

Institute on Lake Superior Geology

April 1-2, 1955

UNIVERSITY OF MINNESOTA
CENTER FOR CONTINUATION STUDY
MINNEAPOLIS 14

INSTITUTE ON LAKE SUPERIOR GEOLOGY

April 1 - 2, 1955

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Institute on Lake Superior Geology

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PROGRAM

Friday - April 1, 1955

8:45 a. m. Auditorium, Museum of Natural History

Carl E. Dutton, Chairman

U. S. Geological Survey, Madison, Wisconsin

Welcome: F. E. Berger, Director, Center for Continuation Study
J. M. Nolte, Dean of University Extension
G. A. Thiel, Chairman, Department of Geology and Mineralogy

1. 9:00 Harold L. James: Sedimentary facies of iron-formation
10:00 Intermission (Please, no smoking in auditorium)
2. 10:10 David White: Origin of the Biwabik iron-formation, Mesabi Range, Minnesota
11:10 Discussion
12:00 Luncheon
3. 1:30 Burton Boyum, Gerald J. Anderson, and Tsu-Ming Han:
Progress report on the primary features of the Negaunee iron-formation, Marquette district, Michigan
2:30 Discussion
3:00 Intermission
4. 3:10 Stanley Tyler: On the origin of the Lake Superior iron ores
4:10 Discussion

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Friday - April 1, 1955

6:30 p.m. Junior Ballroom, Coffman Memorial Union

Dinner

Welcome: G. M. Schwartz, Professor of Geology and Director, Minnesota
Geological Survey

GEOPHYSICS IN THE LAKE SUPERIOR REGION

Gordon Bath, Chairman
U. S. Geological Survey

8:00 Charles E. Jahren: Some magnetic susceptibility measurements
on diamond drill cores from the Cuyuna district

8:15 Edward Thiel: A gravity study of the Lake Superior syncline

8:30 Panel Discussion:

James Balsley, Chief, Geophysical Branch, U. S. Geological
Survey, Washington, D.C.; Harold Mooney, Assistant Professor
of Geophysics, University of Minnesota; George Woollard,
Professor of Geophysics, University of Wisconsin;
Lloyal O. Bacon, Assistant Professor of Geophysics, Michigan
Institute of Mining and Technology, Houghton, Michigan; and
others.

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Saturday Morning - April 2, 1955

9:00 a.m. Auditorium, Museum of Natural History

Carl E. Dutton and S. S. Goldich, Co-Chairmen

(10-15 minutes are allowed for presentation; 5 minutes for discussion)

1. Robert G. Schmidt: Stratigraphy in the central part of the Cuyuna district, Minnesota
2. Justin Zinn, Gerald L. Brooke, Theodore Engel, and Richard Hagni: Studies of stratified rocks occurring below the Huronian succession in the Marquette district, Michigan
3. J. F. Wolff, Sr.: Summary of the sub-divisional correlation of the Middle Huronian iron formations of the Lake Superior district
4. N. King Huber: Environmental control of sedimentary iron minerals
5. Henry Lepp: Magnetite, maghemite, hematite
6. L. C. Kilburn and H.D.B. Wilson: Pyrrhotite iron formations
7. Alan T. Broderick: Some notes on the occurrence of oxidation and soft iron orebodies at considerable depth in the Iron River district, Michigan
8. Howard Evans: Color photographic record of drill core
9. Joseph P. Dobell: Sandstone dikes in Keweenawan lavas
10. J. E. Dryden: A near surface crystalline mass at Manson, Iowa

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Saturday Afternoon - April 2, 1955

1:00 p.m. Auditorium, Museum of Natural History

Carl E. Dutton and S. S. Goldich, Co-Chairmen

1. James W. Trow: Megascopic petrofabrics used in deciphering structure
2. J. M. Neilson and J. P. Dobell: Keweenawan felsites of the Bete Grise Bay area
3. F. M. Swain and N. Prokopovitch: Stratigraphy of Minnesota lake deposits
4. James H. Zumberge: Bottom coring in Lake Superior
5. Gerald M. Friedman: Progress report on the Mamainse "Diabase," Batchawana, Ontario
6. Gerald E. Anderson: The ore minerals of the copper-nickel deposits in the Duluth gabbro
7. Donald H. Yardley: Geochemical exploration for nickel and copper in northern Minnesota
8. M. P. Walle: The work of the Hibbing laboratory of the Division of Land and Minerals

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THE ORE MINERALS OF THE COPPER-NICKEL DEPOSITS IN THE DULUTH GABBRO

Gerald E. Anderson

University of Minnesota, Minneapolis, Minnesota

The discovery in 1948 of appreciable amounts of copper and nickel sulfides near the base of the Duluth gabbro south of Ely, Minnesota, has stimulated field exploration and laboratory studies. The present work on the mineralogy of the sulfide mineralization is being done under the auspices of the Minnesota Geological Survey with the aid of a fellowship sponsored by the E. J. Longyear Company.

The principal mineralization discovered to date is restricted to a narrow band in the gabbro near the base. Definite paragenetic relationships have been determined between the rock silicates, the magnetite, and the sulfides, which in order of abundance are chalcopyrite, pyrrhotite, cubanite, pentlandite, violarite, and pyrite-marcasite. There appear to be two general types of sulfide assemblages. In some specimens relatively massive copper sulfides predominate, whereas in others, pyrrhotite and pentlandite are more abundant and interstitial to the silicates.

The copper-nickel mineralization is characteristic of most, if not all, large differentiated gabbroic intrusions. Brief consideration is given to some hypotheses to explain the origin of the deposits.

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PROGRESS REPORT ON THE PRIMARY FEATURES
OF THE NEGAUNEE IRON-FORMATION,
MARQUETTE DISTRICT, MICHIGAN

Burton H. Boyum, Gerald J. Anderson, and Tsu-Ming Han

The Cleveland-Cliffs Iron Company, Ishpeming, Michigan

A progress summary is presented describing the primary features of the Negaunee iron-formation of the Marquette District, Michigan. The Negaunee iron-formation is distinctive because of its thickness and uniformity and may be considered as being a single unit, by contrast with other major iron-formations of the Lake Superior region in which two to four members are recognized. The general setting and the position in the Huronian section are outlined. Nomenclature and historical highlights are reviewed. The subject of total thickness is developed.

A specific description of the Negaunee iron-formation is detailed. The lower contact with the Siamo formation is examined relative to the "interbedded argillaceous complex". Clastic phases are shown, together with oolitic zones. Attention is given to the igneous rocks found in the Negaunee iron-formation. Special studies using spectrographic analyses and oil field electric logging are presented. The conclusion is reached that the primary Negaunee formation is remarkably uniform and that local primary features cannot be used as horizon markers for great distances, as these features seldom extend more than one-half to one mile along the strike or dip.

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SOME NOTES ON THE OCCURRENCE OF OXIDATION AND SOFT IRON OREBODIES
AT CONSIDERABLE DEPTH IN THE IRON RIVER DISTRICT, MICHIGAN

Alan T. Broderick

Inland Steel Company, Ishpeming, Michigan

The earthy to massive hematite-goethite-limonite orebodies in the Iron River District occur in the oxidized portions of a practically unmetamorphosed chert-siderite iron formation.

In the writer's opinion, the structural and mineralogic evidence supports the classic theory of origin of these deposits, i.e. that they are the result of the oxidation of siderite, the transportation and deposition of iron and the removal of silica by circulating oxygen-bearing meteoric waters.

There is considerable evidence that the replacement of chert by iron oxides and not the leaching of chert is the major ore-forming process.

The circulation has been long held to be artesian. However, since ore has now been found at about 2000 feet vertically below ledge and through oxidation down to nearly 3000 feet, topographic and structural arrangements which could have afforded the necessary hydraulic head have become increasingly improbable.

The writer proposes that heat introduced along the major faults as hot water or steam provided the energy which caused the circulation. The heavy cool column of meteoric water in a limb of iron formation cut at depth by one of these warm channels would tend to move downward in the formation and then rise in the heated channel. Once established, such a circulation might be supported by heat from the wall-rocks if the geothermal gradient were steep enough. Laboratory experiments on the solubility of silica suggest that the silica-bearing solutions must have been warm.

The tendency of many of the orebodies to lie on structural footwalls of either older or younger rocks indicates that another gravity-controlled mechanism must also have been operative. The writer believes that this is simply that the solutions richest in iron, those which would be the most active in replacing the chert, would also be the heaviest and therefore would follow the bottom of any channel and displace any lighter solutions. This density current principle alone might be the circulation-causing force in shallow structures or in cul-de-sac areas lying below the main thermally-stimulated circulation channels.

In some of the Iron River mines, there is evidence of a post-oxidation period of mineralization that is quite distinct from the original ore-forming period. In these areas, irregular mineralized zones occur which cross the normal orebodies. These zones contain specularite, barite, rhodochrosite, quartz, pyrite, hausmanite, magnetite, and traces of chalcopyrite, sphalerite, and pitchblende. These may be the result of a late resurgence of hydrothermal fluid from the same source as that which stimulated the deep meteoric circulation, or it could be a later, completely independent invasion from a new source. Radioactive age determination on traces of pitchblende indicate the latter.

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SANDSTONE DIKES IN KEWEENAWAN LAVAS

Joseph P. Dobell

Michigan College of Mining and Technology
Houghton, Michigan

Sandstone dikes occur in a Keweenawan flow which crops out at Bete Grise Bay on the east side of the Keweenaw Peninsula of Upper Michigan. Three parallel dikes fifteen feet apart were noted. The thickness ranges from an inch to eight inches and the length is from seven to eight hundred feet. Two of the dikes are a few feet beneath the surface of Lake Superior and the third occurs just above the waterline.

The clastic material was injected or wind blown into open fractures which parallel the Keweenaw fault. The dikes are megascopically and mineralogically similar to the Upper Cambrian Jacobsville sandstone.

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A NEAR SURFACE CRYSTALLINE MASS AT MANSON, IOWA

J. E. Dryden

Department of Geology, State University of Iowa, Iowa City, Iowa

A near-surface occurrence of crystalline rock has been discovered at Manson, Iowa, 17 miles west of Fort Dodge, Iowa. Water well records indicate that it is a flat-topped elliptical mass with an area of approximately $1\frac{1}{2}$ square miles. It has steeply dipping sides and rises to within 90 feet of the surface under a cover of glacial drift. The mass is surrounded by a disturbed area measuring 15 miles by 24 miles.

The rock has been cored to a depth of 490 feet. Megascopically, the core is composed of irregularly alternating light gray gneiss, coarse pink and white feldspar, chloritized breccia and chlorite schist with magnetite. A study of selected thin sections suggests an original syenite gneiss extensively replaced by albite and orthoclase. The entire rock is altered to kaolinite and brecciated zones are altered to chlorite.

The lithology suggests that the mass is of pre-Cambrian age. The disturbed area contains sediments reported to be Cretaceous in age.

A cross section of the area reveals evidence of faulting, but the relationship of the faults to the crystalline structure has not been established at this time.

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COLOR PHOTOGRAPHIC RECORD OF DRILL CORE

Howard Evans

Oliver Iron Mining, Research Laboratory, Duluth, Minnesota

The usual method of retaining one-half the drill core for permanent visual record has been supplanted by a color photographic record. The colored photographs, supplemented by the core logs have been found adequate for subsequent reference. This was done to dispense with the labor of splitting the core, to overcome the problem of large storage space and to permit all the core to be available for testing purposes. The original cost of the equipment and the continuous cost of maintaining the program may seem high, but it is only about one-third the cost of splitting and storing core. At the present time, the photographs from over 300,000 feet of drilling are filed in a space approximately 2' x 4' x 4'. If this record had been kept as split core it would have occupied a building 100' x 120' x 10' high, and this space would allow very little room to work. If storage area is limited some of the core eventually will have to be discarded to make room for new core arriving. With the colored photographic record of the drill core, the filing can continue indefinitely without running out of space. It is also more convenient, when there is a desire to review the core from a drill hole, to be able to quickly select the slide from the file, rather than carry on an extended search for it in a storage house and transport it to the examination site.

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PROGRESS REPORT ON THE MAMAINSE "DIABASE",
BATCHAWANA, ONTARIO.

Gerald M. Friedman

Sault Ste. Marie, Ontario, Canada

The Mamainse "Diabase" is located about 38 miles north of Sault Ste. Marie in the District of Algoma within about six miles of the east shore of Lake Superior. The area is one of the most rugged in Ontario. The Mamainse "Diabase" forms a high plateau with an average elevation of about 1600 to 1800 feet and is intersected by deep fault- and joint-controlled valleys. The Griffin Lake diabase intrusion, which post-dates the Mamainse "Diabase", underlies an area of at least three square miles at the eastern margin of the Mamainse "Diabase" and rises to an elevation of 2100 feet towering about 1400 feet above Lake Superior.

The Mamainse "Diabase" is a metadiabase and metabasalt composed of plagioclase (An_{65-70}) and hornblende with locally abundant epidote and chlorite. Its texture ranges from ophitic and poikilophitic to basaltic; metabasalts of porphyritic texture were noted but are rare. Pillow structures suggest deposition in a submarine environment.

A complex series of metamorphosed lavas and sediments, and siliceous iron ore is interbedded with the Mamainse "Diabase" near its northern and southern margins. This complex sequence was overlain by the main mass of the Mamainse "Diabase" prior to folding. The rocks maintain a general east-west to $N 60^{\circ}E$ strike and have a steep dip. Granite dikes locally cut up the "diabase" and interbedded formations and are in turn cut by later diabase dikes which are probably equivalent to Moore's Lower Keweenaw. Faults and joints of several generations are prominent and are locally mineralized with cobaltite, chalcopyrite, pyrite, pyrrhotite, molybdenite, carbonate and quartz veins.

The Griffin Lake diabase intrusion is mostly composed of plagioclase (An_{50-62}) and subcalcic augite ($2V = 35-44^{\circ}$). Quartz and micropegmatite are abundantly disseminated through the rocks, secondary hornblende is locally prominent and epidote has been noted.

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ENVIRONMENTAL CONTROL OF SEDIMENTARY IRON MINERALS

N. King Huber

U. S. Geological Survey, Iron Mountain, Michigan

A recently developed Eh-pH (Eh = oxidation potential) iron mineral stability diagram for hematite, siderite and pyrite has been extended to include magnetite through the utilization of free energy data for these minerals in addition to the solubility data previously used. Physical-chemical data supports the probability of primary (or diagenetic) magnetite in sedimentary iron-formations as suggested by field evidence.

The chemical environments, as indicated by the Eh-pH stability diagram are summarized as follows:

Hematite: Requires oxidizing environment, although stable under moderately reducing conditions above pH of approximately 5.

Siderite: Stable under intermediate Eh conditions, and apparently only below pH of approximately 6.5.

Magnetite: Stable under moderately reducing conditions at pH values of approximately 6 or above.

Pyrite: Moderate to strongly reducing environment through normal pH range.

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SOME MAGNETIC SUSCEPTIBILITY MEASUREMENTS ON
DIAMOND DRILL CORES FROM THE CUYUNA DISTRICT

Charles E. Jahren

U. S. Geological Survey, Austin Junior College, Austin, Minnesota

Measurements of magnetic susceptibility of 57 cores from diamond drilling in the Cuyuna District were made as part of a geophysical study by the U. S. Geological Survey and the Minnesota Geological Survey. Values of susceptibility are calculated from the readings of an alternating current deviation test bridge, slightly modified from commercial design, and the calculated values are tabulated against footage and generalized geologic logs. Susceptibilities of cores with similar values are averaged where this seems feasible. The problems of interpreting scattered readings from adjacent core samples, the effects of varying core recovery, and the comparison of values from oxidized and unoxidized core are discussed.

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SEDIMENTARY FACIES OF IRON-FORMATION

Harold L. James

U. S. Geological Survey, Menlo Park, California

The sedimentary iron-formations in the Lake Superior region can be divided on the basis of the dominant original iron mineral into four principal facies: sulfide, carbonate, oxide, and silicate. As chemical sediments, these rocks reflect certain aspects of the chemistry of the depositional environments. The major control, at least for the sulfide, carbonate, and oxide types, was the oxidation potential. The evidence indicates that deposition took place in restricted basins, which were separated from the open sea by thresholds that inhibited free circulation and permitted development of abnormalities in oxidation potential and water composition.

The sporadic distribution of metamorphism and of later oxidation permits description of the primary facies on the basis of unoxidized, essentially unmetamorphosed material. The sulfide facies is represented by black slates in which pyrite may make up as much as 40 percent of the rock. The free-carbon content of these rocks typically ranges from 5 to 15 percent, indicating that ultra-stagnant conditions prevailed during deposition. Locally, the pyritic rocks contain layers of iron-rich carbonate. The carbonate facies consists, in its purer form, of interbedded iron-rich carbonate and chert. It is a product of an environment in which oxygen concentration was sufficiently high to destroy most of the organic material but not high enough to permit formation of ferric compounds. The oxide facies is found as two principal types, one characterized by magnetite and the other by hematite. Both minerals appear to be of primary origin. The magnetite-banded rock is one of the dominant lithologies in the region; it consists typically of magnetite interlayered with chert, carbonate, or iron silicate, or combinations of the three. Its mineralogy and association suggest origin under weakly oxidizing to moderately reducing conditions. The hematite-banded rocks consist of finely crystalline hematite interlayered with chert or jasper. Oolitic structure is common. This facies doubtless accumulated in a strongly oxidizing, probably nearshore, environment similar to that in which younger hematitic ironstones such as the Clinton oolite were deposited. The silicate facies contains one or more of the hydrous ferrous silicates (greenalite, minnesotite, stilpnomelane, chlorite) as a major constituent. Granule structure, similar to that of glauconite, is typical of some varieties; others are nongranular and finely laminated. The most common association of the silicate rocks is with either carbonate- or magnetite-bearing rocks, which suggests that the optimum conditions for deposition ranged from slightly oxidizing to slightly reducing. All of these rocks show evidence of post-deposition, pre-lithification changes (diagenesis), which in general have produced minerals characteristic of one step lower in the oxidation-potential scheme.

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Harold L. James

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The generalized facies characteristics of the iron-formations in the principal Lake Superior districts are summarized as follows:

1. Mesabi. Most of the Biwabik iron-formation is of the oxide facies, principally magnetite-banded, with a large amount of granular silicate rock. White's study has shown that the oxide-silicate rocks of the main Mesabi grade westward into carbonate and sulfide facies.

2. Cuyuna. Principally silicate and carbonate rocks, verging toward the sulfide facies (which accounts for the high-phos, high manganese ores).

3. Gogebic. Similar to the Mesabi, with magnetite-banded oxide facies and silicate facies predominant. Magnetite-banded rock grades locally into carbonate iron-formation, but much of the carbonate in the rocks can be shown to be the result of diagenesis.

4. Marquette. Lower part of the Negaunee iron-formation is carbonate facies, which grades upward into silicate facies and that in turn to rock of the oxide facies that forms the uppermost part of the formation.

5. Menominee. The Vulcan iron-formation is almost entirely of the oxide facies; the lower member appears to be principally magnetite-banded rock; the upper member is principally hematite-banded rock.

6. Iron River-Crystall Falls district. The main iron-formation is carbonate facies, which is underlain by and gradational into a 50-foot black slate bed that contains 35-40 percent pyrite.

The relationship between the iron-rich rocks and volcanism, stressed by many, is believed to be structural, not chemical: in the Lake Superior region both iron-deposition and volcanism are related to geosynclinal development during Huronian time. In Michigan, the lower Huronian rocks are iron-poor quartzite and dolomite--typical "stable-shelf" deposits; most of the upper Huronian consists of iron-poor graywacke and slate with associated volcanic rocks--a typical "geosynclinal" assemblage. Thus the iron-rich beds of the middle Huronian and lower part of the upper Huronian were deposited during a transitional stage in structural history. The major environmental requirement for deposition of iron-formation is the closed or restricted basin; this requirement coincides in time with what would be a normal stage in evolution of the geosyncline: namely, structural development of offshore buckles or swells that subsequently develop into island arcs characterized by volcanism.

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PYRRHOTITE IRON FORMATIONS

L. C. Kilburn and H. D. B. Wilson

University of Manitoba, Winnipeg, Canada

Large numbers of pyrrhotite iron formations are being discovered in the Canadian shield by airborne magnetic and electromagnetic surveys. One common type of pyrrhotite iron formation consists of banded pyrrhotite-magnetite mixtures in banded cherts and tuffs. These deposits like many other types of pyrrhotite deposit are barren of other base metal mineralization.

Laboratory experiments show that H_2S reacts with magnetite and converts it to pyrrhotite at temperatures as low as $400^\circ C$. Iron silicates are converted in part to pyrrhotite at somewhat higher temperatures.

It is proposed that this type of banded pyrrhotite-magnetite deposit is a normal cherty iron formation which has been metamorphosed by heat and reaction with a sulphur-bearing gas, possibly H_2S , to produce pyrrhotite from some of the magnetite and possibly from some of the iron-bearing silicates.

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MAGNETITE, MAGHEMITE, HEMATITE

Henry Lepp

University of Minnesota, Duluth Branch, Duluth, Minnesota

Differential thermal analyses of magnetite specimens show that magnetite goes through two stages of oxidation when heated in air. The first stage occurs at temperatures between 200 and 560° C, and its intensity is related to the fineness of the specimen. The second stage begins at approximately 565° C and it is often not complete even at 1050° C.

It is suggested that the first stage is a surface phenomena involving the formation of maghemite ($\gamma \text{Fe}_2\text{O}_3$) on the magnetite nuclei. The amount of maghemite formed is a function of the specific surface of the specimen, and of the speed of oxidation. The second stage results from a complete breakdown of the magnetite structure with oxidation to hematite ($\alpha \text{Fe}_2\text{O}_3$).

The behavior of synthetic siderite with respect to oxidation supports the foregoing explanation for the mechanism of magnetite oxidation. Siderite is commonly first oxidized to magnetite. Rapid oxidation of synthetic siderite at moderate temperatures produces $\gamma \text{Fe}_2\text{O}_3$ as an end product, whereas slow oxidation of the same material results in the formation of $\alpha\text{-Fe}_2\text{O}_3$.

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KEWEENAWAN FELSITES OF THE BETE GRISE BAY AREA

J. M. Neilson and J. P. Dobell

Michigan College of Mining and Technology, Houghton, Michigan

Recent field and laboratory studies have been undertaken at the Michigan College of Mining and Technology in an effort to determine the origin of certain felsite masses in the Bete Grise Bay area of the Keweenaw Peninsula. The felsite masses occur in the Keweenawan series of interbedded lava flows and conglomerates. Earlier workers mapped the felsite occurrences and suggested intrusive relationships for some bodies and extrusive relationships for others. Results of the present work indicate that the felsites are rhyolitic differentiates of a magma which provided the chemically-related lavas of the region, and that some felsite masses bear intrusive relations to the older rocks while others were extruded as highly viscous flows. Criteria are presented for the field recognition of both types of felsitic occurrence.

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STRATIGRAPHY IN THE CENTRAL PART OF
THE CUYUNA DISTRICT, MINNESOTA

Robert G. Schmidt

U. S. Geological Survey, Washington, D. C.

[The stratigraphy of the Cuyuna district has been shown to be much simpler than was previously believed. Almost all of the iron ore and manganese iron ore produced in the district is mined from one well-defined stratigraphic unit, here referred to as the "main" iron-formation. Other sediments may be roughly grouped as older or younger than the main iron-formation, and the stratigraphic positions of the other rocks are usually measured from it.

The clastic sediments are dominated by argillites and siltstones. Part of the argillites older than the main iron-formation are sandy or silty, and there are lenses of quartzite near the contact with the iron-formation. Between 1,000 and about 2,000 feet stratigraphically below the iron-formation fine quartz siltstones are abundant. These siltstones are the oldest rocks that have been examined in this study.

The main iron-formation is the best-known stratigraphic unit in the district. Its lithologic variations are similar to some "typical" pre-Cambrian iron-formations in other districts. Extensive changes in lithology and thickness take place in short distances along the strike.

Two general lithologic types have been recognized and mapped. The thin-bedded facies is a thinly laminated rock, which may contain any combination of chert, siderite, minnesotaite, stilpnomelane, and magnetite. The thick-bedded facies is composed of chert and red and brown iron oxides. In part of the district, the entire iron-formation is thick-bedded, in part it is all thin-bedded, and in about one third of the area the thick-bedded facies overlaps the thin-bedded facies and grades downward into it. Several lines of evidence suggest--but do not prove--that the thick-bedded facies was deposited in shallower water. In general, where the iron-formation is thin, the thick-bedded facies is present or dominates, granular textures may be present, and there are quartzite lenses in the adjacent older sediments.

The younger sediments are generally finer clastics, partly ferruginous and partly carbonaceous. Tuffaceous argillites, tuffs, and lava flows make up the 300 feet immediately overlying the main iron-formation.] The volcanic rocks and some associated argillites, which are assumed to be reworked tuffs, are characterized by an unusually high TiO_2 content, generally $1\frac{1}{2}$ to 4 percent and averaging about 2 percent. This titaniferous zone can be easily mapped even where the stratigraphic position of sediments cannot be determined by other means. It is therefore useful in the solution of stratigraphic problems.

[Part of the younger argillites is abnormally ferruginous and locally grades into lenses of lean "upper" iron-formation. The relation of these lenses to a particular stratigraphic horizon is not known, but it is probable that they are not all of the same age. They have not been found closer to the main iron-formation than 500 feet. The transitional contacts of these lenses contrast with the sharp contacts of the main iron-formation.]

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STRATIGRAPHY OF MINNESOTA LAKE DEPOSITS

F. M. Swain and N. Prokopovich

University of Minnesota, Minneapolis, Minnesota

Samples of the bottom sediments of several lakes in Minnesota have been studied. The lakes include Minnetonka, Hennepin County; Prior, Scott County; Johanna, Ramsey County; Cedar, Wright County; Burntside, St. Louis County; and Beaver Bay area, Lake Superior. A preliminary report of the results of these studies will be presented.

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A GRAVITY STUDY OF THE LAKE SUPERIOR SYNCLINE

Edward Thiel

University of Wisconsin, Madison, Wisconsin

Six years ago the Geophysics Section at Wisconsin began a program of regional gravitational mapping in the western United States and Alaska. The first traverses leading westward from Madison across the northern mid-continent in 1949 detected regions of abnormally high gravity. In some cases this "high" was flanked on both sides by gravity "lows". As the data accumulated it became evident that the anomalous area formed a more or less linear feature, offset in several places, extending from the Lake Superior region southward into Kansas. On the south, the anomalous area was blanketed by Paleozoic sediments, and the scarcity of deep boreholes made interpretation difficult. Therefore, the cause of the anomaly was sought first at its northern end, about Lake Superior, where the pre-Cambrian rocks outcrop, facilitating a correlation of gravity and geology.

In the Lake Superior area the large regional anomaly is associated with rocks of Keweenaw age. Positive Bouguer anomalies occur over the dense lava flows of the Keweenaw Peninsula, northwestern Wisconsin, northeastern Minnesota, and Isle Royal; these anomalies reach +60 mgals in Wisconsin and Minnesota. The gravity "lows" occur over basins filled with low density sediments of Upper Keweenaw age; the most striking example is the -90 mgal low on the Bayfield Peninsula. A second thick accumulation of sedimentary rocks is suggested to underlie the -90 mgal low at Cumberland. The structure exhibited by the Paleozoic rocks (River Falls Syncline) in the Cumberland region may represent only the last stage in the development of the more fundamental Keweenaw structure at depth.

Steep gravity gradients indicate the Douglas Fault. A second major fault symmetric to the Douglas Fault is mapped in northwestern Wisconsin on the opposite side of the Lake Superior Syncline. The center of the syncline has been thrust upward between the two faults as a horst. The interruption of the positive anomaly near Mellon is related to the intrusion of a granitic mass. Further detailed geologic correlation is presented in six structure sections along lines of gravity traverse.

An isostatic correction cannot significantly reduce the gravity differentials in the Lake Superior region. Complete local isostasy cannot exist here, but regional isostasy which considers the "highs" and "lows" together may prevail. A "geological correction" which takes account of geology to a radius of 20 miles from a station and to a depth of 38,000 feet was computed for gravity stations in Wisconsin. Such a correction accounts for the greater part of the anomalies. Any attempt to compute variations in the thickness of crustal layers without first allowing for the near-surface geology would have led to serious error in this region.

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MEGASCOPIC PETROFABRICS USED IN DECIPHERING STRUCTURE

James W. Trow

U. S. Geological Survey, Michigan State College, East Lansing, Michigan

Megascopic rock fabrics are integrated with lithology, gross structure, and microscopic petrofabrics in an outline of the sequence of orogenic events of late Huronian time in a part of Dickinson County, Michigan. The fabrics of these Huronian and pre-Huronian rocks are compared to the fabrics of a somewhat similar lithologic sequence of Cambro-Ordovician and pre-Cambrian rocks of Dutchess County, New York, described in detail in the literature by Robert Balk, and briefly examined by the author of the present paper.

Statistical equal-area diagrams of rock fabrics support the conclusions that the rocks of the Dickinson County area experienced 1) late-Huronian deformation within the pattern determined largely by the anisotropism of the pre-Huronian rocks, 2) strong strike-slip movement contemporaneous to and following dip-slip underthrusting and ramping, 3) deformation in some instances facilitated by the development of slip cleavage parallel to bedding and gneissic foliation, and 4) metamorphism of basic intrusives during the waning stages of the orogeny.

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ON THE ORIGIN OF THE LAKE SUPERIOR IRON ORES

Stanley A. Tyler

University of Wisconsin, Madison, Wisconsin

The origin of the Lake Superior iron ores has intrigued geologists for the past one hundred years. Concepts pertaining to ore genesis advanced by Foster and Whitney, Whittlesey, Lapham, Brooks, Irving and Van Hise, Van Hise and Leith, Gruner and Tyler are briefly summarized as a basis for discussion

Although many diverse opinions have been expressed regarding the origin of the ores there seems to be more or less general agreement among the more recent workers upon the following points:

1. The iron formations of the Lake Superior region were originally composed dominantly of silica, with important but subordinate quantities of iron carbonate, iron silicate, iron oxide and iron sulphide.

2. The iron ore is largely a residual product formed by alkaline oxygen-bearing solutions which oxidized the ferrous minerals to the ferric state and removed the silica in solution.

3. Migration of iron and replacement has played an important part in the development of some - perhaps many - ore bodies.

4. Fractures, faults, joints, breccia zones, bedding planes, dikes, sills and impervious sedimentary horizons have exerted a marked control upon the path that the ore forming solutions took through the iron formation.

5. The period of ore formation was largely if not entirely restricted to the pre-Cambrian.

In contrast, general lack of agreement, diverse opinions and some controversy has centered around the following points:

1. Whether the solutions that oxidized the iron and leached the silica were rising hydrothermal waters or cold descending meteoric waters.

2. Whether the silica that was leached from the iron formation during the process of ore formation was largely in the form of chert (quartz) or largely in the form of iron silicates such as minnesotaite, stilpnomelane, chlorite and grunerite.

Emphasis placed upon hot waters, alkaline waters or a silicate facies of the iron formation as necessary requisites for ore formation calls for the most optimum conditions for ore formation. Since the time factor is unknown it seems more probable that the ores may have developed rather slowly under less optimum conditions. Mineralogical and chemical evidence is cited to substantiate the concept that both acid and alkaline solutions have passed through some of the iron ore bodies of the Lake Superior region.

The iron formation is considered to be a peculiar sedimentary rock which is sensitive to the presence of oxygen and to the loss of silica. This concept leads to the conclusion that the ores may have formed at different times under differing sets of environmental conditions.

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THE WORK OF THE HIBBING LABORATORY OF THE
DIVISION OF LAND AND MINERALS

M. P. Walle

Division of Land and Minerals, Department of Conservation, Hibbing,
Minnesota

Following is a list of the more important activities:

1. Geophysical work in connection with state-owned properties, or along public roads to check possibilities for ore or rock materials, largely magnetic and resistivity surveys. Of special importance are areas south of the iron formation involving Cretaceous ore possibilities, for example in the region between Buhl and Kinney. Resistivity tests are useful west of Bovey where the magnetic survey does not help, because of the non-magnetic character of the iron formation.
2. Exploration work on state permits and leases. This includes visual classification for separating the formation into its four main divisions and for sorting of ore materials into merchantable ore, wash ore, jig ore, and magnetic and non-magnetic taconite. Stratigraphic work in the mines is also carried out.
3. An important service is supplying information on drill records and access to drill cores of work done on state lands. The sample library at Hibbing supplements the U. S. Bureau of Mines core library at Fort Snelling.
4. Development of a circuit on the Dings-Davis magnetic separator permitting separation of samples into high-grade concentrates, magnetic middlings, and non-magnetic tailings. This separation facilitates microscopic and spectrographic examinations.
5. Ground mapping of certain areas of state-owned land where anomalies are shown by aerial magnetic surveys.
6. Study of the Duluth gabbro contact areas of interest for copper, nickel, and other metals.
7. Cooperation with various organizations in the preparation of symposiums on mining and geology.

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ORIGIN OF THE BIWABIK IRON-FORMATION,
MESABI RANGE, MINNESOTA

D. A. White

Carter Oil Company, Tulsa, Oklahoma

The later Precambrian Animikie group in northeastern Minnesota consists of three sedimentary units: the Pokegama (quartzite), Biwabik (iron-rich rock), and Virginia (argillite) formations. "Mesabi range" designates the preglacial outcrop belt, $\frac{1}{4}$ to 3 miles wide and 120 miles long, of the Biwabik formation.

Varieties of iron-rich rock ("taconite") are either granular or slaty and consist dominantly of chert, iron silicates, magnetite, and siderite.

The Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty members of the Biwabik formation, which averages 600 feet in thickness, can be further subdivided into smaller lithic units. These members are relatively uniform along most of the range, but only one cherty and one slaty member exist on the Westernmost Mesabi, where the lithic units are intertongued. The Pokegama, Biwabik, and Virginia formations are considered conformable.

Chert, greenalite, minnesotaite, stilpnomelane, magnetite, some hematite, and siderite probably formed either during or shortly after deposition. The rocks are essentially unmetamorphosed.

The Pokegama and Biwabik formations were probably produced by the migration of a series of coexisting environments of deposition during an advance, a retreat, and a second advance of the Animikie sea. The deposits formed, during the retreat, in successive environments seaward from shore, were clastic material, carbonaceous-pyritic mud, chert-siderite, chert-magnetite, and iron silicate. Fine clastics of the Virginia formation, perhaps furnished by an outburst of volcanic activity, spread across the former environments of chemical sedimentation. Possible conditions of iron sedimentation were as follows: derivation of iron and silica by weathering of a low-lying land mass, perhaps under an atmosphere rich in carbon dioxide, and a seasonal climate; tectonic stability; and deposition in a shallow, quiescent epicontinental sea.

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SUMMARY OF THE SUB-DIVISIONAL CORRELATION
OF THE MIDDLE HURONIAN IRON-FORMATIONS
OF THE LAKE SUPERIOR DISTRICT

J. F. Wolff, Sr.

Duluth, Minnesota

For a generation or more there has been general agreement among geologists of the Lake Superior District, that, based on general geologic associations, the major iron-ore producing formations of the (older) Middle Huronian series of iron bearing rocks were of the same general age and broadly of similar character.

A great many geologists have known, especially of later years, that fairly comparable subdivisions of this Middle Huronian iron-formation can be found in the different districts.

The presenter of this brief contribution is not aware of the publication of any correlation diagram which shows major subdivision of the older iron-formation of Mesabi, Cuyuna, Gogebic, Marquette and old Menominee districts into four main layers and even the division of some of these into minor layers having similar characteristics.

This contribution presents such a correlation diagram in color, projected on a screen for convenience of the audience. Four major divisions of the iron-formation are shown, -from the top down being - Upper Slaty, Upper Cherty, Lower Slaty and Lower Cherty, lying between a basal quartzite and quartz-slate and an overlying very thick black-slate and graywacke in places, which locally has a conglomerate and quartzite-quartz-slate at its base. A very great erosion period intervened between the top of the Upper Slaty and the beginning of deposition of the Upper Huronian conglomerate-quartzite-slate series of rocks so that in places only remnants of the Upper Slaty Division are left. In the main area of the Marquette District there is no remnant of it so far as the writer knows but north of Crystal Falls at the Amasa-Porter mine, it was found at the top of the Negaunee iron-formation. A few of the minor subdivisions are shown on the diagram.

The major unconformity between Upper and Middle Huronian rocks is shown graphically, and the relative position of the Upper Huronian iron-formations of the Iron River, Crystal Falls, Florence, Menominee, Marquette-Gwinn, Gogebic and Cuyuna districts is shown also on the diagram, which was compiled from all available sources, including the author's work or visits in all the districts and interviews at different times with geologists active in the several areas.

Minor details may be controversial especially with respect to the greenstones in the Iron River, Crystal Falls and Florence districts whose position in the geologic column may still be open to question and further exploration evidence.

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GEOCHEMICAL EXPLORATION FOR NICKEL AND
COPPER IN NORTHERN MINNESOTA

Donald H. Yardley

University of Minnesota, Minneapolis, Minnesota

Geochemical tests for nickel and copper in glacial soil from the Ely district show that pronounced anomalies overlie mineralized Duluth gabbro. The geochemical pattern demonstrates that the mineralization is parallel to the gabbro-granite contact, but 300 feet or so from the contact. The profiles of copper distribution are similar to the nickel profiles, with copper present in greater amount. Both metals are confined to the finer soil fractions.

The processes by which the heavy elements migrate is not clear. It is believed that natural earth currents may play some part in distribution of the heavy elements. The vertical distribution is being tested to facilitate investigation of the process of migration.

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STUDIES OF STRATIFIED ROCKS OCCURRING BELOW THE HURONIAN
SUCCESSION IN THE MARQUETTE DISTRICT, MICHIGAN

Justin Zinn, Gerald L. Brooke,
Theodore Engel, and Richard Hagni

Michigan State College, East Lansing, Michigan

Several remnants of metamorphosed stratified rocks are known to occur along the margin of the Marquette syncline or adjacent to nearby Huronian synclines in the Marquette district. These remnants are apparently all of greater age than the Mesnard quartzite. Three such remnants have been restudied so far and they are the Lake Enchantment (Mud Lake) sediments, the Holyoke formation and the Kitchi schist. The restudies included detailed mapping and petrographic examination of the rocks of each area in the attempt to establish more definitely the age and origin.

The Holyoke formation and the Lake Enchantment sediments overlie the Keewatin greenstones with marked unconformable contacts and the Kitchi formation is believed to have a similar relationship. These formations therefore belong to the time interval between the Keewatin and the base of the Huronian in Michigan. Each of these sedimentary remnants is distinctly different from the others and they are not believed to be of the same age. The Holyoke formation appears to be tillite and it may provide a clue in correlating the Michigan Huronian with that on the north shore of Lake Huron.

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BOTTOM CORING IN LAKE SUPERIOR

James H. Zumberge

University of Michigan, Ann Arbor, Michigan

During the summer of 1953 several cores were recovered from the bottom sediments of Lake Superior. The research was accomplished through a cooperative venture between the U. S. Fish and Wildlife Service and The Great Lakes Research Institute, a research organization of the University of Michigan dedicated to scientific investigations of the Great Lakes.

The cores were obtained with a gravity coring rig which consisted of a weighted 5-foot length of 3-inch diameter pipe to which two 10-foot sections of 2-inch I. D. diameter pipe was attached. The maximum core recovery was about 8 feet.

Ten cores were taken at Stations between Keweenaw Bay and Isle Royale, and Grand Marais, Minnesota and Bayfield, Wisconsin. The core material is fine grained ranging from clay to silt size. The chief difference in the cores is their color variation. Some are reddish, ranging from 10 R 3/2 to 2.5 YR 5/2 (Munsell), while others are grey. In one core the upper 6 feet is red and the lower 1 foot is grey. No relationship between color and depth of water or color and geographic location is apparent.

A mineralogical study of one core recovered in 630' of water showed that the composition is about 75 percent quartz and feldspar and only 25 percent clay minerals. The latter group include kaolinite and a possible interlayered chlorite-illite mineral as indicated by X-ray diffraction studies presently under way at Ohio State University.