orebody; on the other hand there are instances where the greenstone appears to have been enriched in iron adjacent to ore. The restriction of orebodies to the iron formation and to certain zones or structures within it
suggests that the iron-bearing material which formed the orebodies was not derived from an outside source but came from the iron formation itself.

The areas of ore occurrence are also zones of intense oxidation within the iron formation. The iron formation is more or less completely oxidized in the vicinity of the larger orebodies but tends to be less oxidized where the orebodies are small. This oxidation is almost completely restricted to the iron formation itself. The occurrence of "paint rock" or oxidized greenstone is not widespread and unoxidized chloritic schist is frequently in contact with ore. These features suggest that the ore forming process included oxidation as well as introduction of iron.

The orebodies often contain abundant chlorite (thuringite) and iron formation adjacent to ore often contains this mineral but it is not commonly found in iron formation away from ore. The chlorite is usually concentrated along the "replacement bands" of the ore where it is frequently intergrown with fine-grained hematite. Textural relationships between the chlorite and hematite suggest that the chlorite deposition followed the hematite very closely in time. The close spatial relationship of this hydrous iron-bearing mineral to the orebodies and its textural relationship with the hematite in the "replacement bands" suggests that it was a product of the same process which produced the ore. Since chlorite is a common alteration product of hydrothermal solutions its occurrence suggests that hydrothermal solutions produced the ore. The occurrence of quartz-chlorite-hematite veinlets in the iron formation near ore also suggests the occurrence of hydrothermal iron-bearing solutions.
The source of the introduced iron which produced the orebodies has not been determined. There are some sections of iron formation in the jaspilite which are well banded in contrast to the barren chert but contain little iron. These areas might be considered as sources of the iron which went to form the orebodies but the lack of porosity in these barren areas suggests that they have not been leached.

The recognized controls on the occurrence of ore must also have some genetic significance. The observed relationship of ore to intrusive contacts (see Figures 13 and 15) appears to be of importance in considering the genesis of these ores. The relationship illustrated in Figure 13 strongly suggests a genetic relationship between the intrusive stringers and the ore which occurs along their contacts. The width of ore along each stringer appears to be proportional to the width of the stringer and where the stringers pinch out the ore also pinches out. At points where the stringers converge the ore selvages also approach one another and finally appear to merge into a solid band of ore.

The positive relationship of ore occurrence to converging intrusive contacts as illustrated in Figure 13, may also apply on a much larger scale, to the occurrence of ore in narrowed or "pinched" structures in the iron formation. It is possible that many of the narrowed structures are the result of semi-concordant intrusives which separated the iron formation into a series of more or less disconnected lenses. If the ore is related to intrusive contacts, then the thinned portions of the lenses would be areas in which two intrusive contacts approach one another making them, from an empirical standpoint, the most favorable sites of deposition.
for the ore. While this would explain the localization of ore in thinned areas of iron formation the difficulty in distinguishing between intrusive and extrusive material in the Soudan area makes it impossible to evaluate this hypothesis.

Summary

The occurrence of textures in the ore which duplicate those in unenriched iron formation and the lack of slump structures or porosity strongly suggests a volume-for-volume type of replacement of iron formation by hematite as the origin of the Soudan ores. The relationship of orebodies to secondary structures such as intrusive contacts and dikes as well as the abrupt terminations of some of the orebodies indicate that the ore forming process took place after initial deposition of the iron formation. Hydrothermal solutions are suggested as the agency by which the ore was formed due to the occurrence of chlorite as disseminations and veinlets in the ore. The source of the iron which these solutions carried has not been recognized.

During this and previous studies of the Soudan area several controls on the occurrence of ore have been recognized. These include localization by jaspilite host rock, intrusive contacts, structural thinnings and to a minor extent faulting and brecciation. Although these features are considered significant the actual occurrence of ore in some areas where these controls have not been observed suggests that other unrecognized controls probably exist. Future work in this area may establish these controls and their recognition may have an important bearing on the origin of these ores.
SUMMARY OF CONCLUSIONS

1. The greenstone of the Soudan area is chemically and lithologically different from the greenstone commonly found in the Vermilion district. The principal differences are: 1) the wide range in composition of the rocks at Soudan as compared to the uniform composition of the Ely greenstone; 2) the deficiency in lime of basic varieties of greenstone at Soudan, as compared to the normally basaltic composition of the Ely greenstone; and 3) the heterogeneous assemblage of volcanic flows, tuffs, intrusives, and clastic sediments of acid to basic composition in the greenstone at Soudan, as compared to the usual basic lava of the Ely greenstone.

The many primary textures and structures which are preserved in the greenstone indicate that the rocks have not been extensively sheared although the greenstone was supposedly deformed by two major orogenies.

A zone of siliceous and sericitic schists commonly separates the iron formation from greenstone of basic composition. These schists are largely derived from fragmental rocks and sediments, and they probably were formed during a period of clastic sedimentation which preceded deposition of the iron formation.

2. The inclusion of granitic pebbles in a fragmental rock of the greenstone indicates that the greenstone partially consists of clastic material derived from an older granitic terrane. The abundance of quartz and sericite in sedimentary
beds of the greenstone may also be related to this source. The presence of granitic rocks older than the greenstone has not previously been recognized in Minnesota.

3. The iron formation shows regular variations in iron content, internal structure, and size of depositional units. These variations can be mapped, with the barren chert representing the lowest iron content, least regularity of internal structure, and smallest depositional unit, and the jaspilite representing the maximum development of these features. The lithologic varieties appear in a consistent sequence as vertical and lateral facies changes. This indicates that changes in sedimentary conditions were orderly, and that the changes were related to both time and space during the period of sedimentation. In the iron formation at Soudan the principal sequence of change is in the direction of time, and the sequence of deposition in the iron formation is visualized as beginning with chert and ending jaspilite. The primary sediment probably consisted of iron carbonate and silica with subsequent alteration of the carbonate to iron oxides.

4. The iron formation occurs as a series of complex elongate folds developed in a single belt of iron formation. This structure is difficult to reconcile with the apparent lack of folding in the greenstone and suggests that many of the structural relationships between iron formation and greenstone are of primary origin. Extreme distortion of the iron formation is due to its deformation as a plastic material.
5. Structural relationships between the greenstone of the Soudan area and a belt of sedimentary rocks to the south indicate that the sediments are the older rocks and conformably underlie the greenstone. No sediments older than the Ely greenstone are recognized by the Minnesota Geology Survey, and this belt of sediments has previously been correlated with the Knife Lake group.

In interpreting this relationship, there are two alternatives: 1) if the greenstone at Soudan correlates with the Ely greenstone, then sediments older than Ely greenstone are present; 2) if the sediments correlate with the Knife Lake group, then the greenstone and iron formation at Soudan are intercalated with the Knife Lake sediments. Either case would require a revision of the Earlier Precambrian stratigraphic column.

6. The ore deposits occur as secondary replacement deposits of hematite within the iron formation. The hypothesis that the deposits represent oxidized siderite bodies is not sufficiently supported by the evidence of volume relationships between the ore and the iron formation. The occurrence of ore is localized by jaspilite, intrusive contacts, structural thinnings in the iron formation, and to a minor extent by faulting and brecciation.
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TITLE OF THESIS

Full Name

Place and Date of Birth

Elementary and Secondary Education

Colleges and Universities: Years attended and degrees

Membership in Learned or Honorary Societies

Publications

Major Department

Minor(s)

Date Signed

Professor in charge of thesis