

Eleventh Annual

Institute on Lake Superior Geology

May 6-8, 1965



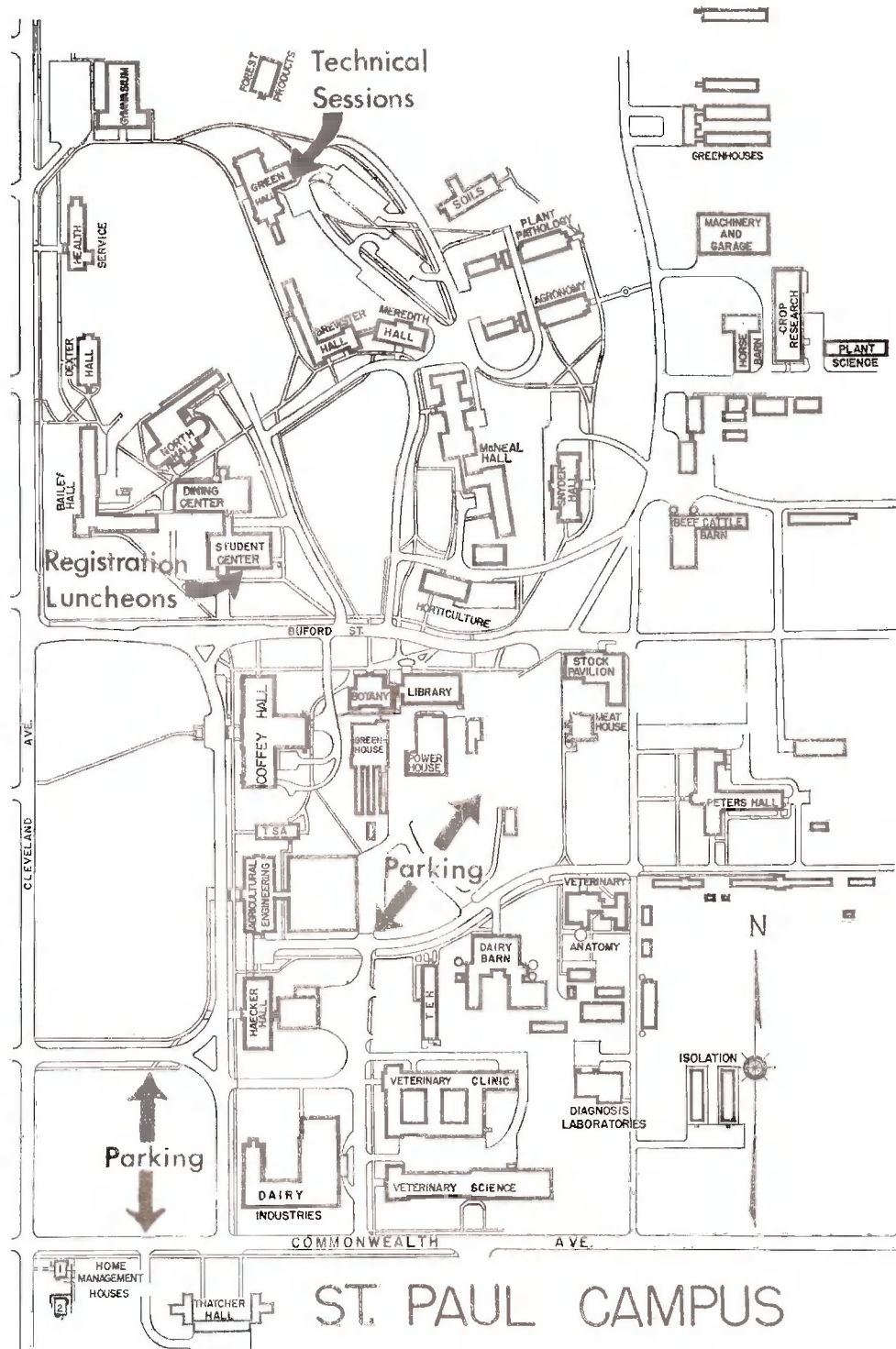
University of Minnesota

St. Paul, Minnesota

11th Annual Institute on
Lake Superior Geology

Sponsored by:

Minnesota Geological Survey
University of Minnesota
and
The Twin City Geologists



ST. PAUL CAMPUS

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P R O G R A M

Thursday, May 6

- 8:00 - 9:20 a.m. Registration and coffee hour, 2nd floor of Student Center,
St. Paul Campus
Technical sessions, 2nd floor, Green Hall
- 8:45 - 9:00 Business Meeting.....D. H. Hase, Secretary, conducting

Session I

Co-chairmen: John W. Gruner and Ralph Marsden

- 9:00 Progressive contact metamorphism of the Biwabik Iron-formation on the
Mesabi range, Minnesota.....Bevan M. French
- 9:20 The distribution of manganese in the Biwabik Iron-formation,
Minnesota.....Henry Lepp
- 9:40 Some aspects of iron-formations in Australia and South
Africa.....Gene L. LaBerge
- 10:00 Coffee break
- 10:45 Structure and lithology of the metamorphosed Biwabik Iron-formation,
Dunka River area, Eastern Mesabi district, Minnesota...Bill Bonnicksen
- 11:05 Structural control of the Mount Wright-Mount Reed iron deposits,
Quebec.....Peter J. Clarke
- 11:25 Petrology of the silicate iron-formation in the Republic mine area,
Marquette County, Michigan.....Tsu-Ming Han and James W. Villar
- 12:15 Luncheon, Student Center, 2nd floor, North Star Ballroom

Session II

Co-chairmen: George M. Schwartz and James Neilson

- 1:30 Tectonics of the Keweenaw basin, western Lake Superior
region.....Walter S. White
- 1:55 An aeromagnetic survey of western Lake Superior.....Richard J. Wold
- 2:15 The Sauble geophysical anomaly, Lake County,
Michigan.....Howard J. Meyer and William J. Hinze
- 2:35 Contributions of rock physics to geology.....Robert J. Willard
- 2:50 Coffee break
- 3:35 Geological analysis and remedial action in an open pit
rock slide.....D. H. Yardley
- 3:55 Measurement of in-situ stresses in a St. Cloud quarry--a
progress report.....Charles Fairhurst
- 4:15 An example of statistical analysis and possible interpretation of
structural data from Arvon Hill, Skanee quadrangle, Upper
Peninsula, Michigan.....J. D. Juilland

Thursday, May 6 (continued)

Annual Banquet

Twins Motor Motel
1975 University Avenue
(University at Prior)

6:00 p.m. Social Hour

7:00 Dinner

Address: Professor Campbell Craddock will speak on "Geologic structure of West Antarctica," a summation of six austral seasons of field work illustrated with many fine colored pictures.

Friday, May 7

Session III

Co-chairmen: Carl E. Dutton and H. L. James

- 9:00 Stratigraphy, structure, and granitic rocks in the Marenisco-Watersmeet area, Michigan.....Crawford E. Fritts
9:20 Ages of mafic dikes near Granite Falls, Minnesota.....Glen R. Himmelberg, Gilbert N. Hanson
9:40 Structure and stratigraphy of the Knife Lake Group east of Ely, Minnesota.....John C. Green
10:00 Coffee break
10:40 Keweenaw fault, Houghton County, Michigan.....Kiril Spiroff
11:00 The sedimentology of the Precambrian Rove Formation in northeastern Minnesota.....G. B. Morey
11:20 Petrology of the Amberg Precambrian crystalline complex, northeastern Wisconsin.....Dennis P. Rebello
11:40 Sedimentation of Middle Precambrian quartzites in Finland.....Richard W. Ojakangas
12:15 Luncheon, Student Center, 2nd floor, North Star Ballroom

Session IV

Co-chairmen: G. A. Thiel and Don Lindgren

- 1:30 A study on the hydrology of potholes in Minnesota.....George M. Schwartz
1:50 Geology of the Fillmore County district iron ores, southeastern Minnesota.....R. L. Bleifuss
2:10 Organic geochemistry of Rossburg peat bog, Aitkin County, Minnesota.....F. M. Swain, Mykola Malinowsky, and David Nelson
2:30 Preliminary results of geochemical prospecting north of the Marquette iron range, Michigan.....Kenneth Segerstrom
2:50 Coffee break
3:20 Protoclastic borders of the felsite near Bergland, Michigan.....Joseph P. Dobell and Robert W. Leonardson
3:40 Some aspects of the pegmatites in the Felch district, Dickinson County, Michigan.....Geoffrey W. Mathews

Friday, May 7 (continued)

7:30 - 9:45 p.m. Tour of U. S. Bureau of Mines, Research Center, Fort Snelling. Bus will leave at 7:30 p.m. from Student Center, St. Paul Campus with an intermediate stop at Twins Motor Motel and will return to the same locations.

Saturday, May 8

8:00 a.m. to 6:00 p.m. Field trip to St. Cloud district. Buses will depart from and return to the Student Center, St. Paul campus. Field trip will include tour of the Cold Spring Granite Company's finishing plant and visits to three "granite" quarries. Participants will be provided with a guide-book and lunch. Field clothes and hard hats are advised.

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GEOLOGY OF THE FILLMORE COUNTY DISTRICT
IRON ORES, SOUTHEASTERN MINNESOTA

R. L. Bleifuss
Mines Experiment Station
University of Minnesota, Minneapolis^{*/}

Iron ores have been known to exist in southeastern Minnesota since the earliest geological reconnaissance of the area by the Owen's survey in 1852. The development of the Fillmore County district was stimulated by the demands for iron ores during World War II, and initial ore shipments were made in 1943. Cumulative iron-ore production through 1964 has been about $6\frac{1}{2}$ million tons, and current production is about $\frac{1}{2}$ million tons per year. Reserves carried on the tax rolls in 1964 are in excess of $2\frac{1}{4}$ million tons.

The iron ores lie on Paleozoic limestones ranging in age from the Middle Ordovician to Middle Devonian. The commercial ore bodies are restricted to two dolomitic limestone units: the Middle Ordovician Galena Formation, and the Middle Devonian Cedar Valley Formation. The iron ores, and the widespread iron-rich weathering residuum which is developed on nearly all of the formations in the area, has been assigned to the lower, Iron Hill Member, of the Cretaceous Windrow Formation. The unconsolidated clays, sands, and gravels overlying the ores are assigned to the upper, or Ostrander Member of the same formation.

Previous investigators have postulated that the ores in the district originated by intensive chemical weathering, which resulted in the widespread replacement of certain favorable dolomitic limestone bedrock units by iron. In the most recent paper on the area, Sloan (1964) agrees with the Cretaceous age of the iron ores postulated by previous workers, and further emphasizes the importance of humid, temperate, to sub-tropical climatic conditions that prevailed in the area during the time of the transgression of the Cretaceous seas over Minnesota.

The present study has produced evidence that the ores are related to primary siderite-rich beds that originated during the transgression of the Devonian seas. The uniform thickness, chemical composition, and physical characteristics of the ore preclude their formation by the surficial weathering of a normal dolomitic limestone without an intermediate concentration step. The author believes that the physical-chemical conditions required to precipitate relatively pure siderite in an otherwise normal carbonate environment were present during the Devonian. This would require a euxinic environment in an estuary or bay with limited mixing of normal marine waters. The iron was transported in solution by streams draining a low-lying coastal plain under arid or semi-arid climatic conditions.

^{*/}Work done on behalf of the Minnesota Geological Survey

The ultimate source of iron was the normal sediments of the drainage basin; no specific iron-rich source beds are required.

The ores are not necessarily dependent upon unique Cretaceous climatic conditions, and the advisability of placing them within the Windrow Formation is dubious.

STRUCTURE AND LITHOLOGY OF THE METAMORPHOSED BIWABIK IRON-
FORMATION, DUNKA RIVER AREA, EASTERN MESABI DISTRICT, MINNESOTA^{*/}

Bill Bonnichsen
Department of Geology and Geophysics
University of Minnesota, Minneapolis

A three-mile-long belt of metamorphosed Biwabik Iron-formation in the Dunka River area, near Babbitt, Minnesota, at the eastern end of the Mesabi Range, is being developed by Erie Mining Company as a taconite property.

The Biwabik Iron-formation, Animikian in age, rests with profound unconformity on granitic rocks of the Giants Range batholith and is overlain conformably by the Virginia Formation. The Pokegama Quartzite, which lies immediately below the Biwabik Iron-formation in other parts of the Mesabi range, is virtually absent at Dunka River. All of these older rocks have been intruded and thermally metamorphosed by the Keweenaw Duluth Gabbro Complex. The iron-formation and other Precambrian rocks are covered locally by as much as 100 feet of glacial drift.

At Dunka River, the iron-formation ranges in thickness from 175 to 300 feet, and varies as much as 100 feet in a short distance horizontally as a result of both depositional and structurally-induced thinning and thickening. The Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty Members of the Biwabik Iron-formation are recognizable at Dunka River and, except for a markedly thinned Lower Cherty Member, the formation is similar in thickness and stratigraphy to other localities in the Eastern Mesabi district. A persistent 5- to 15-foot diabase sill, believed to be part of the Duluth Gabbro Complex, occurs throughout the property at the same stratigraphic position in the Upper Slaty Member.

The minerals of the Biwabik Iron-formation--quartz, magnetite, fayalite, ferrohypersthene, hedenbergite, hornblende, cummingtonite, and lesser amounts of diopside, actinolite, andradite, calcite, and pyrrhotite--are characteristic of a high temperature metamorphic environment. The mineralogy and paragenesis are similar to that at the Peter Mitchell mine of the Reserve Mining Company (Gundersen and Schwartz, 1962). Quartz is the most abundant mineral in the iron-formation, and grains developed in relatively pure layers are as much as 5 to 10 mm. in diameter. Magnetite, the second most abundant mineral, has been coarsened by the metamorphism; its grain-size varies considerably from layer to layer but, in general, increases northward through the property. The taconite shows retrograde metamorphism with hydrous iron-silicate minerals forming at the expense of anhydrous varieties.

^{*/}Work done partly on behalf of the Minnesota Geological Survey

The Biwabik Iron-formation and overlying Virginia Formation strike N. 25-35° E. and dip 15-35° SE. The outcrop belt of these rocks is truncated at a slight angle by the intrusive Duluth Gabbro Complex, and in the northern part of the area both formations are cut out completely. Southward, the iron-formation extends uninterruptedly down-dip beneath the overriding gabbro and Virginia Formation and can be mined for some distance below the outcrop by open-pit methods.

Although the structure is superficially simple, the iron-formation is locally faulted and folded and is pervasively jointed. A few steeply-dipping faults that strike northward and northwestward cut and displace the formation; maximum displacements do not exceed a few tens of feet. Small-scale folds, some of which are related to the northward-trending faults, produce local flattening of the beds and widening of the outcrop belt. Two sets of systematic joints, sub-parallel to the major fault sets, and many other joints occur throughout the rocks at Dunka River. The north- and northwest-trending faults and systematic joint sets appear to be related to regional stress patterns; most of the other structures are probably related to emplacement of the gabbro.

STRUCTURAL CONTROL OF THE MOUNT WRIGHT -
MOUNT REED IRON DEPOSITS, QUEBEC

Peter J. Clarke
Department of Natural Resources, Province of Quebec,
Quebec, Canada

The Mount Wright - Mount Reed district, located about midway between Seven Islands and Schefferville in northern Quebec, has proven to be an important source of concentrating grade iron ore. The district contains the southern extension of the Labrador Trough, which has been deformed and metamorphosed by the Grenville Orogeny. It is underlain by Proterozoic metasediments, including gneisses, marble, quartzite, iron-formation and aluminous schists, which rest on a basement of remetamorphosed granulite and gneiss. Acidic and basic intrusions are common in the gneisses below and above the iron-formation respectively.

The Proterozoic metasediments change in sedimentary facies from near-shore deposits in the northwest to deeper water deposits in the southeast. Their structural style varies in different parts of the district, depending on the presence or absence of folds of two structural trends (northeast to east and northwest to north). In a part of the district relative simple folds of only one trend dominate; in another part cross folds are developed, and folds of both trends are about equally abundant. Much of the valuable oxide-facies iron-formation occurs in the cross-folded zone, and the important iron deposits lie in structural basins separated by domes of older gneiss. Where the cross-folds are spaced relatively uniformly, iron deposits are repeated at about four-mile intervals on a rough grid with axes trending northeast to east and northwest to north.

PROTOCLASTIC BORDERS OF THE FELSITE
NEAR BERGLAND, MICHIGAN

Joseph P. Dobell and Robert W. Leonardson
Department of Geology and Geological Engineering, Michigan
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An intrusive mass of felsitic rock located along the north side of Gogebic Lake near Bergland, Upper Michigan, shows distinctly protoclastic borders at contacts with basalt and sandstone which indicates that the rock was at least partially solidified at the time of emplacement.

Zones showing protoclastic structure vary in width from one to four feet, and grade away from contacts to a directionless fine grained felsite. The most conspicuous features of these border zones are a distinct banding resembling flow (fluxion) structure or sedimentary banding, and a granular texture which gives the weathered rock the appearance of a very coarse sandstone or a granule conglomerate.

MEASUREMENT OF IN-SITU STRESSES IN A SAINT CLOUD QUARRY
A PROGRESS REPORT

Charles Fairhurst
School of Mineral and Metallurgical Engineering
University of Minnesota, Minneapolis

The phenomenon of rock "pressure" is well known to quarry workers and often results in effects such as undesired fracturing of blocks during quarrying. Modification of quarrying procedures appears to affect the incidence of pressure effects.

The paper describes surface strain gauge and borehole deformation measurements now in progress in a Saint Cloud quarry to determine the magnitude and orientation of the stresses considered to be responsible for the pressure effects. The geology of the area is briefly described. Preliminary results from one quarry suggest that substantial (4000 lb. per sq. in.) horizontal (lateral) stresses exist in the directions suspected by the workmen.

Further tests, which will be discussed, are planned to determine whether the stresses are regional (i.e. externally developed) or residual (i.e. internally developed, for example during cooling). Hast (1958) has measured high horizontal stresses in underground mines in Scandinavia. The major axes of the stress ellipsoids at various points appear to be directed towards the center of earthquake activity in Scandinavia. He suggests that similar regional stresses may be expected in the Great Lakes region of North America. The possibility that the stresses may be residual is suggested by the fact that pressure effects are most serious in the finer-grained rocks.

PROGRESSIVE CONTACT METAMORPHISM OF THE BIWABIK
IRON-FORMATION ON THE MESABI RANGE, MINNESOTA

Bevan M. French
Theoretical Division, NASA, Goddard Space
Flight Center, Greenbelt, Maryland

The Biwabik Iron-formation, on the Mesabi range in northern Minnesota, is the middle unit of the three-fold Animikie Group of Middle Precambrian age. On the eastern end of the range, the Animikian rocks have been metamorphosed by the intrusive Duluth Gabbro Complex; mineralogical changes in the sediments, particularly in the iron-formation, appear related to the gabbro.

From the data of the present study, four metamorphic zones may be distinguished within the Biwabik Iron-formation by changes in mineralogy along the strike of the formation toward the gabbro contact:

(1) unaltered taconite extends from the western limit of the Mesabi range approximately to the town of Aurora. It is composed of quartz, magnetite, hematite, siderite, ankerite, talc, and the iron silicates chamosite, greenalite, minnesotaite, and stilpnomelane. Of these, only quartz, hematite, chamosite, greenalite, siderite, and some magnetite are considered primary. The textures of the other minerals indicate a secondary origin, possibly through diagenesis or low-grade metamorphism prior to intrusion of the Duluth Gabbro Complex.

(2) transitional taconite contains the same mineralogy but exhibits extensive replacement by quartz and ankerite. Incipient metamorphic changes in this zone are the partial reduction of hematite to magnetite and the appearance of clinozoisite in the underlying Pokegama Formation.

(3) moderately metamorphosed taconite is characterized by development of the iron-rich amphibole grunerite and by the disappearance of original iron carbonates and silicates. Calcite appears from reaction of ankerite and quartz to form grunerite.

(4) highly metamorphosed taconite, within two miles of the Duluth Gabbro contact, is completely recrystallized to a metamorphic fabric and is composed chiefly of quartz, iron amphiboles, iron pyroxenes, magnetite, and rare fayalite and calcite. Small veins and pegmatites reported from this zone may represent minor introduction of material from the gabbro.

The following mineralogical changes occur along the strike of the iron-formation toward the gabbro contact:

- (a) partial reduction of hematite to magnetite
- (b) development of clinozoisite (in the Pokegama Formation)
- (c) formation of grunerite

- (d) appearance of iron-rich clinopyroxene (hedenbergite)
- (e) disappearance of hematite
- (f) appearance of ferrohypersthene
- (g) appearance of graphite (from organic matter).

All the changes, which represent the complete transition from unmetamorphosed to highly metamorphosed taconite, occur within a horizontal distance of about two miles near Mesaba.

Compositions of the carbonate minerals in the iron-formation were determined by combining refractive index measurements with X-ray diffraction data to obtain values for the Ca, Fe, and Mg components. In unaltered taconite, siderite compositions approximate $\text{Ca}_5\text{Fe}_{7.5}\text{Mg}_{2.0}$; ankerite compositions from the same material are quite uniform at approximately $\text{Ca}_{5.3}\text{Fe}_{2.4}\text{Mg}_{2.3}$. The calcites that appear in the metamorphosed taconite are Fe-rich and Mg-poor, approximating $\text{Ca}_{8.9}\text{Fe}_{1.0}\text{Mg}_1$.

No definite change in siderite or ankerite compositions is noted along the strike of the Biwabik Formation; there is no indication of progressive removal of iron from the carbonate with increasing metamorphism. By contrast, calcites from the metamorphosed taconite increase in Ca, becoming virtually pure CaCO_3 near the gabbro.

The present study indicates that metamorphism of the Biwabik Iron-formation by the Duluth Gabbro Complex was largely isochemical and was characterized chiefly by progressive loss of H_2O and CO_2 . There is no indication that the original mineralogy consisted only of quartz and magnetite, or that large quantities of other components were introduced into the sediments from the gabbro, as has been proposed (Gundersen and Schwartz, 1962).

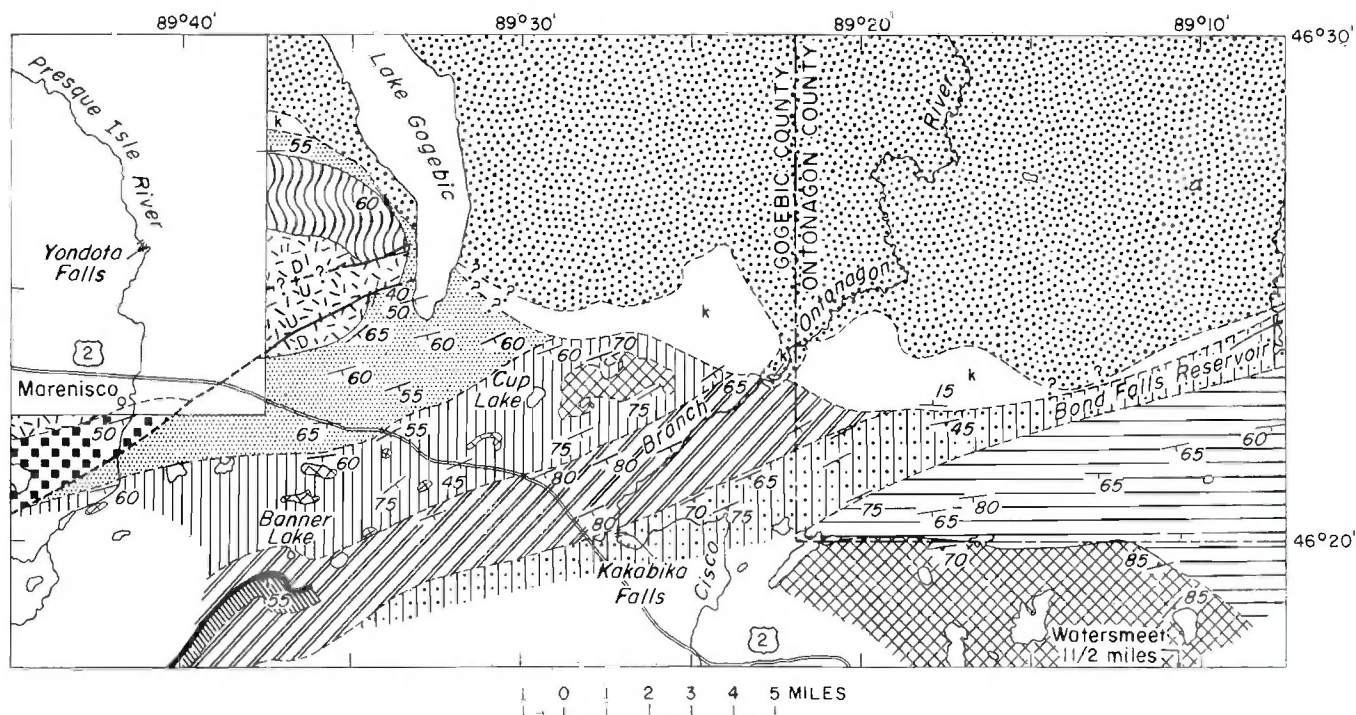
STRATIGRAPHY, STRUCTURE, AND GRANITIC ROCKS IN THE
MARENISCO-WATERSMEET AREA, MICHIGAN^{*/}

Crawford E. Fritts
U. S. Geological Survey, Denver, Colorado

Recent detailed mapping near Lake Gogebic, Michigan, reconnaissance, and review of data from the Marenisco-Watersmeet area recorded by the Michigan Geological Survey since 1900 have led to reinterpretation of regional stratigraphy and structure. The Tyler Slate of the Gogebic Range wraps around the nose of an east-plunging anticline west of the lake and conformably underlies a thick sequence of south-dipping meta-volcanic and metasedimentary rocks, which apparently underlies the Michigamme Slate (fig. 1, on next page). North of Cup Lake, graded bedding in quartzite formerly interpreted as folded and overturned strata of the Marenisco Range indicates that rocks there actually are right side up. Similarly, near Kakabika Falls, pillow structures in metavolcanic rocks indicate that strata of the Turtle Range also are right side up. The principal structure between Marenisco and Watersmeet, therefore, is a south-dipping monocline. Although diamond-drill data indicate a synclinal flexure near Banner Lake, field evidence at present does not require tight folding or large-scale faulting there. However, a fault of large throw accounts for the westward disappearance of the Tyler Slate near Marenisco, and it is possible that other faults will be found farther east as mapping continues.

Rocks formerly mapped as Presque Isle Granite include at least three distinctive lithologic units of different ages. Banded gneiss and a younger equigranular granite unconformably overlain by the Tyler Slate west of Lake Gogebic probably are pre-Animikie in age. Well foliated, well lineated, biotite-rich, granitic to quartz monzonitic gneiss intrudes rocks stratigraphically above the Tyler south and east of Marenisco and probably is post-Animikie in age. In the Marenisco-Watersmeet area, the metamorphic grade of Animikie strata, in general, increases southeastward toward the center of a broad zone underlain, in part, by the post-Animikie gneiss. It is likely, therefore, that the metamorphism accompanied and perhaps followed emplacement of this gneiss.

^{*/} Work done in cooperation with the Geological Survey Division
of the Michigan Department of Conservation



E X P L A N A T I O N

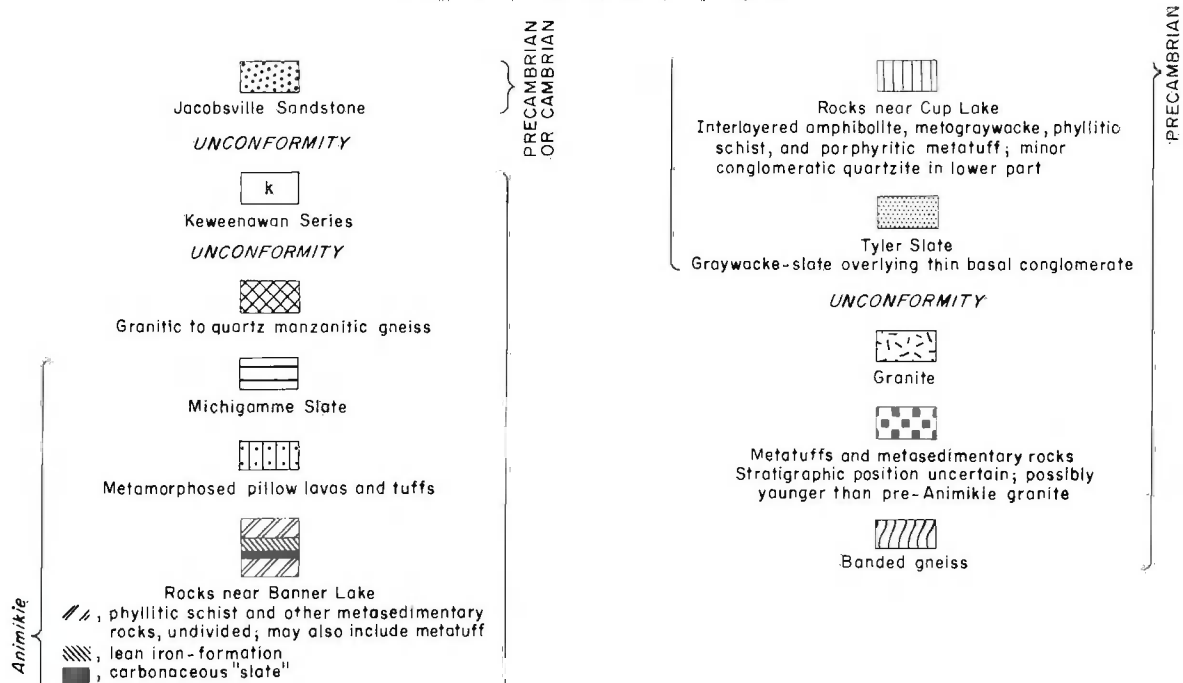


Figure 1. Preliminary geologic map of the Marenisco-Watersmeet area, Michigan, showing tentative interpretation of stratigraphy and structure by C. E. Fritts, 1965.

STRUCTURE AND STRATIGRAPHY OF THE KNIFE LAKE GROUP
EAST OF ELY, MINNESOTA^{*/}

John C. Green
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In the Gabbro Lake 15-minute quadrangle just east of Ely, Minnesota, Precambrian Knife Lake rocks occur in two belts. The southern belt, composed of schist, gneiss, and migmatite, is derived from graywacke, conglomerate, and arkose, and is intruded and metamorphosed by the Giants Range batholith of Algoman age. It is faulted against the basal part of the older but lower-grade Ely Greenstone on the north side of the belt, along the major North Kawishiwi fault.

The northern and wider belt has been metamorphosed only to the chlorite zone. Its contact with the underlying Ely Greenstone is mostly faulted, but locally conformable with a basal conglomerate. Above this are, successively, 0-2,500 feet of mixed felsic tuff and clastic sediments, 1,500-4,500 feet of chloritic clastic sediments, a predominantly mafic volcanic unit 0-2,250 feet thick, and a thick sequence of felsic volcanic rocks, mainly pyroclastic, as much as 8,000 feet thick. Within this unit near Fall Lake is a 500-foot bed of siliceous limestone and chert conglomerate. The felsic volcanic rocks interfinger with mafic volcanics similar to Ely Greenstone northwest of Fall Lake, and are faulted against mafic volcanics and sediments of unknown correlation in the northwest and north-central borders of the area.

Knife Lake time in this area evidently was one of great crustal disturbance, with rapid erosion of the older greenstones and the rocks that intrude them, and extensive volcanic activity, probably mostly underwater. An active, island arc type of environment is envisioned. This activity culminated in the batholithic intrusions and extensive faulting of the Algoman orogeny.

^{*/} Work done on behalf of the Minnesota Geological Survey

PETROLOGY OF THE SILICATE IRON-FORMATION IN THE REPUBLIC
MINE AREA, MARQUETTE COUNTY, MICHIGAN

Tsu-Ming Han and James W. Villar
Cleveland-Cliffs Iron Company, Ishpeming, Michigan

The iron-rich metasediments at the Republic mine can be subdivided into four lithologic types according to major mineral constituents. These include a quartz-specular hematite-muscovite conglomeratic member at the base of the Goodrich Formation and three lithologic types within the Negaunee Iron-formation, which normally reflect a close relationship between stratigraphic position and major mineral assemblage. In descending stratigraphic order the mineral assemblages generally are: quartz-specular hematite, quartz-magnetite, and quartz-grunerite-magnetite. The type characterized by the latter assemblage, the subject of this study, is as much as 500 feet thick and commonly contains a series of sill-like amphibolites.

The rock is typically banded as a result of compositional variations in the ratios of quartz, magnetite, and grunerite. Bands with oolites of quartz-magnetite, quartz-grunerite-magnetite, and grunerite-magnetite are common. Locally, carbonate occurs as a major constituent of some bands.

Five generations of minerals are recognized: (1) scattered grains of original clastic quartz and fine-grained magnetite, (2) quartz, magnetite, grunerite, garnet, calcite, hornblende, and pyroxene, formed during regional metamorphism, (3) stilpnomelane, minnesotaite, hornblende, and calcite, formed during retrograde metamorphism, (4) quartz-calcite, quartz-hematite, and an unidentified brownish green silicate, formed as fracture fillings subsequent to metamorphism, and (5) martite and hematite, formed from magnetite and grunerite during supergene oxidation.

Paragenetic studies indicate that grunerite formed, at least in part, at the expense of magnetite and quartz during metamorphism in the Republic mine area. This is indicated by the following observations:

- (1) growth of grunerite porphyroblasts in nearly pure magnetite bands,
- (2) presence of magnetite-quartz remnants within grunerite bands,
- (3) magnetite grains within grunerite bands exhibit irregular or subrounded crystal outlines in contrast to subhedral and euhedral magnetite in assemblages lacking grunerite,
- (4) common development of thin grunerite layers between magnetite and quartz bands, and
- (5) growth of grunerite along the borders of magnetite-rich veinlets that cut quartz bands.

This reaction is further substantiated by determinations of ferric and ferrous iron contents of the iron-formation, which reveal

an inverse relationship between the quantities of magnetite and grunerite.

This does not preclude the participation of other reactants such as carbonates and layered iron silicates in the development of grunerite.

AGES OF MAFIC DIKES NEAR GRANITE FALLS, MINNESOTA^{*/}

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Precambrian rocks exposed in the Minnesota River valley near Granite Falls, Minnesota consist of interlayered metamorphic rocks intruded by numerous mafic dikes. Existing structures in the metamorphic rocks resulted from dynamothermal metamorphism about 2.6 billion years ago. A later 1.8 b.y. thermal event is reflected in potassium-argon and rubidium-strontium ages of biotite from the metamorphic rocks.

The dikes can be divided petrographically into tholeiitic diabase, hornblende andesite, and olivine diabase. Older tholeiitic diabase dikes are cross-cut by several varieties of hornblende andesite dikes. In addition, shear zones, which by field evidence could have formed during the late stages of the 2.6 b.y. event, cross-cut the tholeiitic diabase but are cut by hornblende andesite dikes. One of the hornblende andesite dikes is intruded by a 1.8 b.y. granitic body. The relative age of the olivine diabase with respect to the other dikes was not determined in the field.

In this study, a potassium-argon determination on hornblende from the metamorphosed country rock gives an age of 2.8 b.y., which indicates that the hornblende was not affected by the 1.8 b.y. thermal event. Hornblende from a tholeiitic diabase dike gives an age of 2.0 b.y.; four of the varieties of hornblende andesite dikes gave concordant biotite and hornblende potassium-argon ages of 1.7 - 1.8 b.y.

If the 2.0 b.y. age is real, the shearing occurred between 2.0 and 1.8 b.y. ago. If, however, this 2.0 b.y. value reflects the loss of argon at 1.8 b.y., the intrusion of the tholeiitic diabase and the shearing could have taken place at the close of the 2.6 b.y. metamorphic event.

^{*/}Work done on behalf of the Minnesota Geological Survey

AN EXAMPLE OF STATISTICAL ANALYSIS AND POSSIBLE INTERPRETATION
OF STRUCTURAL DATA FROM ARVON HILL, SKANEE QUADRANGLE,
UPPER PENINSULA, MICHIGAN

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Arvon Hill is located in Skanee quadrangle, Upper Peninsula of Michigan, about 13 miles northeast of L'anse.

Regionally, the area is underlain by Lower Precambrian metamorphic rocks, which are overlain unconformably by Animikian metasediments. Younger glacial deposits are virtually absent except along the flanks of the hill.

Five major types of rocks have been recognized in the Argon Hill area, namely, quartzite (Ajibik), amphibolite gneiss, migmatite, granitic rock, and dioritic rock. The last four rock types form the Lower Precambrian or Archean basement; the quartzite occurs on the flanks of the hill. An anticlinal structure is inferred from the distribution of the rock units.

Foliations, lineations, and joints were recorded and plotted on Schmidt nets for statistical analysis. Structural data from the Lower Precambrian rocks were separated from those of the Animikian rocks.

The present-day structure observed in the rocks was analyzed first. The limbs of the quartzite were then rotated back to horizontal. The same amount of rotation for the underlying rocks was used, thus rotating all structures to their assumed position before folding of the quartzite. These new sets of readings were plotted, contoured, and interpreted as the pre-quartzite structure.

Joints were analyzed separately. As indicated by Badgley's "triangle of intersection," the joint system in the Lower Precambrian rocks resulted from two periods of stress, whereas the joint system in the quartzite is the result of only one period, the second.

It is concluded that at least two periods of folding affected the area as a result of forces from approximately the same direction.

SOME ASPECTS OF IRON-FORMATIONS IN AUSTRALIA AND SOUTH AFRICA

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The extent of Proterozoic iron-formations in the Hamersley Range of Western Australia has been recognized only recently. The Hamersley Range, which covers about 40,000 square miles, probably contains more exposed iron-formation than any equivalent area in the world. Three banded iron-formations having an aggregate thickness of more than 3,500 feet and, probably, a total of more than 80,000 feet of Proterozoic sediments occur in the area.

In South Africa, a more or less continuous belt of Proterozoic iron-formation that is part of the Transvaal System extends for more than 800 miles. The iron-formation is locally more than 5,000 feet thick, but is generally 800-2,000 feet thick.

A brief account of the general Proterozoic stratigraphy and the stratigraphy of the iron-formations from each area will be presented to show how they differ from the stratigraphy of the Lake Superior region. Layers of altered pyroclastic rocks in the iron-formations indicate that there was volcanic activity during much of the time the iron-formations in each area were being deposited.

Certain features of the iron-formations in Western Australia and South Africa are very similar to those in iron-formations in the Lake Superior region, but others--notably the occurrence of crocidolite asbestos and the virtual absence of granules--are distinctly different. There is more similarity between Australian and South African iron-formations than there is between iron-formation of either area with the Lake Superior region.

THE DISTRIBUTION OF MANGANESE IN THE
BIWABIK IRON-FORMATION, MINNESOTA

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The weighted mean Mn content of the Biwabik Iron-formation based on 948 individual samples is 0.48 per cent. This represents an enrichment of about 4.8 times the mean crustal abundance (Clarke) of this element. The Biwabik shows a mean Mn/Fe ratio of 0.016 as compared to a crustal average of 0.022 for this ratio, thus indicating a slight geochemical separation of Mn and Fe.

Samples of iron-formation that have been oxidized without appreciable leaching or iron enrichment have considerably lower Mn/Fe ratios than do unoxidized taconites. Core samples of ores (enriched oxidized taconites containing more than 40 per cent Fe) show only a slightly lower mean Mn/Fe ratio than unaltered taconite, but their mode and median for this ratio are much lower. The sideritic sections of the iron-formation contain the most manganese and the goethite-rich oxidized sections contain the least.

There appears to be no significant variation in the Mn content of the Biwabik laterally if only unoxidized samples are considered. There is, however, a significant difference between the four members; the means in per cent Mn are as follows: Lower Cherty - 0.67, Lower Slaty - 0.44, Upper Cherty - 0.34, Upper Slaty - 0.29.

In an attempt to show the local variations in the Mn content a trend surface was computed for an area with closely spaced holes. The trend surface ($\%Mn = X_n = f(U,V,W)$) accounts for 52 per cent of the sum of squares. Deviations from the trend surface cut across the formation thus suggesting that some of the variability may be due to secondary oxidation and leaching along joint planes.

SOME ASPECTS OF THE PEGMATITES IN THE FELCH DISTRICT,
DICKINSON COUNTY, MICHIGAN

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Numerous simple, unzoned pegmatites cut the pre-Animikian metamorphic units in the Felch district. Size and shape of the pegmatites vary from small sinuous bodies in the Mill Pond Granite Gneiss to large irregular masses in the Solbert Schist.

In an attempt to subdivide the pegmatites into meaningful groups, the Be, Mo, and Ti contents of twenty unclustered pegmatites were determined spectrographically. Ratios of the concentrations of these elements provide a basis for separating the pegmatites into two distinct groups. A similar analysis was run on the granite dikes and samples of the granite gneiss in the Felch district. Seven of the pegmatites (Group I pegmatites), characterized by a relatively high Ti:Be+Mo ratio, plot in the same area of a relative-percent triangle diagram as the granite dikes and the granite gneiss. Group II pegmatites, comprising the remaining thirteen of the pegmatites and characterized by a relatively low Ti:Be+Mo ratio, plot in a distinctly different region on the diagram. Correlation coefficients between Be-Mo, Be-Ti, and Mo-Ti also emphasize the difference between the two groups. Group I pegmatites and the granite dikes and gneiss show small positive correlations between Be and Mo and relatively large negative correlations between Be-Ti and Mo-Ti. Group II pegmatites have a large positive correlation between Be-Mo and small correlations between Be-Ti and Mo-Ti, positive and negative respectively.

There appears to be no simple relation between geographical location, size, shape, or host rock unit and the two groups of pegmatites. The strikes of bodies within the different groups, however, are divergent. Strikes of Group I pegmatites are confined to the range N. 30° E. - N. 80° E., whereas the strikes of Group II pegmatites are seemingly haphazard.

It is suggested that the two groups of pegmatites in the Felch district represent either (1) different parental sources, or (2) intrusion at different stages of the progressive differentiation of a single parent magma under different tectonic controls.

THE SAUBLE GEOPHYSICAL ANOMALY, LAKE COUNTY, MICHIGAN

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A detailed gravity and magnetic survey was conducted of the Sauble anomaly of Lake County, Michigan. This outstanding anomaly is a circular magnetic and gravity high having residual maximum amplitudes of 1,130 gammas and 22 milligals respectively. The combined gravity and magnetic analysis method utilizing Poisson's equation was applied to the residual anomalies. An idealized case was employed to check the accuracy of the combined analysis method. The composition, form, size, and depth of the anomalous body were studied further by depth determinations and by fitting idealized cases to the observed anomaly profiles. It was concluded that the anomalous body is a very basic Precambrian intrusive stock. The elevation of the top of the body and the Precambrian surface in this area is about 8,000 to 9,000 feet below sea level.

THE SEDIMENTOLOGY OF THE PRECAMBRIAN ROVE FORMATION
IN NORTHEASTERN MINNESOTA^{*/}

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The Middle Precambrian Rove Formation, the upper part of the Animikie Group, is estimated to be at least 3,200 feet thick, and is exposed between northwestern Cook County, Minnesota and the Thunder Bay district, Ontario. It is a sequence of graywacke, argillite, locally abundant intraformational conglomerate, quartzite, and carbonate rocks. This sequence was deposited some time between 2.0 b.y. and 1.7 b.y. ago in a northeast-trending basin, the configuration of which was probably controlled by a pre-existing structural grain.

Detailed mapping in the South Lake 7 $\frac{1}{2}$ -minute quadrangle, combined with a field and laboratory study of approximately 150 other scattered stratigraphic sections provide a basis for the recognition of four informal lithologic units. From oldest to youngest these are: (1) lower argillite, 400 feet thick; (2) transition beds of inter-bedded argillite and graywacke, 70 - 100 feet thick; (3) thin-bedded graywacke, as much as 2,000 feet thick; and (4) upper graywacke-quartzite, at least 700 feet thick.

It is concluded that the argillite and associated graywacke-sandstone and graywacke-siltstone units were deposited in moderately deep, quiet water which was probably marine. Repeated sedimentation units one to three feet thick indicate sediment transport and deposition by turbidity currents. A sedimentation unit reconstructed from composite sections consists of (1) a basal conglomeratic graywacke, (2) a structureless unit that grades indistinctly into (3) a graded graywacke that is overlain by (4) a laminated graywacke, which may be modified by (5) small-scale cross-bedding, or (6) contorted bedding. Any one or several of these may be absent, but the unit is always overlain by (7) an argillite.

Post-depositional soft-sediment structures such as load casts, flame structures, clastic dikes, bed pull-aparts, overfolds, and micro-faults indicate rapid deposition of Rove sediments, active bottom currents, and post-depositional deformation.

A detailed analysis of paleocurrent directional indicators such as grain lineations, groove casts, flute casts, dendritic ridges, and cross-bedding show that the turbidity currents had a southerly trend perpendicular to the axis of the Rove basin. However, ripple marks, winnowed lag deposits at the tops of many graywacke beds, and festoon-type cross-bedding show that the turbidities were later modified by bottom currents that trended southwesterly parallel to the axis of the basin.

^{*/}Work done on behalf of the Minnesota Geological Survey

The heavy minerals of the Rove are characterized by epidote-group minerals, apatite, sphene, and tourmaline, and are typical of pre-Middle Precambrian igneous rocks now exposed north of the present outcrop area of the Rove Formation.

Thin section and X-ray analyses of 200 samples show that the graywackes consist of angular, poorly sorted grains of clastic quartz and plagioclase ($An_{10}-An_{25}$) embedded in an argillaceous matrix that now consists of quartz, chlorite, and muscovite. The fine-grained, fissile argillite and mudstone have the same mineralogy and micro-textures as the graywacke.

Erosion subsequent to pre-Keweenawan tilting removed an unknown amount of the formation prior to the deposition of Lower Keweenawan sedimentary rocks. The intrusion of Middle Keweenawan igneous rocks caused local metamorphism of the Rove Formation to a variety of mineral assemblages now assigned to the pyroxene- and hornblende-hornfels facies, but the remainder is essentially unmetamorphosed.

SEDIMENTATION OF MIDDLE PRECAMBRIAN QUARTZITES IN FINLAND

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The Jatulian quartzites, metamorphosed 1,800 m.y. ago, were studied in eastern, central, and northern Finland to decipher the sedimentary history of the original sandstones. Erosional remnants of the formation, several hundred meters thick, indicate an initial distribution over an area of about 400,000 km². The quartzites at some localities are completely recrystallized; at other localities they are sheared but retain sedimentary characteristics. Most of the quartzites were formed under conditions of the amphibolite facies, with the degree of metamorphism increasing from east to west.

The sandstones were mainly clayey orthoquartzites, clayey subarkoses, and clayey arkoses. The clayey matrix has been recrystallized into mica. Zircon is the only abundant nonopaque detrital heavy mineral; most other heavy minerals were formed during metamorphism.

The source rocks were mainly granitic with indeterminate proportions of granites and gneisses. Zircon varieties indicate derivation from both para- and ortho-gneisses. Large parts of the formation are mineralogically and texturally mature; evidently detritus on the weathered, vegetation-free landmass, as well as similar sediment supplied by streams from the east, was reworked by wind and then by the shallow sea. Clay was probably carried into the sea with quartz sand, separated there by wave and current action, and then again mixed with sand prior to burial. Carbonates and shales were deposited upon the sandstones.

Analysis of cross-bedding indicates that the major paleocurrent movement in the Jatulian Sea was toward the west-northwest, with a secondary but prominent current movement toward the south-southwest. One of these currents probably moved parallel to the shoreline and the other normal to it. The sea probably transgressed eastward upon a stable, low-lying landmass.

PETROLOGY OF THE AMBERG PRECAMBRIAN CRYSTALLINE
COMPLEX, NORTHEASTERN WISCONSIN

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Reconnaissance study of parts of northeastern Wisconsin by J. A. Cain and others has resulted in recognition of the Quinnesec Formation, pink Amberg Granite, and gray Amberg Granite. Detailed mapping of approximately 100 square miles during the summer of 1964 has resulted in the identification of an additional unit, the Amberg Granodiorite. In addition, diabase and basalt dikes were found cutting the granitic units.

The Quinnesec Formation include greenstones and meta-basalts, which contain plagioclase and hornblende and minor amounts of chlorite, epidote, and quartz. The unit is exposed along the north and northeastern boundaries of this area and in a small triangular patch south of Amberg.

The major part of the area is underlain by the pink Amberg Granite, which is circular in outline. The rocks are fresh, massive, coarse-grained pink granites. Locally they have a rapakivi texture. Xenoliths of Quinnesec Formation and gray Amberg Granite are not uncommon. The rocks are composed of microcline-perthite, sodic oligoclase, quartz, biotite, and hornblende. Minor shear zones are present. Lineation and foliation are poorly developed. The unit intrudes the gray Amberg Granite, Amberg Granodiorite, and the Quinnesec Formation.

The gray Amberg Granite is exposed in the center of the area and is almost surrounded by the pink unit. It consists of fresh, massive, medium- to fine-grained gray granites composed of orthoclase-perthite, oligoclase-sodic andesine, quartz, biotite, and hornblende.

The Amberg Granodiorite covers most of the southeastern part of the area. It is coarse-grained, altered, and has abundant xenoliths of the Quinnesec Formation. Shear zones and mafic schlieren are common throughout the unit. The rocks consist of orthoclase-perthite, oligoclase-andesine, quartz, biotite, and hornblende.

Modal analyses and chemical analyses for alkalies suggest that the granitic units represent independent intrusions. Field and petrographic data point to a magmatic origin for the granites.

A STUDY ON THE HYDROLOGY OF POTHOLES IN MINNESOTA^{*/}

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A study of the hydrology of potholes (ponds) in Minnesota by the writer and associates has been carried out since 1962. Potholes and adjacent lakes were selected in various parts of the state to represent as many different topographic and geologic situations as practical. Detailed observations were made on 39 potholes and lakes and limited observations on about 60 others.

The field work included sinking test holes adjacent to shore to determine the character of the soil and the depth of the water table, observing the water (and ice) levels in the ponds, collecting bottom sediments, and classifying samples of the bottom sediments according to soil type. Limited X-ray and pollen studies of selected samples were also made. Cross-sections and graphs were prepared of all pertinent data.

Tentative results and conclusions include the following:

1. The glacial deposits adjacent to the water are extremely variable lithologically, but most are reasonably permeable as shown by movement of water out of test holes.
2. No consistent relation exists between the open water surface and the groundwater surface except in the Anoka Sand Plain.
3. Most of the ponds and lakes show a similar pattern of fluctuation of the water levels throughout the year.
4. With few exceptions, the water levels in the ponds are determined mainly by the relation of precipitation to evapotranspiration.
5. In highly permeable soil, such as in the Anoka Sand Plain, the open water and groundwater surfaces coincide and fluctuate together by movement of water from one to the other as required by 4, above.
6. Most lakes and potholes do not contribute significant quantities of water to underground storage.
7. The bottoms of potholes normally consist of silt, clay, and organic matter.
8. In ponds that lose water by seepage, the water level rises during the spring break-up and periods of heavy rains, then declines far beyond possible loss by evapotranspiration and continues to decline after the freeze-up; collapse of the ice occurs in severe cases of loss of water. In contrast, most ponds remain relatively stable while covered by ice.

^{*/} Funds to start the program were made available in 1962 by the Minnesota State Soil Conservation. Supervision of the project and additional funds were provided by the Department of Agricultural Engineering.

PRELIMINARY RESULTS OF GEOCHEMICAL PROSPECTING
NORTH OF THE MARQUETTE IRON RANGE, MICHIGAN

Kenneth Segerstrom
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Geochemical prospecting by means of sampling of surficial material has been conducted in Marquette County during the past two field seasons. More than 600 samples have been collected and chemically analyzed for their total heavy-metals content. Many of the samples were also analyzed for copper, lead, zinc, and manganese, and some samples were examined spectrographically for cobalt, nickel, and other elements. A few were assayed for gold and silver.

Preliminary results have encouraged the continuance of sampling in the so-called "Northern Range," just north of the Dead River storage basin, and have discouraged its continuance in the "Southern Range," between the Dead River and the Marquette Iron Range. In the Northern Range good results have been obtained on the lee side, glacially speaking, of ridges of resistant pre-Animikie graywacke and volcanic rocks which lie on the limbs and crest of an anticlinorium. The ridges are bordered to the north and south by synclinal valleys underlain by poorly resistant slate. The stoss side of ridges tend to have a thick till cover and the valleys are deeply filled with glaciofluvial sand. Soils underlain by the till and the sand do not show concentrations of heavy metals. The best results are obtained where the cover of surficial materials (chiefly glacial) is thin, and where there are abundant admixtures of colluvium derived from the bedrock ridges.

Anomalous concentrations of copper and lead or zinc, of the order of hundreds of parts per million, have shown up in samples taken in N $\frac{1}{2}$ sec. 30, T. 49 N., R. 27 W. In that area of no mines or prospects, the exposed bedrock locally contains fine-grained disseminated pyrite and galena. In the same township, lesser anomalies that are likewise apparently unrelated to known sulfide deposits have shown up in SE $\frac{1}{4}$ sec. 21, NW $\frac{1}{4}$ sec. 27, S $\frac{1}{2}$ sec. 26, and NW $\frac{1}{4}$ sec. 36.

KEWEENAW FAULT, HOUGHTON COUNTY, MICHIGAN

Kiril Spiroff
Michigan Technological University,
Houghton, Michigan

The talk will describe a few of the geologically interesting features found associated with the Keweenaw Fault in Houghton County, Michigan.

ORGANIC GEOCHEMISTRY OF ROSSBURG PEAT BOG,
AITKIN COUNTY, MINNESOTA^{*/}

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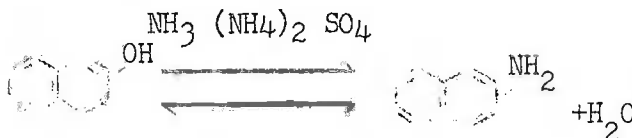
Rossburg peat bog occupies about 600 acres in secs. 18 and 19, T. 47 N., R. 25 W. and sec. 24, T. 47 N., R. 26 W., Aitkin County, Minnesota. Coarse-detritus, reddish brown Sphagnum moss peat extends to depths of from 12 to 19 feet and is underlain by fine-detritus, dark brown to black copropel, and sapropel-peat to depths of 22 feet or more. Below the peat lies slightly calcareous and organic clay to depths of 27 feet or more, beneath which lies sand.

Moisture content of the peat is 85-90%; that of the underlying clay 50-68%, and of the sand 34%. Ignition loss ranges from 67.6% to 96.5% in the peat and from 11.0% to 15.5% in the clay and sand. pH values increase gradually from 4.0 at the surface of the peat to 7.2 at the base of the peat and are about 6.8-7.0 in the clay and sand. Eh values gradually decrease from +420 mv at the surface of the peat to -20 mv at 28 feet in the sand; in general, Eh values are negative below 16 feet in the peat.

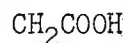
Kjeldahl nitrogen averages about 1% in the upper 3 feet of the peat, below which it increases to between 1.8% and 2.8%; it decreases abruptly to 0.5% or less in the underlying clay. Protein amino acids show distribution consistent with variations in type of peat and nitrogen content. Basic amino acids occur throughout the peat and indicate prevailing acid conditions in the history of the bog.

Total carbohydrates average about 100 mg/gm expressed as glucose equivalent in Sphagnum peat, but decrease to 50-70 mg/gm in copropelic peat. Glucose and arabinose are the predominant mononaccharides.

Saturated and aromatic hydrocarbons and hydrated phenols increase in total amount from 2×10^{-4} g/g at the surface of the moss peat to 4×10^{-4} g/g at 4 feet, below which a decrease occurs to base of moss peat. Absorption spectra of chromatographic fractions show that 2-naphthol is an important hydrocarbon constituent of the moss peat. It is suggested to have formed either from a protein-naphthylamine by Bucherer reaction:



or from a plant-growth accelerator (auxin) such as naphthylacetic acid:



^{*/} Work done partly on behalf of the Minnesota Geological Survey

Beta-carotene as observed in UV-visible spectra is a significant component of the copropelic peat but is nearly absent from the overlying moss peat. It is interpreted as originating from phytoplankton when there was a lake in the area. Pheophytin a from chlorophyll shows a similar relationship to facies of the peat.

Carbonyl-group compounds observed in IR spectra are quantitatively more important in the moss peat than in the underlying lake peat.

The organic analyses aid in understanding the developmental history of the deposits and in evaluation of them as commercial sources of plant nutrients and peat chemicals.

TECTONICS OF THE KEWEENAWAN BASIN,
WESTERN LAKE SUPERIOR REGION-*/

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The subsurface structure of the western Lake Superior region has been analyzed by combining surface geologic, aeromagnetic, gravity, and paleomagnetic data. Surface attitudes and map patterns suggest that the upper Keweenawan sedimentary rocks have the general form of a lens thickening to the southeast, away from a feathered edge along the Minnesota shore of Lake Superior. Graphic subtraction of the assumed gravitational effect of this sedimentary lens from the Bouguer anomalies of the region leaves a residual anomaly due primarily to the mafic lavas and intrusives. When residual maps for various assumed thicknesses of the sedimentary rocks are compared with the aeromagnetic maps, the patterns more or less coincide when the thickness of sedimentary rocks under the Bayfield Peninsula is assumed to be at least 25,000 feet. The analysis leads to recognition of the following stages in the tectonic history of the region:

(1) Accumulation, during middle Keweenawan time, of a thick series of lava flows and mafic intrusives in two basins or troughs, separated by a positive area that trends more or less north-south across the Bayfield Peninsula, Wisconsin, in which the lavas are thin or absent.

(2) Evolution of the present Lake Superior basin, with axis trending northeast, during late Keweenawan time.

(3) Development of the Ashland syncline and the major faults of the region (Douglass, Keweenaw, Lake Owen) still later in Keweenawan time.

If the Duluth Gabbro Complex is a sheet of fairly uniform thickness dipping to the southeast under Lake Superior, the combined thickness of gabbro plus lavas should attain a maximum somewhere under the lake. The gravity maximum is actually about 10 miles northwest of the Minnesota shore of the lake, suggesting that the gabbro pinches out beneath the lavas somewhere near the shore.

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CONTRIBUTIONS OF ROCK PHYSICS TO GEOLOGY

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Laboratory study of rock behavior can be a useful guide to understanding of rock behavior in the field. A goal of rock physics research at the Bureau of Mines Minneapolis Center is the identification, classification, and definition of rock and mineral properties that influence behavior under laboratory-imposed stresses. A significant part of the current research effort involves petrographic analysis of rock fabric in core samples.

Most rock material can be regarded as having some degree of fabric anisotropy, as expressed by population parameters of mineral species, a tangible end-product of geologic history. Such parameters of compositional anisotropy may at times be reflected in the mechanical response of laboratory specimens to artificially-created stresses. For example, tensile failure studies in such rocks as granite and gneiss show definite correlation of fracture path characteristics with fabric anisotropism, as expressed in feldspar, amphibole, mica, and quartz. Similarly, field correlation exists for rocks having rift, grain, bedding, or other planar features, resulting in fracture patterns which are used to advantage by quarrymen. Shear failure, on the other hand, is not necessarily related to fabric anisotropy.

Inclusion of fabric anisotropism in field study can supplement correlation of deformed and/or fractured rock material with stresses to which it has been subjected during its geologic history. Such fabric study can be facilitated by petrographic work without use of a U-stage. Thus, by making thin sections normal to core axes drilled from field-oriented rock in three, mutually-perpendicular directions, a three-dimensional picture is obtained of fabric anisotropy such as, e.g., foliation. Rock physics is using this approach in the testing of an oriented block from the St. Cloud area to correlate fabric anisotropy with field anisotropy.

AN AEROMAGNETIC SURVEY OF WESTERN LAKE SUPERIOR

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In March 1964, an aeromagnetic survey was conducted over the western half of Lake Superior, covering the area westward from the tip of the Keweenaw peninsula to Duluth, Minnesota. The survey consisted of 7,500 miles of north-south flight lines spaced at six-mile intervals. A digital recording proton precession magnetometer system installed in a Navy P2V-5 (Neptune) aircraft, flown 3,000 feet above sea level, was used in the survey.

The results of the survey indicate a very flat magnetic character over the major portion of Lake Superior. Several known geologic features are traced by the magnetic anomalies: the Keweenaw, Douglas, and Lake Owen faults, and the Gogebic and Marquette iron ranges. The existence of the Isle Royal fault appears to be confirmed, and possibly it extends as far east as Superior Shoals. The existence of a North Shore fault is questionable; however, a fault may be present south of Isle St. Ignace.

Western Lake Superior appears to be underlain by a syncline, bounded on the north and south by major fault systems, which continues southeasterly into the eastern half of Lake Superior.

GEOLOGICAL ANALYSIS AND REMEDIAL ACTION
IN AN OPEN PIT ROCK SLIDE

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Two rock slides in the same wall of an open pit in iron-formation were studied to determine the cause of the slope failures, and to propose remedial measures to prevent further failures.

The upper slide zone is about 200 feet higher in elevation and 400 feet west of the lower one. Although the immediate cause of the rock failures was mining activity, the real cause of the instability is the presence of geologic structural defects.

The iron-formation strikes N.35°E. and dips 12°SE. A system of near-vertical joints cuts the strata; the most prominent set strikes N.45°W., parallel to the pit wall and to the ore-trough. A 50- to 100-foot thick fault zone that strikes N.50°E. and dips 25-30°SE crosses the upper slide area and the top of the lower one.

The base of the upper slide is a 3-foot chloritic "green shale" layer. Where it is fractured and permeable to water, the material is physically weak and tends to "squeeze out." This layer is stratigraphically above the lower slide area. The chronology of the slope failures and check surveys also support the conclusion that the two slides are not expressions of a single deep-seated cause and thus could be treated independently.

Remedial action for the lower unstable zone consisted of changing the mining sequence so as to decrease the ratio of weight to potential failure plane area.

The upper slide area constituted an unusual problem because economic considerations required haulage over rock-fill and over the unstable zone where all the elements creating instability still existed. The remedial design involved removal of the slide rock and installation of post-tensioned cables in rock back-fill. The system is designed to provide lateral restraint to the "squeezing" layer, increased frictional resistance at the back-fill bench interface, and increased shear resistance within the back-fill by placing it in compression. This is believed to be the first designed use of post-tensioned rock-fill for control of a potential slide zone.