

INSTITUTE ON LAKE SUPERIOR GEOLOGY

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April 21 - 22, 1958

Duluth, Minnesota.

UNIVERSITY OF MINNESOTA
Center for Continuation Study
of the
General Extension Division
Minneapolis, Minnesota

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UNIVERSITY OF MINNESOTA
Center for Continuation Study
Duluth 12

Institute on Lake Superior Geology

April 21-22, 1958

PROGRAM

Monday Morning - April 21, 1958
Science Auditorium, University of Minnesota, Duluth

- 9:00 General Meeting of the Institute .. General Chairman, Ralph W. Marsden
9:15 Welcome J. M. Nolte

SESSION I

Co-chairmen: Henry Lepp, Thomas E. Stephenson

- 9:30 H. M. Gehman: PETROLOGY OF THE BEAVER BAY DIABASE
9:55 E. N. Cameron: THE CRITICAL AND TRANSITION ZONES OF THE EASTERN
PART OF THE BUSHVELD COMPLEX
10:20 G. V. Keller*, C. J. Zablocki & F. C. Frischknecht: ELECTRICAL
METHODS OF GEOPHYSICAL PROSPECTING IN THE LAKE
SUPERIOR DISTRICT
10:45 C. E. Jahren: MAGNETIC SUSCEPTIBILITY AND ITS CORRELATION WITH
MAGNETITE CONTENT IN TACONITE
11:10 G. D. Bath: GEOPHYSICAL STUDIES IN NORTHERN MINNESOTA
11:35 G. M. Schwartz: GEOLOGICAL IMPLICATIONS OF MAGNETIC AND GRAVITY DATA
OF THE LAKE SUPERIOR REGION
12:00 LUNCH - MAIN BALLROOM, KIRBY STUDENT CENTER

SESSION II

Co-chairmen: John W. Gruner, Ralph W. Marsden

- 2:00 R. W. Bayley: GEOLOGY OF THE MENOMINEE IRON-BEARING DISTRICT,
MICHIGAN
2:25 C. E. Dutton: STRATIGRAPHY OF PRE-Keweenaw ROCKS IN PARTS OF
NORTHERN MICHIGAN
2:50 S. S. Goldich*, A. O. Nier: PROBLEMS OF THE DIVISION OF PRECAMBRIAN
TIME
3:15 S. S. Goldich, A. O. Nier, H. W. Krueger*, J. H. Hoffman: DATING
OF PRECAMBRIAN IRON FORMATIONS
COFFEE BREAK
4:10 James Trow: RELATION OF SHEAR JOINTS TO A TEAR FAULT IN THE
STURGEON QUARTZITE
4:35 H. E. Wright, Jr.: PROBLEMS -- SOLVED AND UNSOLVED -- IN THE
GLACIAL HISTORY OF NORTHEASTERN MINNESOTA
7:00 DINNER - MAIN BALLROOM, KIRBY STUDENT CENTER
Speaker: Howel Williams
Topic: "VULCANISM AND GLOWING AVALANCHES"

Tuesday Morning, April 22, 1958

SESSION III

Co-chairmen: Jack V. Everett, Josiah Royce

- 9:00 R. L. Blake: A STUDY OF THE IRON SILICATE MINERALS WITH SPECIAL
EMPHASIS ON THE IRON FORMATION IN THE CUYUNA
DISTRICT, MINNESOTA

Lake Superior Geology

- 9:20 C. A. Beckman: PETROGRAPHY OF THE WESTERN MESABI RANGE, MINNESOTA
 9:40 J. N. Gundersen: THE MINERALOGY OF THE METAMORPHOSED BIWABIK IRON
 FORMATION, EASTERN MESABI RANGE, MINNESOTA
 10:00 A. M. Goodwin: ALTERATION STUDIES AT HELEN SIDERITE MINE
 10:25 M. W. Bartley: ANIMIKIE SEA
 10:45 C. L. Iverson: THE PROPERTIES OF SILICA GEL AND ITS POSSIBLE RELATION-
 SHIP TO THE DEVELOPMENT OF LAKE SUPERIOR TYPE IRON ORES
 11:05 G. H. Spencer, Jr.: THE ROLE OF INTERSTITIAL AND COMBINED WATERS IN THE
 DEVELOPMENT OF LAKE SUPERIOR IRON ORES
 11:25 T. M. Han: THE MINERALOGY, PARAGENESIS, AND ORIGIN OF THE CUYUNA
 SULFIDE DEPOSITS
 12:00 LUNCH - MAIN BALLROOM, KIRBY STUDENT CENTER

SESSION IV

Co-chairmen: Robert L. Heller, Fred T. Jensen

- 1:30 G. C. Amstutz: THE GENESIS OF LAKE SUPERIOR COPPER DEPOSITS
 1:50 Moses Passer: PEAT RESEARCH AT THE UNIVERSITY OF MINNESOTA
 2:10 W. L. C. Greer: RECENT SPODUMENE DISCOVERIES IN NORTHWESTERN ONTARIO
 2:30 L. C. Binon: IRON ORES OF THE PACIFIC NORTHWEST
 2:50 E. L. Buetner: CHARACTERISTICS OF SOME IRON-BEARING FORMATIONS
 IN NORTHERN WISCONSIN
 3:10 E. R. Mead: RECENT IRON FINDS IN NORTHWESTERN ONTARIO

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THE PETROLOGY OF THE BEAVER BAY COMPLEX

Harry M. Gehman

Three gabbroic intrusions, with minor associated rock types, form the Beaver Bay complex in southeastern Lake County, Minnesota. The gabbros intrude the Middle Keweenawan North Shore volcanic group. The oldest intrusion, the Beaver River gabbro, contains calcic plagioclase (An_{65}), medium olivine (Fa_{40-55}), titanite ($Ca_{40}Mg_{38}Fe_{22}$), and accessory minerals. Xenoliths of anorthosite are abundant locally in this unit, together with a few xenoliths of leucocratic granite.

The second intrusion, the Beaver Bay ferrogabbro, shows marked compositional variation from the lowest to the highest exposures. Differentiation through crystal settling has produced a progressive change in the composition of the primary precipitate minerals: olivine, clinopyroxene, and plagioclase. The progressive change in olivine composition from Fa_{66} to Fa_{99} allows subdivision of this unit into hortonolite-, ferrohortonolite- and fayalite-ferrogabbro. High-calcium clinopyroxene likewise shows a progressive change in iron and magnesium content from augite ($Ca_{39}Mg_{33}Fe_{28}$) to ferrohedenbergite ($Ca_{43}Mg_{02}Fe_{55}$). Pigeonite, inverted pigeonite, and primary hypersthene are present as interprecipitate phases in the lower part of the intrusion; however, in rocks with olivine more iron-rich than Fa_{82} , ferroaugite is the only pyroxene present. Absolute iron-enrichment of the rocks is indicated by chemical analyses of samples from varying heights in the intrusion. Silica- and alkali-enrichment become apparent only in the upper fayalite-ferrogabbro where large amounts of micropegmatite and thick sodic plagioclase rims are present.

The Black Bay gabbro forms dikes and small sills surrounding and intruding the ferrogabbro. It is generally coarse-grained with numerous coarser pegmatitic zones. Its chemical and mineralogical composition is very similar to that of the numerous pegmatitic veins and schlieren common to fine-grained gabbroic sheets throughout the world.

THE CRITICAL AND TRANSITION ZONES OF THE EASTERN
PART OF THE BUSHVELD COMPLEX

Eugene N. Cameron

Structural and petrologic features of the Critical and Transition zones of the eastern part of the Bushveld Complex, disclosed by detailed mapping and study of selected areas, throw further light on the evolution of the complex and suggest additional investigations that may be fruitful.

Both Critical and Transition zones vary in composition and sequence of rock units. The Critical Zone, the more intensively studied of the two, is divisible along strike into at least three sectors, differing in sequence of major units. The northern sector is poorly exposed. In the southern and central sectors, the Critical zone consists of a lower pyroxenite series and an upper anorthosite series, but the sequences of units in these series are not the same in the two sectors. Relations between sectors are obscured by faulting and folding along the line of the Steelpoort Valley.

Cognate xenoliths, discontinuities, and irregularities in the layered structure of the Critical zone, together with repetitions of rock types, indicate formation from a moving rather than a static magma. Penecontemporaneous folding and fracturing indicate local disturbances during consolidation, but clear evidence of major disturbances is not at hand.

The occurrence of blocks of metamorphosed sediments at points well above the floor of the complex is a feature deserving further study. The xenoliths may be a part of the more general problem of adjustments of the floor and roof of the complex during differentiation and consolidation. At present, such movements cannot be fully distinguished from movements that took place after consolidation.

Many of the rock types of the Critical zone are satisfactorily explained by a combination of fractional crystallization, gravitative settling, and mechanical sorting of crystals due to variations in velocity of magmatic currents. The more extreme types of anorthosites, pyroxenites, and chromitites appear to require supplementary processes. Possible reactions during and after burial of settled crystals, and the influence of thermal gradients between the magma-accumulate interface and the roof and floor of the complex appear to deserve further study.

ELECTRICAL METHODS OF GEOPHYSICAL PROSPECTING IN THE LAKE SUPERIOR DISTRICT

G. V. Keller, C. J. Zablocki and F. C. Frischknecht

The electrical properties of ores and host rocks and the uses of electromagnetic methods of prospecting have been studied in the Lake Superior iron and copper districts. Both borehole and laboratory measurements of electrical properties were made.

The investigations suggest that electrical surveys may be a useful supplement to magnetic surveys. In many cases, for example, iron ores could be distinguished from the adjacent rocks because of their higher conductivities. Similarly, in the native copper ores from the southern shores of Lake Superior, electrical polarization was found to correlate with the amount of copper.

Experimental electromagnetic surveys were made in three areas where the iron-formation is covered by 100 feet of glacial till. A conductive zone in the hanging wall could be traced in these areas, but the effect of the iron-formation itself could not be detected. The possibility of distinguishing between the effects of induced and remanent magnetization was also indicated by the electromagnetic measurements.

MAGNETIC SUSCEPTIBILITY AND ITS CORRELATION WITH
MAGNETITE CONTENT IN TACONITE

Charles E. Jahren

Magnetic susceptibility measurements have been made on samples of drill core from iron-formations and other magnetic rocks in northeastern Minnesota. The relation $k = 0.001157 V^{1.394}$ where k is the susceptibility and V is the volume percent magnetite between the limits 10 and 40 percent was found to hold for taconite in the eastern end of the Mesabi range. Susceptibility was measured by inserting each specimen into a Helmholtz coil and recording the change in self-inductance of the coil as indicated by an a c bridge. Magnetite content for each depth interval was determined by magnetic separation. The susceptibility of individual samples from the same rock formation differed greatly. In an effort to get reliable averages, as many as 250 samples were measured from some holes.

GEOPHYSICAL STUDIES IN NORTHERN MINNESOTA

Gordon D. Bath

The physical properties of rocks in northern Minnesota are being studied to obtain a better understanding of the regional geology. A major part of the investigation consists of studying the magnetic properties of large rock units to determine their effects on the earth's magnetic field. Other phases of the work include regional gravity measurements in the Cuyuna district, various types of electric logging in drill holes, and electromagnetic surveys to trace the iron-formation beneath glacial drift.

Many of the aeromagnetic anomalies over iron-formations in areas of moderate to intense metamorphism are attributed to the effects of regional remanent magnetization alone. Such anomalies occur over iron-formations of the East Mesabi, Gunflint, Vermilion and South Cuyuna districts, and in the iron-formations of the Gogebic district near Mellen, Wisconsin. In the Duluth area, magnetic lows caused by remanent magnetization are found over thick sequences of gabbro and extrusive rocks near the base of the Duluth gabbro.

During the past year, traverses were run along roads using a total-field magnetometer. These measurements show there is remanent magnetization in the lower cherty member of the Biwabik iron-formation in the Main Mesabi district, and locally in the iron-formations of the North Cuyuna district.

GEOLOGICAL IMPLICATIONS OF MAGNETIC AND GRAVITY
DATA OF THE LAKE SUPERIOR BASIN

George M. Schwartz

The great syncline which is partly occupied by Lake Superior presents many structural problems which have been only partly solved. Geophysical data accumulated in recent years from many sources furnishes evidence regarding some of the problems. There has long been a suggestion that a fault is responsible for the straight shore-line and deep water offshore along the Minnesota coast. Flights with the airborne magnetometer across the syncline including the lake, as well as gravity and geological data, fail to confirm the existence of the fault and it is of reasonable certainty that such a fault does not exist. The Douglas fault, which is well defined on geological evidence, is characterized by a very large negative magnetic anomaly.

Another problem has been the possibility of an extension of the Duluth Gabbro beyond the abrupt ending of outcrops to the north of the St. Louis River at West Duluth. Aeromagnetic profiles fail to indicate any large, near surface mass of gabbro south of Duluth. If the gabbro at Duluth were continuous with gabbro on the south limb in Wisconsin, it would be expected that it would also outcrop around the southwest end of the syncline. Such does not seem to be the case.

Local details of the aeromagnetics furnish important data on the geology where the rocks are buried beneath a heavy cover of glacial drift. A local magnetic low occurs along the west contact of the gabbro as was shown by ground work in 1942 and confirmed by aeromagnetic data. The lower part of the gabbro (layered series) and the flows beneath the gabbro surprisingly are characterized by a regional magnetic low, but the flows above the gabbro and associated diabases generally produce a magnetic high, as expected.

A large, broad magnetic high in the vicinity of Culver, between Cloquet and the Mesabi, may result from a deeply buried iron formation. Work is being continued on these anomalies by the United States Geological Survey.

GEOLOGY OF THE MENOMINEE IRON-BEARING DISTRICT, MICHIGAN

Richard W. Bayley

The Menominee iron-bearing district includes 150 square miles in southern Dickinson County, Michigan. In the period 1877 to 1936, 85 million tons of iron ore were extracted from its mines, most of it of Bessemer grade, but the district is now virtually inactive. The district has been recently studied by geologists of the U. S. Geological Survey and the Geological Survey Division, Michigan Department of Conservation, as a part of a continuing project to re-evaluate the Precambrian iron ranges of Michigan.

The rocks are mostly of Precambrian age, capped here and there by Cambrian sandstone, and extensively covered by Pleistocene glacial deposits. Two main divisions are recognized, lower Precambrian rocks (Archean of older reports), and middle Precambrian rocks, the Animikie series (Huronian series of older reports). The rocks of the two major divisions are separated by a profound unconformity. The Animikie series, which corresponds in the middle and upper parts to the Animikie group of Minnesota, is composed of three groups of rocks separated from one another by unconformities. From oldest to youngest, these are the Chocolay group, the Menominee group, and the Baraga group. The Menominee group contains the major iron-formation. Mafic dikes and sills of Animikie age cut every formation.

The gross structure of the district is a northwest-striking trough. The trough is underlain by steeply folded Animikie rocks, which are flanked by domal areas of lower Precambrian (pre-Animikie) gneiss, granite and greenschist. The older rocks north of the trough are chiefly gneiss, overlain unconformably by Animikie strata. The older rocks south of the trough are altered volcanic rocks which are cut, in turn, by quartz diorite, and granite, both large scale intrusives. The internal structure of the trough is dominated by three major strike faults which separate the Animikie rocks into monoclinical blocks, and separate the Animikie rocks from the pre-Animikie rocks along the south flank of the trough. The two central fault blocks form northwest-striking ridges, referred to as the north and south iron ranges. The formations of the ranges dip steeply south or are overturned and dip north. Both ranges show second order folds, most of them west-pitching right-lateral folds, some overturned, some faulted along over-extended south limbs. Most of the high grade iron ore bodies mined in the district were related to such structures, particularly to pitching synclines.

The iron-formation of the Menominee group is composed chiefly of quartz and iron oxide minerals, and averages approximately 32 percent iron. The prospect for finding new high grade ore bodies is not encouraging, but some favorable areas have not been explored. The economic utilization of the iron-formation entails problems of beneficiation similar to those encountered with Mesabi

taconites. The area of iron-formation close to the surface in the district is roughly 14,000,000 square feet, which equals about 140,000,000 tons of iron-formation, or about 70,000,000 tons of concentrate, for a depth of 100 feet. If the Brier slate member, which lies between the two iron-bearing members of the Vulcan formation, and which contains an average of 18 percent iron, could also be beneficiated, mining would be simplified and the quantity of concentrate from a given property would be increased by 30 percent.

STRATIGRAPHY OF PRE-KEWEENAWAN ROCKS
IN PARTS OF NORTHERN MICHIGAN

Carl E. Dutton

U. S. Geological Survey Professional Paper 314C of the above title, prepared by H. L. James, summarizes the results of 15 years of cooperative investigation with the Michigan Geological Survey in the study of Iron and Dickinson counties. The areal and structural basis of the principal nomenclature, as shown in the following table modified from the report, will be discussed.

LITHOLOGIC SEQUENCE OF PRECAMBRIAN ROCKS
IN IRON AND DICKINSON COUNTIES, MICHIGAN

Precambrian	Upper Precambrian	Keweenawan	Díabase dikes and sills (probable age about 1100 million years)				
			Intrusive contact				
	Middle Precambrian			Granitic intrusive rocks (probable age 1400 million years)			
				Intrusive contact			
				Metadiabase and metagabbro			
				Intrusive contact			
		Paint River Group		Fortune Lakes slate			
				Stambaugh formation			
				Hiawatha graywacke			
				Riverton iron-formation			
				Dunn Creek slate with Wauseca pyritic member			
		Baraga group	Animikie series	Badwater greenstone			
				Michigamme slate			
				Fence River formation	Amasa formation		
				Hemlock greenstone with Mansfield and Bird iron-bearing slate members			
				Goodrich quartzite			
		Menominee group		Unconformity			
				Vulcan iron- formation	Loretto slate member		
					Curry iron-bearing member		
					Brier slate member		
					Traders iron-bearing member		
	Chocolay group		Felch formation				
			Unconformity				
			Randville dolomite	Saunders formation			
			Sturgeon quartzite				
			Fern Creek formation				
			Unconformity				
Lower Precambrian			Intrusive or replacement contact — ? — ?				
	Dickinson group	Six-Mile Lake amphibolite		Quinnesec formation (position indeterminate)			
		Solberg schist, with Skunk Creek member					
		East Branch arkose					
	Unconformity — ? — ?						
	Granite gneiss						
	Quartzite and schist (small bodies included in granite gneiss)						

PROBLEMS OF THE DIVISION OF PRECAMBRIAN TIME

S. S. Goldich and A. O. Nier

Division of the Precambrian based on rock types or degree of metamorphism is unsatisfactory. A^{40}/K^{40} dating now in progress supports a three-fold division of the Precambrian in the Lake Superior region. Although many problems remain to be solved, tentative dates for the three divisions are as follows:

Late Precambrian	1.6 - 0.5 b y
Middle Precambrian	2.5 - 1.6 b y
Early Precambrian	older than 2.5 b y

The oldest A^{40}/K^{40} date obtained for rocks in the Lake Superior region is about 2.7 b y. It appears likely that present day radioactive dating methods may prove inadequate to resolve time beyond 2.7 b y, although geologic evidence clearly indicates that sedimentary processes were active before this date.

The end of Middle Precambrian time is marked by folding and metamorphism of Animikian and equivalent sediments in an east-west belt extending from Minnesota to Michigan. Deep-seated metamorphism was accompanied by intrusion of granitic magma.

The Keweenawan North Shore volcanic group and the Duluth gabbro complex are assigned to middle Late Precambrian. The main gabbro intrusion is dated at 1.1 b y, but folding and metamorphism of the extent developed at this time in the Grenville Province remains to be recognized in the Lake Superior region.

DATING OF PRECAMBRIAN IRON FORMATIONS

S. S. Goldich, A. O. Nier, H. W. Krueger, J. H. Hoffman

Precambrian iron formations have been studied intensively by geologists and problems of origin and correlation have ranked high in these investigations. Progress of an investigation to date the iron formations of the Precambrian of North America is reported.

A^{40}/K^{40} dating indicates that iron formations were involved in each of the major orogenies of the Precambrian of the Canadian Shield. Soudan-type of iron formations in Minnesota and Ontario were folded in an orogeny dated at 2.7 b y. Mesabi-type of iron formations in Minnesota, Wisconsin and Michigan were involved in folding at about 1.7 b y. Iron formations in Quebec (Ungava-type) were folded in the 1.1 b y Grenville orogeny.

Geologic data suggest that iron formations were deposited during each of the three major divisions of the Precambrian, as well as at different times within the divisions. Further geologic studies are needed.

Two periods of mineralization are inferred for the Soudan Mine in Minnesota by A^{40}/K^{40} dates on samples of sericite. The older sericite (2.5 b y) is related to mineralization following folding in Early Precambrian time. A younger sericite (1.7 b y) indicates that the deposit was reopened at the time of the Middle Precambrian (post-Animikian) orogeny.

THE RELATION OF SHEAR JOINTS TO A TEAR FAULT IN THE STURGEON QUARTZITE

James Trow

Six miles east of Norway, Michigan, adjacent to a dam across the Sturgeon River, slates and conglomerates of the Fern Creek formation and the Sturgeon quartzite are overturned and dip steeply northeastward. These strata are cut by northeast-trending tear faults that dip steeply southeastward. In the slates, east-striking slaty cleavage anomalously dips vertically and not at a more gentle angle than the overturned beds. In the quartzites, conjugate shear joints strike essentially east; one set dips gently north, the other gently south. A third set of joints is parallel to the faults. This discussion concerns the relation of the conjugate shear joints to one of the faults.

A simplified solution for A, B and C tectonic axes in brittle (competent) rocks is here presented: Instead of bisecting the actual acute angle between conjugate shear joints as plotted on a stereogram to find the direction (C) of maximum shortening of the rock, as proposed by Bucher (1920, Jour. Geology, pp. 716-717), here the obtuse angle between the face poles lie on the AC-plane; the contemporary B fold axis is perpendicular to this plane.

In this area, the slaty cleavage (AB-plane) in the Fern Creek formation is perpendicular to the C axis as determined by bisecting the angle between shear joints of the quartzite. Both structures, therefore, are presumed to be contemporaneous; both are presumed to be younger than the overturning of the strata. The angle between shear joints increases from 44° away from the fault to a maximum of 92° adjacent to the fault. Contours of these values trend parallel to the fault.

Two promising hypotheses are examined to explain the geographic relation between conjugate joints and the fault: (1) The more traditional explanation involves uniform stress anisotropism imposed upon a rock unit of geographically varying internal properties; i.e., the quartzite near the fault was more ductile (less competent) than elsewhere during jointing because of aqueous solutions and high temperatures of hydrothermal origin. This hypothesis is rejected because the timing required by the hypothesis does not correspond to the paragenesis of structural events as inferred from field and thin section evidence. (2) A less conventional explanation involves geographically non-uniform stress anisotropism imposed upon a rock unit of geographically uniform properties so that in the vicinity of the pre-existing fault, rejuvenated fault movement acted as a safety valve to relieve local stress on the rock. Trigonometric stress analysis based on Coulomb's equation for friction suggests that for angles between joints here observed, local diastrophic force farthest from the fault was 2.44 times as much as local stress on the rock adjacent to the fault, all other things being equal. The latter hypothesis, reached through inductive reasoning from field data, is further corroborated.

rated by Seigel (1950, Trans. Am. Geophys. Union, pp. 611-619) who reached the same conclusion on theoretical grounds alone, through deductive mathematical logic. A U-stage petrofabric study of the quartzite and a model experiment are planned for further investigation of these phenomena.

The economic application of this principle lies in the marked savings that should result from such a study of joints in planning an exploratory drilling program for direct shipping iron ore at the intersection of an iron formation and a tear fault. Jointed quartzites, or other brittle rock, near an iron formation should indicate (1) the location of a tear fault nearest to the most steeply dipping of the conjugate (gently dipping -- not parallel to the fault) shear joints, (2) the strike and dip of the tear fault through the quartzite from a statistical analysis of the steeply dipping joints (parallel to the fault), and (3) the expected direction of refraction (if any) of the fault as it passes from the quartzite into more ductile (less competent) beds.

PROBLEMS -- SOLVED (?) AND UNSOLVED -- IN THE GLACIAL
HISTORY OF NORTHEASTERN MINNESOTA

H. E. Wright, Jr.

Recent field studies of glacial deposits in northeastern Minnesota, pursued with the support of the Minnesota Geological Survey, have revealed the record of fluctuations of three late Pleistocene ice lobes:

- (1) The Superior lobe of red drift, whose source was the Lake Superior basin,
- (2) The Rainy lobe of dark gray to brown drift, brought by ice from the northeast.
- (3) The St. Louis sublobe of the Des Moines lobe, composed of yellowish-brown drift of northwestern source. Earlier Pleistocene drifts are exposed in the iron mines but their relations are obscure.

As currently interpreted, the sequence of glaciation in the late Pleistocene is as follows:

- (1) Cary subage of Wisconsin glacial age. Rainy and Superior lobes covered entire northeastern quarter of State..
- (2) Cary-Mankato interval. Ice retreated into Lake Superior basin.
- (3) Mankato subage. Superior lobe readvanced to Lake Mille Lacs. Rainy lobe may have stood at Vermilion moraine.
- (4) Mankato-Valders interval (Two Creeks interstadial). Ice retreated into Canada. Large lake in Superior basin.
- (5) Valders subage. Superior lobe readvanced out of west end of basin, extending west to Lake Mille Lacs and north to Mesabi Range, bringing red clayey till and reworked lake clays. Contemporaneous advance of St. Louis sublobe from west to a broad zone of junction with the Superior lobe extending from Aitkin (Aitkin County) to Aurora (St. Louis County).
- (6) Late Valders. Retreat of ice, with formation of glacial lakes Aitkin, St. Louis and Duluth.

The above sequence is based on stratigraphic and geomorphic relations and is supported by radiocarbon dates from adjacent regions. These dates place the Cary subage about 13,000 years ago for this area, the Mankato about 12,000 and the Valders about 10,500 years.

Some of the major unsolved problems in the glacial history of northeastern Minnesota include the following:

- (1) Relationship between the Rainy and Superior lobes during the Cary.
- (2) The extent of deglaciation during the interstadial intervals.
- (3) The source of carbonate in the red Valders drift of the Superior lobe.
- (4) The relation of the Valders advance to the development of Glacial Lake Agassiz in northwestern Minnesota.
- (5) The nature of the junction of Superior and St. Louis sublobes during the Valders, and the associated drainage relations.

Discovery of buried soils, bones, peat and wood in any of these younger glacial deposits will aid in solving some of these problems through their contribution to climatic reconstruction and radiocarbon dating. The basic task, however, is field study of stratigraphic and geomorphic relations, accompanied by appropriate laboratory work.

A STUDY OF THE IRON SILICATE MINERALS WITH SPECIAL EMPHASIS ON THE
IRON-FORMATION IN THE CUYUNA DISTRICT, MINNESOTA

Rolland L. Blake

Petrographic and mineralogical studies were made on samples of relatively unoxidized, silicate-rich iron-formation from the central part of the Cuyuna District and from the Troy pit, near Eveleth, in the Mesabi District.

Most of the open pit and drill core samples from the Cuyuna District represent the thin-bedded facies described by Schmidt of the U. S. Geological Survey. The open pit samples are from the main iron-formation and some drill core samples are from the upper iron-formation. Textures and structures of these rocks are described. Minerals identified were carbonate, stilpnomelane, minnesotaite, chlorite, a kaolinite-type mineral that is not greenalite, nontronite, amphibole, quartz, magnetite, hematite and goethite. Evidence will be presented to show that the iron carbonate is usually rich in manganese; this carbonate appears to be the primary source of manganese found in the manganese iron ores of the district. Mineral associations as related to metamorphism are discussed.

Samples of silicate-rich rock from the upper cherty member of the Biwabik iron-formation at the Troy Pit are described. The rock contains a green silicate with a kaolinite-type structure and varying amounts of either fine hematite or of coarse magnetite and martite.

Three samples of stilpnomelane and one of minnesotaite were purified from fissure-fillings in the main iron-formation of the Cuyuna District. Their chemical analyses, optical properties, DTA curves, and X-ray diffractometer powder patterns are presented and results of several other tests are discussed.

PETROGRAPHY OF THE WESTERN MESABI RANGE, MINNESOTA

C. A. Beckman

About 200 samples from the Western Mesabi (Hibbing to the West Itasca County line) have been studied. Most of the samples are from unoxidized Biwabik formation, with a few samples from the Virginia and Pokegama formations, and with very few samples in or near any known ore bodies.

The Virginia formation occasionally shows development of lineation as a result of the recrystallization of clay minerals, and other minerals include quartz, siderite, chlorite, graphite and pyrite. Most of the samples of the Virginia are fresh and show only slight decomposition for a few feet at the very top.

Minerals in the Upper Slaty member are mainly quartz, siderite and stilpnomelane, with minor magnetite and chlorite. Quartz, siderite and stilpnomelane are quite often intimately intergrown, with quartz and siderite occasionally present as microspherulites. Granules are rare in the Upper Slaty.

Fresh material from the Upper Cherty member is found east of Keewatin, with very little, if any, fresh material west of Keewatin. The chert granules almost always show some recrystallization.

The Lower Slaty member is thin in the West Mesabi, usually about 15 feet thick, locally up to 40 feet thick, and pinches out west of Coleraine. The only fresh material was found east of Keewatin.

Fresh material from the Lower Cherty member west of Nashwauk is usually found only in drill holes close to the southern boundary of the Biwabik formation outcrop. There appears to be a persistent zone of oxidation west of Nashwauk, which includes the Upper Cherty, Lower Slaty and about the top one hundred feet of the Lower Cherty. Minerals in the Lower Cherty are chert, minnesotaite, magnetite, greenalite, stilpnomelane, siderite, calcite and chlorite. Minnesotaite and greenalite are often intimately associated; carbonate has often replaced the silicates and chert granules; and the chert granules often show syneresis cracks and occasionally appear broken. Thin magnetite bands often show minor shearing and brecciation. The amount of carbonates and silicates appears to increase toward the bottom of the Lower Cherty. The "red basal taconite" was found in every hole which cut the Pokegama formation. This was the only unit in which oolites were found. Hematite is very fine-grained, with much of it being less than .005 mm. in diameter. Other minerals are quartz, carbonate and chlorite.

The Pokegama formation contains quartz of igneous, metamorphic and sedimentary origin, usually with some feldspar and, occasionally, a chlorite cement.

THE MINERALOGY OF THE METAMORPHOSED BIWABIK IRON FORMATION
EASTERN MESABI RANGE, MINNESOTA

J. Novotny Gundersen

For the purposes of this investigation, the Biwabik iron formation was subdivided into 24 members that can be identified in almost all diamond drill cores from the Eastern Mesabi Range. In summarizing the mineralogical information of this brief report, the less appropriate but more common terms, cherty and slaty, will be used.

Stratigraphic control, presumably by reason of initial composition, is most apparent from the almost ubiquitous occurrence of olivine near the bottom of the Upper Cherty and throughout the Lower Slaty and from the relative scarcity of olivine elsewhere in the strata. Some hypersthene and minor amounts of grunerite may have originated during the formation of these magnetite-quartz-olivine hornfelses. Minor amounts of idocrase, wollastonite and andradite also reflect the initial composition of the carbonate horizons above the Upper Slaty.

Metasomatic mineral assemblages occur in all taconite horizons intruded by pegmatitic veins. Within the intruded taconite horizons, hedenbergite, Ca-Fe rich carbonate, ferrotremolite, potash and plagioclase feldspar, chalcopyrite and pyrrhotite are the most obvious metasomatic additions. Hypersthene, almandite and epidote occur only locally adjacent to the pegmatites and are probably controlled by the initial composition of the taconite horizons in which they occur. The pegmatitic veins consist of varying amount of quartz, potash feldspar and ferrotremolite with subordinate amounts of biotite (now mainly chlorite), pyrite, chalcopyrite, Ca-Fe rich carbonate, hypersthene and plagioclase and minute amounts of muscovite and molybdenite.

Olivine-bearing hornfelses, as well as taconite containing metasomatic mineral assemblages, are of varying grain size, depending upon their proximity to the gabbro or pegmatite contacts, respectively. The coarse-grained, recrystallized or reconstituted rocks are only slightly replaced by grunerite but most of the material bedded between magnetite layers or lamellae of the prevailing less coarse-grained taconite more distant from these contacts now consists mostly of grunerite. Within the transitional rock types between these two extremes, the late replacement or reconstitution nature of grunerite is clearly distinguished from the earlier olivine, hypersthene, hedenbergite and chert-magnetite assemblages that are replaced by grunerite. The chert-magnetite assemblages are commonly present as relics preserving granules and other primary sedimentary structures.

ALTERATION STUDIES AT HELEN SIDERITE MINE

A. M. Goodwin

The Helen iron formation and associated siderite ore bodies is contained in an assemblage of Precambrian volcanic flows and pyroclastics. The assemblage has been tilted nearly vertical; the erosion surface thus presents a stratigraphic cross-section. The nature of the volcanics and their relationship to iron formation are reviewed.

Large-scale outpouring of basic volcanics led to explosive discharge of acid to intermediate volcanic types followed by development of iron formation. Attention is directed to wall rock alteration which occurred largely during development of iron formation.

Chemical alteration of volcanics underlying iron formation has been investigated by means of chemical analyses of diamond drill core. Principal chemical changes during alteration were removal of silica, calcium and alkalis and addition of ferrous iron, carbon dioxide and manganese; aluminum and titanium remained essentially constant. Volcanics were considerably altered to a stratigraphic depth of 150 to 200 feet below iron formation; below this depth, alteration was reduced in intensity and of uniform degree. Volcanics underlying iron formation are composed of acid and basic zones, the acid zone lying to the west. The degree and nature of chemical alteration varied somewhat with volcanic type. The acid-basic contact zone, though gradational and irregular, plunges eastward at roughly 45 degrees with respect to the present erosion surface. The contact zone may be related to original volcanic fissures or similar linear features.

Quantitative determinations indicate that the weights of silica leached from volcanics on the one hand and present in iron formation and ore body on the other, are similar in magnitude. Ore constituents, though, have been added throughout and an outside source is indicated. Possible sources are considered. In general, relations suggest that hot-spring type activity operated during development of iron formation and closed the volcanic cycle.

THE ANIMIKIE SEA

M. W. Bartley

The great sea from which the Animikian sediments were deposited during the Proterozoic era was responsible for major iron ore deposits of the Canadian shield.

The variations in lithology, mineralogy and, in some cases, attitude of the beds are due to facies changes and differing metamorphism, not to differing ages of deposition.

Periods of orogeny, followed by extensive erosion is the cause of the present localization of the iron-bearing horizons as opposed to previous postulation that the iron formations were deposited in restricted basins by local, small bodies of water.

THE PROPERTIES OF SILICA GEL AND ITS POSSIBLE RELATIONSHIP
TO THE DEVELOPMENT OF LAKE SUPERIOR TYPE IRON ORES

Cedric L. Iverson

It is assumed that the silica in the iron formations was deposited in the form of hydrous silica gels. It is suggested that natural silica gels are a mixture of polysilicic acid and hydrated silicates. Adsorption by silica gel and the effect of pH and the chemical nature of the surrounding medium on this property, is discussed. It is suggested that silica deposited under alkaline conditions will contain adsorbed magnesium, calcium, alumina and, possibly, oxygen while gel deposited under acid conditions may adsorb only alumina and carbonaceous matter. The effects of age, pressure and temperature on the dehydration of these gels are considered. Heat is considered to be the major factor in dehydration. Late stage dehydration reactions consist of the release of hydroxyl ions, oxygen and free electrons. It is considered possible that late stage reactions could result in the formation of hot alkaline oxidizing solutions. It is suggested that solutions derived from silica gels which were laid down under certain restricted conditions, may be capable of oxidizing and leaching the iron formation along the channelways through which they escape during dehydration.

THE ROLE OF INTERSTITIAL AND COMBINED WATERS IN THE DEVELOPMENT
OF LAKE SUPERIOR IRON ORES

G. H. Spencer, Jr.

A hypothesis is suggested to explain the leaching of silica from iron formation which may explain the development of some of the Lake Superior iron ores. It is suggested that connate waters trapped in the original fine-grained, iron-rich sediments under certain restricted conditions were sufficiently abundant to later form a solvent for part of the silica during diagenesis or metamorphism. The conditions necessary to effect solution of the silica are believed to be moderate temperatures in the range of 100 to 150° C, and sufficient fracturing of the iron formation to allow escape of the silica charged waters. Magnesium, hydroxyl, and possibly oxygen ions adsorbed during sedimentation and released during diagenesis may have furnished reagents which break down iron minerals to the oxide form. Other products of this breakdown, notably alkali bicarbonate, assist in the solution of silica in the channels along which the escaping waters migrate. The necessary temperatures could be furnished by regional metamorphism, shearing, simple depth of burial or intrusives. Fracturing could be accomplished by all of these forces, possibly including differential rates of compaction.

This hypothesis is distinguished from other ideas on the origin of Lake Superior iron ores in that any set of geologic conditions which will produce the necessary temperatures and fracturing will start the ore-making process in an iron formation with the necessary chemical composition, water content, and geologic environment.

THE MINERALOGY, PARAGENESIS AND ORIGIN
OF THE CUYUNA SULFIDE DEPOSITS

T. M. Han

The sulfide deposits are located in south central Aitkin and in southwestern Carlton counties. They are normally overlain by about 40 feet of glacial drift.

The deposits are essentially made up of a sulfide-bearing black slate, composed of quartz, sericite, chlorite, biotite, ilmenite, leucoxene, amorphous carbon, calcite, magnetite, pyrrhotite, pyrite, marcasite with traces of chalcopyrite, marmatite, arsenopyrite, and antigorite.

It is believed that the deposits are a metamorphosed sulfide iron formation of the greenschist facies. They are underlain by and gradational into a thin bedded recrystallized cherty carbonate iron formation.

The iron is thought to have been primarily deposited as iron sulfide resembling the pyrite in the black slate of the Iron River-Crystal Falls District. Subsequently, it was subjected to regional metamorphism which led to the formation of pyrite and marcasite from pyrrhotite.

The conclusions are supported by geographic, stratigraphic, mineralogic and geochemical evidence. Core specimens from thirty drill holes in the area were studied.

The paragenesis of the iron sulfide minerals and their relationships are pictorially illustrated.

THE GENESIS OF THE LAKE SUPERIOR COPPER DEPOSITS*

G. C. Amstutz

The Lake Superior copper deposits are best explained by a uniform single origin. The field evidence and the microscopic, paragenetic statistical and geochemical analyses lead to the conclusion that the copper is a normal co-magmatic syngenetic constituent accumulated in the hydromagmatic phases of the Lake Superior basalt magma.

First, the copper was brought up in and with the lavas and stayed in the hydromagmatic and hydrothermal portions of the lavas or escaped into the sediments and fractures. After the lavas ceased to extrude, the volatile fractions still continued to leak out from the same magma chambers as hydrothermal fluids, most of which reached the surface and formed the exhalative sedimentary red bed coppers of White Pine, etc.

* (The basis for this paper is experience gained while working for the Bear Creek Mining Company in the summer of 1957. The author acknowledges the Company's permission to publish this paper and emphasizes the fact that opinions expressed therein are his own and not those of the Company.)

PEAT RESEARCH AT THE UNIVERSITY OF MINNESOTA

Moses Passer

About 50 per cent of the United States peat supply is found in Minnesota -- some 7 billion tons in some 7 million acres that comprise about 14 per cent of the area of the State. With the objective of developing utilization of this resource, the Iron Range Resources and Rehabilitation Commission in 1954 established the "Chemical Products from Peat" project at the University of Minnesota. This is a cooperative research project conducted in three departments of the University;

Department of Chemical Engineering, Minneapolis Campus
Department of Soils, Institute of Agriculture, St. Paul Campus
Duluth Branch Department of Chemistry, Duluth Campus

The general research activities of these three groups are aimed at developing basic chemical information about peat, its constituents and its derivatives, with the viewpoint of developing chemical products from peat that may be useful as industrial chemicals and/or in agricultural applications. The project is at present engaged in the following areas:

- (a) Development of processes for preparing high-nitrogen organic fertilizer products and special amendments for humus-deficient soils. Chemical studies of the products.
- (b) Agronomic and horticultural evaluation of the experimental soil products. Basic studies of their effects on plants.
- (c) Fundamental studies of the chemical and physico-chemical nature of peat and its constituents, particularly humic acids. Includes functional group analyses, molecular weight studies and solvent-extraction methods.
- (d) Systematic sampling of Minnesota peat bogs. Development of a chemical group analysis for the organic constituents of peat, and analysis of bog samples.
- (e) Exploratory studies of new and potentially economic chemical applications for peat.
- (f) A complete survey of the world's literature on peat and related topics has been established in the form of a punched card system.
- (g) During the summer of 1957, members of the project participated in the "Technical Peat Exchange Mission to the USSR". This mission made a thorough study of the Russian peat industry, visiting their fundamental and applied research laboratories, experimental peat bogs, chemical pilot plants, agricultural experiment stations, and full-scale establishments for the various processes of peat production and its consumption, both as a fuel and for chemical purposes.

RECENT SPODUMENE DISCOVERIES IN NORTHWESTERN ONTARIO

W. L. C. Greer

Intensive prospecting following a discovery at Georgia Lake early in 1955 resulted in the finding of at least four major deposits of spodumene. Drilling has indicated reserves in excess of eight million tons, grading 1% Li_2O or better.

Most of the showings are in the Beardmore area. Post-ore diabase sills and dikes have complicated the situation from the mining point of view. No production has been had from any deposit as yet.

IRON ORES OF THE PACIFIC NORTHWEST

L. C. Binon

The existence of iron deposits in the States of Washington, Oregon, Montana and Idaho has long been known. The first use of these ores was as a flux in the smelting of non-ferrous ores. A small iron mining industry has existed intermittently on markets in the non-ferrous smelting, cement and paint industries. Several early attempts to establish an integrated steel industry in the Puget Sound area failed for a number of reasons, one of which was the lack of suitable iron ore. The discovery of Precambrian sedimentary iron formations in southwestern Montana and their preliminary exploration during the past three years by large experienced mining companies indicates that a detailed study of this long-desired goal may now be practical.

Fifty or more iron deposits of ten different types are known in the area. The Precambrian sedimentary iron formation and contact replacement deposits offer the greatest immediate economic potential. Large tonnages of ferruginous laterite and titaniferous beach sand ores are available but the complex metallurgy has retarded their development. Ferruginous schists and siderites of sedimentary origin, bog ores, massive sulfide deposits and associated gossans, and veins of primary iron oxide have all been explored or considered as resources for the production of metallic iron. Occurrences of each type are described, together with an evaluation of their economic potential.

CHARACTERISTICS OF SOME IRON-BEARING
FORMATIONS IN NORTHERN WISCONSIN

E. L. Beutner

Increased interest in lean ores during recent years has led to re-examination of drift-covered areas in northern Wisconsin where magnetic anomalies had indicated the presence of iron-bearing rocks but where little direct geological information was available.

Exploration drilling was done at Magnetic Center in Iron County and near Butternut, and in Agenda Township in Ashland County. The characteristics of the iron formations and related rocks are described. It is suggested that the sedimentary and volcanic environments in which certain Middle and Upper Huronian sediments were deposited in the East Gogebic Range area also existed to the south and west in Wisconsin. While part of the iron bearing sequence resembles the typical banded cherty iron formations of the better known ranges, there is also much material which, while iron bearing, contains little well-defined chert. The presence of abundant other minerals such as chlorite and mica seems to indicate that mud, possibly of volcanic origin, as well as silica, was being deposited with the iron-bearing sediments here.

The magnetite-grünerite iron formation and black slate association in Agenda Township closely resembles the metamorphosed Upper Huronian Bijiki formation on the Marquette Range.

RECENT IRON FINDS IN NORTHWESTERN ONTARIO

E. R. Mead

Modern beneficiation techniques have changed the economic outlook for low grade iron deposits in the Canadian Shield. Most of the previously known iron formations have been staked and intense prospecting has led to many new discoveries.

The occurrences are discussed in groups according to the sedimentary belts in which they lie. Studies of the new finds and their enclosing sequences should throw new light on the complicated stratigraphy of the area.

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