

14TH ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY



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**SPONSORED BY DEPARTMENT OF GEOLOGY,
WISCONSIN STATE UNIVERSITY, SUPERIOR
AND MINNESOTA GEOLOGICAL SURVEY**

MAY 5 - 6 - 7, 1968

TECHNICAL SESSIONS
ABSTRACTS

For

14TH ANNUAL

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Held On Campus Of

WISCONSIN STATE UNIVERSITY, SUPERIOR, WISCONSIN

MCCASKILL HALL

May 6-7, 1968

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14th ANNUAL
INSTITUTE ON LAKE SUPERIOR GEOLOGY
McCASKILL HALL

WISCONSIN STATE UNIVERSITY
SUPERIOR, WISCONSIN

May 6-7, 1968

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The field trip conducted in connection with the Institute was held in the Duluth Complex area of Ely, Minnesota on Sunday, May 5th, 1968. This trip was hosted by the Minnesota Geological Survey, P. K. Sims, Director. Extra field trip guides are available.

PROGRAM

14th Annual

INSTITUTE ON LAKE SUPERIOR GEOLOGY

McCaskill Auditorium
Wisconsin State University
Superior, Wisconsin

Sunday, May 5, 1968

8:00 - 10:30 p.m. Smoker and Advanced Registration
Hiawatha Room, Student Union

Monday, May 6, 1968

7:45 a.m. Registration - Lobby, McCaskill Hall

8:30 a.m. TECHNICAL SESSION I - McCaskill Auditorium

Co-chairmen: C. Iverson and R. L. Bleifuss

Welcome Karl W. Meyer, President
Wisconsin State University, Superior

1. Trace Elements in Minnesota Iron Formations
Henry Lepp
2. Rare-Earth Elements in the Duluth Gabbro
Larry A. Haskin and Barton Denechaud
3. Geophysical Study of Lake Superior
Richard J. Wold
4. The Paleomagnetism of Middle Keweenaw
Volcanic Units
H. C. Palmer
5. Rb-Sr Ages of Intrusions Along the
Keweenaw Fault in Northern Michigan
Sambhudas Chaudhuri, G. Faure and
Douglas G. Brookins
6. An Investigation of the Vertical Velocity,
Density and Porosity Distribution in the
Jacobsville Sandstone, Houghton County,
Michigan
Lloyal O. Bacon, R. W. Ingalls
and J. F. Stafford
7. A Gravity Survey of a Portion of the
Flin Flon Greenstone Belt in Northeastern
Saskatchewan
Donald Gendzwill
8. The Penokean and Hudsonian Orogenies in the
Great Lakes Region, and the Age of the
Grenville Front
William R. Church

12:30 p.m. Luncheon
Hiawatha Room, Student Union

1:30 p.m.

TECHNICAL SESSION II - McCaskill Auditorium

Co-chairmen: R. W. Marsden and G. L. LaBerge

1. Stratigraphic and Structural Framework of the Vermilion District and Adjacent Areas, Northeastern Minnesota
Paul K. Sims, G. B. Morey,
R. W. Ojakangas and W. L. Griffin
2. Volcanism, Sedimentation, and Stratigraphy of the Western Vermilion District, Northeastern Minnesota
Richard W. Ojakangas and G. B. Morey
3. Geology of the Duluth Complex in the Perent Lake and Kawishiwi Lake Quadrangles, Lake and Cook County, Minnesota
Donald M. Davidson, Jr.
4. An Investigation of Rocks of Possible Cretaceous Age, Walberg Creek Area, St. Louis County, Minnesota
S. Viswanathan and Paul K. Sims
5. Metamorphism of the Biwabik Iron Formation, Dunka River Area, Minnesota
Bill Bonnichsen
6. Differentiation Sequence of the Great Lakes Nickel Intrusion
N. D. MacRae and E. J. Reeve
7. Sulfide Assemblages of the Great Lakes Nickel Intrusion
Paul R. Mainwaring
8. Study of a Selected Area of Lake Superior: Progress Report
Joseph W. Horton, R. C. Brown,
D. W. Davidson, A. B. Dickas,
W. Lunking and R. K. Roubal

6:30 p.m.

ANNUAL BANQUET

Sky Lounge, Student Center

Address: "Recent Lunar Exploration Results"
Dr. John F. McCauley
USGS Branch of Astrogeology
Flagstaff, Arizona

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or marine

Tuesday, May 7, 1968

8:40 a.m.

TECHNICAL SESSION III - McCaskill Auditorium

Co-chairmen: J. W. Trow and P. E. Giblin

1. The Federal-Provincial Committee on Huronian Stratigraphy -- Progress Report
James A. Robertson, K. D. Card
and M. J. Frarey
2. Stratigraphic Relationships of Some Keweenawan Rocks of Michigan and Wisconsin
Harold A. Hubbard
3. Distribution Patterns of Post-glacial Sediments in Lake Superior
William R. Farrand
4. Palynological Study of Post-glacial Bottom Sediments from Deep-Water Localities in Lake Superior
William S. Benninghoff and
Judith M. Franklin
5. New Light on Animikie Algal Structures Through Darkfield Illumination
W. W. Moorhouse
6. Possible Glacial Origin for Three Precambrian (Huronian) Conglomerates, North Shore of Lake Huron
G. M. Young and F. W. Chandler
7. Ice-stagnation Features of the Bloomer Moraine, Northwest Wisconsin
Robert F. Black
8. The Seaman Method of Mineral Identification as Used at Lake Superior State College
C. Ernest Kemp

12:20 p.m.

Luncheon
Hiawatha Room, Student Union

1:15 p.m.

Business Meeting - McCaskill Auditorium
Chairman: Paul K. Sims

1:30 p.m.

TECHNICAL SESSION IV - McCaskill Auditorium

Co-chairmen: G. Durfee and H. H. Woodard

1. Current Investigations of Meteorite Impact Structures in the Canadian Shield
Michael R. Dence and
Nicholas M. Short
2. Petrographic Evidence for a Meteorite Impact Origin of the Sudbury Structure, Ontario
Bevan M. French
3. Progress of Geologic Investigation of the Mellen Granite, Ashland County, Wisconsin
Michael M. Katzman
4. Varieties of Flows in the North Shore Volcanic Group, Minnesota
John C. Green
5. Structure and Significance of Intrusive Sandstone Dykes of the Siamo Slate of the Marquette Trough, Upper Peninsula, Michigan
C. McA. Powell
6. The Sedimentology of the Middle Precambrian Thomson Formation
G. B. Morey and R.W. Ojakangas
7. The Sequence of Geological Events in the Marquette Iron Range During the Penokean Orogenic/Metamorphic Cycle
Larry L. Babcock
8. Chert Bed Characteristics in the Lake Superior Iron Formations
Joseph T. Mengel

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TRACE ELEMENTS IN MINNESOTA IRON FORMATIONS

Henry Lepp, Chairman
Department of Geology
Macalester College
St. Paul, Minn.

This is a progress report on a continuing investigation of minor elements in Minnesota iron formations. The elements cobalt, nickel, and gallium were determined in composite samples of the Biwabik iron formation, the Trommald formation, and of oxidized material from the Biwabik formation. Samples of iron silicate (grunerite), magnetite, chert, and dolomite separated from the Biwabik formation also were analyzed.

Cobalt and gallium were determined at the laboratories of the General Atomic Corporation by neutron activation analysis. A composite sample of the Biwabik iron formation showed 9.51 p.p.m. cobalt and 16 p.p.m. gallium. Composites of Oxidized Biwabik formation gave similar results. A composite sample of the Trommald formation from the North Cuyuna district showed 36 p.p.m. cobalt and 27 p.p.m. gallium. The South Cuyuna district composite showed 25 p.p.m. cobalt and 57 p.p.m. gallium. Analyses of minerals separated from specimens of the Biwabik formation show cobalt to range from 1.7 p.p.m. in chert to 10.1 p.p.m. in iron silicates. Gallium values for chert are 1.8 p.p.m. and for iron silicate, 18 p.p.m.

Nickel is being determined colorimetrically and at the time of this writing replicate analyses are being run. Preliminary results indicate that nickel seems to correlate with cobalt. The highest nickel values were found in samples of the Trommald formation.

Very little is available in the published literature on trace elements in iron formations or ironstones. Moreover, as pointed out by James (1966) the available analyses must be viewed with caution because marked differences have been reported for the same samples by different laboratories. The comparison with even the few published values that are available, therefore, must be viewed with the realization that the variation in values due to the analyst and the analytical method may be as great or greater than that between sample variation.

The results of this investigation to date seem to corroborate the work of Landergren (1948) on trace elements in iron rich rocks in that the trace element abundances in these Precambrian iron formations are low when compared to similar values in younger ironstones. There appears to be a general increase in trace elements in the Cuyuna district which represents the deeper part of the depositional basin.

James, H. L., 1966, Chemistry of the iron-rich sedimentary rocks: U. S. Geol. Surv., Prof. paper 440-w, 60 p.

Landergren, Sture, 1948, On the geochemistry of Swedish iron ores and associated rocks: Sueriges Geol. Under., Arsbok 42, No. 5, Ser. C, N_o. 496, 182 p.

RARE-EARTH ELEMENTS IN THE DULUTH GABBRO

Larry Haskin, Department of Chemistry, University of Wis., Madison
Barton Denechaud, Department of Chemistry, University of Wis., Madison

Rock samples from the Duluth complex have been analyzed for rare earths by a neutron activation method. Like most of the gabbros and diabases investigated from other locations, the Duluth gabbros have significantly lower total rare-earth contents and lower ratios of light to heavy rare earths than basalts. Variations in rare-earth abundances with rock type and location for Duluth samples will be discussed.

GEOPHYSICAL STUDY OF LAKE SUPERIOR

Richard J. Wold, Assistant Professor
Department of Geology
University of Wisconsin
Milwaukee

Since 1964 the University of Wisconsin has been conducting an underwater gravity survey of Lake Superior and has occupied over 1600 gravity stations in the lake and bays. The majority of the stations are located on a five mile grid with closer spacing in some areas. The survey was conducted with L & R underwater gravimeters and the positioning was provided by IORAC Service Corporation.

The gravity data analyzed in conjunction with aeromagnetic data suggest two major structural features in the western part of the lake. One of the features is a ridge running north-south in the vicinity of 91°00'W. The second major feature is a ridge extending southwestward from Isle Royale.

Both gravity and magnetics indicate a major fault just north of Isle Royale trending eastward to the area of Superior Shoal. Another fault noted in the magnetics trending from Isle St. Ignace to Isle Royale is also confirmed by the gravity. There is no evidence in the gravity for the postulated fault extending from Superior Shoal to the Keweenaw Peninsula.

Most of the faults postulated by Hinze on the basis of an aeromagnetic survey in eastern Lake Superior are supported by the gravity survey. The two strongest positive anomalies in the eastern part of the Lake correspond with magnetic highs. They occur around Standard Rock and northwest of Michipicoten Island.

The gravity field in eastern Lake Superior does not show the strong anomalies seen in western Lake Superior except for the low north of Superior Shoal. The field seems to support the suggestion that the Lake Superior syncline curves around the Keweenaw Peninsula to the southeast.

THE PALEOMAGNETISM OF MIDDLE KEWEENAWAN VOLCANIC UNITS

H. C. Palmer, Assistant Professor
Department of Geophysics
The University of Western Ontario, London, Ontario

Paleomagnetic results from over 300 samples of Middle Keweenawan volcanics and sills from the Lake Superior region have been obtained. The Logan sills, the sections of volcanics at Alona Bay and the Osler volcanics all have reversed polarity. The section of volcanics on Michipicoten Island is of positive polarity. The North Shore volcanics of Minnesota, the lavas at Gargantua Point and the section at Mamianse Point have both normal and reversed polarity sequences. All sections of reversed polarity yield closely grouped pole positions (mean 148° W, 50° N) which are different from the pole positions calculated from sections of positive polarity which are also closely grouped about a mean position of 177° W, 34° N. The asymmetry of normal and reversed directions of magnetization may be attributed to a very hard but small secondary component of magnetization which has been added to all these Keweenawan rocks subsequent to their eruption.

RB-SR AGES OF INTRUSIONS
ALONG THE KEWEENAWAN FAULT IN NORTHERN MICHIGAN

S. Chaudhuri, Department of Geology, Kansas State Univ., Manhattan
G. Faure, Department of Geology, Ohio State University, Columbus
D. G. Brookins, Department of Geology, Kansas State Univ., Manhattan

In northern Michigan several intrusive bodies occur at different locations near the Keweenawan fault. These bodies occur near the base of the Middle Keweenawan Portage Lake Lava Series, but their exact geologic age and mode of origin are not clear.

Rb-Sr whole rock study of four felsite samples from the Bare Hills yields a least-squares isochron age of 934 ± 6 m.y. with initial $\text{Sr } (87/86) = 0.7166 \pm 0.0003$. A similar study of the syenodiorite of the Mount Bohemia area yields an age of 1130 ± 25 m.y. with initial $\text{Sr } (87/86) = 0.7045 \pm 0.001$.

These data suggest at least two distinct periods of igneous activity in Michigan during late Precambrian time, an early syenodioritic intrusion and later felsitic intrusion. These two intrusions also resulted from different magma sources as indicated by the large difference in initial $\text{Sr } (87/86)$ ratio.

Since both contemporaneity and consanguinity of the Mount Bohemia syenodiorite and the Middle Keweenawan Portage Lake Lava Series are possible and plausible, the period of intrusion of the syenodiorite may date the culmination of extrusion. Later emplacement of the Bare Hills felsite may have occurred at a time when the Keweenawan sedimentation was already in progress.

AN INVESTIGATION OF THE VERTICAL VELOCITY, DENSITY AND
POROSITY DISTRIBUTION IN THE JACOBSTOWN SANDSTONE,
HOUGHTON COUNTY, MICHIGAN

L. O. Bacon, Professor of Geophysics, Michigan Technological University
R. W. Ingalls, Senior in Applied Geophysics, Michigan Tech. University
J. F. Stafford, Senior in Applied Geophysics, Michigan Tech. University

A laboratory study was made of the pulse velocity, density and porosity on core samples taken at ten foot intervals from a 3628 foot diamond drill hole in the Jacobstown sandstone near Rice Lake, Houghton County, Michigan.

Calculations based on the data provides a vertical velocity function, $V = 10,200 - 2.42 z$ to a depth, z , of 1200 feet and a velocity function to 3600 feet of $V = 8100 + 1.90 z$. The large velocity gradient might cause considerable error if these functions were extrapolated to depths below 1200 feet and 3600 feet respectively; therefore use of a constant velocity of 9000 ft/sec to the first major velocity discontinuity and of 13000 ft/sec beyond that discontinuity is recommended for use on all reflection seismic calculations.

Application of the constant value functions to Bacon's area-2 reflection data (1964) from a location 10 miles southwest of Rice Lake gives a thickness of the Jacobstown formation of 10,000 feet and the depth to the first major velocity discontinuity of approximately 2000 feet in that area.

The average value of porosity to the 1200 foot depth is 14.2 percent with a range of 10 to 17 percent. Below 1200 feet the porosity decreases to 3.5 percent at 3600 feet. The density of the Jacobstown had an average value of 2.25 grams per cubic centimeter to the 1200 foot depth and a constant 2.55 grams per cubic centimeter below 1800 feet.

A GRAVITY SURVEY OF A PORTION OF THE FLIN FLON GREENSTONE
BELT IN NORTHEASTERN SASKATCHEWAN

D. Gendzwill, Assistant Research Officer
Saskatchewan Research Council
Saskatoon, Saskatchewan

An interpretation of the Bouguer gravity in the Precambrian Amisk Lake-Flin Flon Area of northern Saskatchewan shows that the outcropping Amisk Group of basic to acidic volcanics and clastic sediments is limited in depth to a maximum of about 5 kilometers. Lighter rocks with more or less uniform density underlie the Amisk Group. Granite and granodiorite rocks intrude the volcanic sequence but are also limited in depth. Most of the density variations do not persist to depths of more than 3 to 5 kilometers.

Densities of 1585 rock samples were determined in the laboratory. Analysis of the densities shows that some basic volcanic rock units have mean densities as low as 2.66, other units have mean densities as high as 3.03. Gradations in density of volcanic rocks due to variations in metamorphic grade or composition cause broad gravity anomalies.

Crustal seismic work in the area shows that P wave velocities of 6.0 to 6.15 km/sec exist to depths of 10 km to 15 km. Material with this velocity at such depth can only be low density rock such as granodiorite. This conclusion supports the gravity interpretation since both methods indicate lighter material at depth. This low density rock might represent older rocks on which the Amisk Group was deposited or it could indicate an increased quantity of granitic material emplaced in the Amisk rocks at depth.

THE PENOKEAN AND HUDSONIAN OROGENIES IN THE GREAT LAKES REGION,
AND THE AGE OF THE GRENVILLE FRONT

William R. Church
Assistant Professor
Department of Geology
University of Western Ontario, London

Huronian rocks deformed during the Penokean orogeny define an approximately east-west trending fold belt modified in the form of a large Z-shaped orocline, which extends from Minnesota to Ontario as far east as the Grenville Front. The long held view that the folds in the Huronian of Ontario are coeval with those of the Penokean fold belt of the Lake Superior region is supported by the correlation made by Young (1966) of the Cobalt Group of Ontario with the lower part of the "Aniakie Series" of Michigan. This correlation is based on the occurrence in both units of exotic rock types including tillite, aluminosilicate-bearing orthoquartzite, and banded ferruginous quartzite.

Nipissing diabase of Ontario, which has a Rb-Sr isochron age of 2100 m.y. (Van Schmus, 1965), was intruded after initiation of Penokean deformation (Church, 1965), and it is therefore certain, if the latter age is valid, that both the deposition of the Huronian and the major phase of Penokean deformation are older than ca. 2100 m.y. The Huronian of Ontario is everywhere metamorphosed, and ages of the order of 2000 m.y. cited by Fairbairn, Pinson, and Hurley (1966), and also Knight (1966), to represent the age of Huronian sediments and volcanics, are more probably minimum ages of the Penokean metamorphism.

Metamorphism of the Huronian of Ontario is irregularly developed both geographically and with reference to the Penokean fold sequence. It is most strongly developed along the northern margin of the southern belt of folded Huronian, where it varies in grade from lower greenschist (chlorite) to lower almandine-amphibolite (staurolite) facies (Card, 1964). Secondary post-Nipissing diabase deformation is also strongly developed in this region, and early Penokean structures pre-dating the diabase are usually completely transposed by the later deformation. Towards the south the secondary deformation is more weakly developed and large scale primary folds are prominent. With respect to the second phase of deformation, metamorphism in the north was pre-kinematic, whereas to the south the metamorphism was both pre- or syn-kinematic and post-kinematic. The relationship of the earlier metamorphism, during which kyanite was formed in orthoquartzites, to the secondary deformation is not at present entirely clear. Andalusite in quartzites, and biotite and garnet in pelites, were produced during the post-kinematic phase of metamorphism. In Michigan, granites and associated pegmatites considered by James (1955) to be post-deformation and post-metamorphic have ages of ca. 1900 m.y. (Aldrich, Davis, and James, 1965). These ages being minimum ages they corroborate the isotopic data of

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Fairbairn, Pinson and Hurley (1966) and Knight (1966) in suggesting that the regional metamorphism of the Huronian is related to the Penokean orogeny, rather than to the Hudsonian orogeny which is commonly given an age of ca. 1750 m.y. However, granites and the pegmatites intrusive into the Huronian of Ontario have both Rb-Sr and Rb-Sr isochron ages of ca. 1750 m.y. (Wetherill, Davis and Tilton, 1960; Davis and others 1967), and may therefore correctly be described as Hudsonian. The granites post-date the second phase of Penokean deformation and regional metamorphism, but pre-date a late phase of brittle deformation. Brooks (1967), considers the pre-granite deformation and regional metamorphism of the Huronian in the vicinity of the Grenville Front to coincide with the formation of the Front, from which it therefore follows that the Grenville Front must be a Penokean feature. It is not inconceivable that it was also a significant feature at the time of Huronian sedimentation, the area east of the Front possibly being a region of positive relief during early Huronian time (Young, 1968). The late phase of post-granite brittle deformation, which is quite strongly developed along the northern margin of the southern belt of Huronian, may be related to the post-granite cataclastic deformation commonly observed along the Front. The cataclastic deformation, according to Brooks (1967) deforms Keweenawan olivine-diabase dykes, and is therefore probably Grenville in age.

The length of time during which Phanerozoic orogenic events takes place is in general of the order of tens of millions of years or less. The difference in age of the Penokean and Hudsonian orogenies is of the order of 350 m.y. In terms of Phanerozoic geology therefore, the Penokean orogeny represents no more than a relatively minor episode during a period of crustal stability extending from 2400 m.y. to 1700 m.y. Alternatively, the Penokean orogeny may represent the initial phase of the break down in crustal stability leading to the extensive Hudsonian cycle of magmatic activity. The general absence of sediments in the age range 2100 to 1700 m.y. would tend to support the latter possibility.

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STRATIGRAPHIC AND STRUCTURAL FRAMEWORK OF THE VERMILION
DISTRICT AND ADJACENT AREAS, NORTHEASTERN MINNESOTA

P. K. Sims, Director, Minnesota Geological Survey, Minneapolis, Minn.
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The Vermilion district, in northern St. Louis County, lies between the Vermilion batholith on the north and the Giants Range batholith on the south. It contains the dominantly mafic volcanic rocks that comprise the Ely Greenstone and younger clastic rocks that have been called the Knife Lake Group. Iron-formations of Keewatin type, which include the Soudan, occur at several stratigraphic positions in the Ely Greenstone and in the overlying volcaniclastic rocks. A variety of porphyries intruded the bedded rocks and in part are contemporaneous with them. All the bedded rocks are older than the intrusive rocks of the Vermilion and Giants Range batholiths, which have been dated as Algoman (2,400-2,750 m.y.) in age by S. S. Goldich and others. The Algoman intrusive rocks in the area are syntectonic with respect to the metamorphism and deformation of the older rocks.

The sequence of bedded rocks in the district resembles that described from the greenstone belts of Canada by A. M. Goodwin and others. In general, initial volcanic flows, dominantly basaltic in composition, pass upward into volcaniclastic rocks of intermediate and, locally, felsic composition, and these in turn pass upward into clastic sedimentary rocks, originally mainly graywacke and mudstones of similar composition. Deposition of iron-rich sediments was repeated numerous times, particularly in the lower and intermediate parts of the volcanic and clastic sequence. Pillowed basaltic flows were extruded locally during the deposition of the volcaniclastic and clastic rocks. To judge from their distribution and thickness, the flows and associated volcaniclastic rocks accumulated to great thicknesses in local volcanic centers and formed discontinuous deposits. In contrast, the younger clastic rocks probably were deposited over a much wider area.

The rocks of the Vermilion district are separated from the Vermilion batholith by a major high-angle fault, the Vermilion fault, and lesser sub-parallel and branching faults. The abrupt transition from granite and associated high-grade metamorphic rocks on the north side of the fault to greenschist-facies rocks in the district proper suggests that the Vermilion fault had a dominantly vertical component of movement. The displacement of steeply-dipping Precambrian metamorphic rocks along a branching fault is left lateral--a horizontal distance of one mile--suggesting that there also was a substantial horizontal component of movement. The fault is thought to have formed initially prior to or during igneous intrusion but to have moved also subsequent to emplacement.

On the south side of the district, the granitic rocks of the Giants Range batholith have intrusive relations to the older volcanic

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and sedimentary rocks. Adjacent to the batholith, the older bedded rocks are regionally metamorphosed to the amphibolite facies both along and across strike. Staurolite and locally almandine are developed in pelitic rocks having appropriate composition, the mafic rocks are metamorphosed to amphibolites.

Internally, the rocks comprising the Vermilion district are deformed by both folding and faulting. Except locally, the strata dip steeply and generally plunge steeply, thus, the present earth's surface is essentially a section perpendicular to the plunge. Faults of variable trend cut the rock sequence and break it into a number of separate blocks. Correlation from block to block is difficult, and complicated by the difficulty of distinguishing minor and intermediate-scale folds from lithologic lenses.

The widespread showings of disseminated iron and copper sulfides, the occurrence of iron sulfides and quartz along fault zones, and the resemblance of the rock sequence to that in areas known to contain base metal sulfide deposits warrant investigation of the region as a potential source of base metal sulfide ores. Formerly the district was a significant source of high-grade hematite, having yielded more than \$100 million worth of iron ores.

VOLCANISM, SEDIMENTATION, AND STRATIGRAPHY OF THE
WESTERN VERMILION DISTRICT, NORTHEASTERN MINNESOTA.

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The Vermilion district in northern St. Louis County contains a wide variety of rocks that in the past have been assigned to either one of two large groups. These groups are (1) the Ely Greenstone, composed dominantly of pillowed mafic flows with minor diabase, tuffaceous sediments, and lenses of iron-formation, and (2) the overlying Knife Lake Group, composed of a heterogeneous mixture of clastic and volcaniclastic sediments. Because the Saganaga Granite intrudes the Ely Greenstone at the east end of the district, and because the Knife Lake Group contains pebbles derived from the granite, it has been assumed that these two groups were formed in separate and distinct geologic environments separated in time by a period of igneous intrusion and erosion. This stratigraphic concept led most early workers to assign almost all occurrences of pillowed mafic flows to the Ely Greenstone without regard to their detailed stratigraphic relationships. The areal distribution of these rocks was then explained by structural complexities such as tight isoclinal folding.

Detailed field studies at the western end of the district, in the vicinity of Tower and Soudan, indicates that no major unconformity exists between the rocks previously assigned to the Ely Greenstone and the Knife Lake Group. Rather, the lithologic associations and tectonic history in this part of the Vermilion district appears to be analogous to "volcanic pile accumulations" in Archean basins of Canada as described by Goodwin (1967), in which thick sequences of mafic flows grade through increasing proportions of volcanic fragmental rocks to thick piles of felsic pyroclastics intercalated with and overlain by clastic sediments.

Three principle lithologic assemblages are tentatively recognized in the Tower-Soudan area, but their age relationships to one another are obscured by stratigraphic complexities, faulting and folding.

The oldest rocks, composed primarily of pillowed mafic flows with minor amounts of intrusive diabases and diorite, tuffaceous sediments, and lenses of iron-formation that extend from Tower eastward through Ely, are still assigned to the Ely Greenstone. The second assemblage consists predominantly of "typical" gray to black graywacke and interbedded slate with rare tuffaceous beds and mafic flows. The remaining assemblage is characterized by its heterogeneity. It is composed of

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several lensoid and gradational rock units including tuffaceous (greenish gray) graywacke and greenish-gray interbedded slate, feldspathic quartzites, conglomerates, quartz-rich tuffs, quartz porphyries, pillowed mafic to intermediate flows, minor sericite schists, volcanic agglomerates and breccias, black slates, diabasic greenstones, and iron-formations (including the Soudan Iron Formation which has traditionally been assigned to the upper part of the Ely Greenstone). Thus it contains rock types that are both typical of and intermediate between the other two assemblages. Pillowed mafic flows are not necessarily indicative of the early stages of this volcanic accumulation and, therefore, cannot be assigned *a priori* to the Ely Greenstone. This stratigraphic succession presents many as yet unresolved stratigraphic problems, especially in establishing formal stratigraphic names for rocks in the two younger lithologic assemblages, and in redefining a regionally useful contact between the Ely Greenstone and the Knife Lake Group.

Original sedimentary features are abundant in this area of low-grade metamorphism. The sedimentary rocks have all the essential characteristics of true volcanoclastic sediments in that the clastic constituents have their counterparts in associated volcanic rocks and appear to have been derived from them by rapid, contemporaneous erosion. The graywacke beds of the intermediate and upper lithologic assemblages commonly display excellent graded bedding, some have loaded soles, and some show scour features. The conglomerates, generally composed of quartz porphyry clasts and minor iron-formation clasts, commonly have "disrupted frameworks" with the pebbles not being in contact with each other. They are interbedded with and commonly grade into gritty and sandy quartz-rich tuffs which are difficult to distinguish from quartz porphyries that were penecontemporaneously extruded or emplaced at shallow depths. The grading and the "disrupted frameworks" indicate that basin gradients were sufficient for turbidity currents and submarine slumping to be active. The lack of large-scale cross-bedding and related features, and the preservation of fine laminations suggests deposition in at least moderately deep water.

The thickness of the pile is difficult to estimate because of complex structure, but probably totals somewhere between 10,000 and 40,000 feet and hence is probably of geosynclinal dimensions.

GEOLOGY OF THE DULUTH COMPLEX IN THE PERENT LAKE AND
KAWISHIWI LAKE QUADRANGLES, LAKE AND COOK COUNTY, MINNESOTA

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The Perent Lake and Kawishiwi Lake 7 1/2 - minute quadrangles are located in Lake and Cook counties, Minnesota, about thirty miles north of Little Marais. Field mapping and research was done during 1966 and 1967 and was supported by the Minnesota Geological Survey.

The area is situated in the upper part of the Duluth Complex and associated granophyre. The bedrock consists mainly of gabbroic and troctolitic anorthosite, although troctolite, gabbro, anorthosite and intermediate rock types have also been noted. Leucocratic rocks, in addition to the granophyre, intrude the complex. Also of interest is the presence of a weakly mineralized (Cu-Ni), fine- to a medium-grained gabbroic anorthosite, similar to a part of the mineralized rock in the Gabbro Lake quadrangle, South Kawishiwi River area. Structural analysis and interpretation is being coordinated with recent geophysical investigations, as yet unfinished. Preliminary analysis of the fracture pattern suggests two distinct trends, which may have implications on the tectonics of the Lake Superior Basin.

AN INVESTIGATION OF ROCKS OF POSSIBLE COUTCHICHING AGE,
WALBERG CREEK AREA, ST. LOUIS COUNTY, MINNESOTA

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The discovery of a cataclastic gneiss below Keewatin (Ely) pillowed basalts, amphibolites, and minor intercalated metasediments during reconnaissance mapping in the Walberg Creek area in the summer of 1967 led to a detailed field investigation followed by laboratory studies. The area is on the northern fringe of the Giants Range batholith, along its contact with the Ely-Knife Lake sequence of rocks, just east of Idington. The cataclastic gneiss occurs on the northwest limb of a complex anticline, three miles wide, that trends east-northeasterly and plunging steeply eastward. The core of the fold is occupied by a foliated hornblende granodiorite of Algoman age, cut by an aplitic leucogranodiorite. Both of these intrusive rocks are mylonitized at places. Inclusions of amphibolite occur rarely in the granodiorite within the core of the fold.

Three possible explanations for the cataclastic gneiss were considered during the mapping:

1. It represents part of a succession that is older than the greenstone, and thus is equivalent to the Coutchiching of A.C. Lawson.
2. It represents a sheared facies of the foliated hornblende granodiorite that characterizes the core of the anticline, and
3. It represents a segment of the Keewatin volcanics, modified in texture and composition by shearing with synchronous introduction of granitic material.

Results of petrographic studies, modal analyses, and determination of the compositions of plagioclases and hornblendes from the critical lithologic units, using the electron microprobe, are summarized below.

The cataclastic gneiss is composed of 12-26 percent hornblende, 67-73 percent calcic oligoclase, 3-12 percent K-feldspar, 1-5 percent quartz, and a total of 1-5 percent epidote, sphene, apatite, pyrite and opaques. The plagioclase ranges in composition from An_{18} - An_{27} . The hornblende contains 11.6-12.9 percent MgO, 15.4-17.4 percent Fe-oxides, and 11.7-12.2 percent CaO. The gneiss contains plagioclase phenocrysts interpreted as a relict volcanic texture. Most of the plagioclases are saussuritized; microscopic evidence indicates that the K-feldspars and quartz were introduced into the rock.

The amphibolite has 39 percent hornblende, 53 percent andesine, 1-2 percent K-feldspar, 1 percent quartz, and a total of 6 percent sphene,

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chlorite, apatite, and opaques. The plagioclase is unzoned and has a composition of An_{33} - An_{46} . The hornblende contains 11 percent MgO, 17.4 percent Fe-oxides, and 12.1 percent CaO. The presence of euhedral zoned relict plagioclase phenocrysts is indicative of a volcanic parentage.

The interlayered metasediments occur as discontinuous layers generally three inches to one foot thick, and are represented by biotite-plagioclase (An_{25})-quartz-microcline schist with minor amounts of hornblende, hornblende-plagioclase-microcline-quartz schist with subordinate biotite, and striped hornblende-plagioclase (An_{31})-epidote-microcline-quartz rock.

The foliated hornblende granodiorite is composed of 15-18 percent quartz, 14-16 percent K-feldspar, 54-59 percent calcic albite, 8-12 percent hornblende, and a total of about 1 percent biotite, chlorite, sphene and apatite. The plagioclase is distinctly zoned, has sodic oligoclase cores, and ranges from An_9 to An_{11} . The hornblende contains 10.8 percent MgO, 17.9 percent Fe-oxides, and 11.3 percent CaO. The rock is allotriomorphic-granular, and has myrmekitic intergrowths and hornblendes with poikilitic quartz.

Graphical analyses of these data lead to the following conclusions:

- (1) The cataclastic gneiss closely resembles the amphibolite in composition. Both rocks have relict volcanic textures and hence are meta-igneous. The gneiss, therefore, does not represent the Coutchiching of A.C. Lawson, which is a metasedimentary formation.
- (2) The cataclastic gneiss and the foliated hornblende granodiorite are two distinctly different rock types. The plagioclase in the gneiss ($+ An_{27}$) is too calcic to be produced by shearing of the granodiorite, for the granodiorite has plagioclase of the composition An_{10} ; shearing of this rock would produce a more sodic and not a more calcic plagioclase.
- (3) On the other hand, shearing of the amphibolite which has a calcic plagioclase ($+ An_{46}$) could indeed produce the more sodic plagioclase observed in the cataclastic gneiss.

From the available field and laboratory evidence, we conclude that the cataclastic gneiss is a segment of the Keewatin volcanics, modified in texture and composition by shearing with synchronous introduction of granitic material by the invading Algonian pluton. This conclusion is consistent with observations elsewhere (Griffin, 1967) that the Giants Range batholith has modified various country rocks by metasomatic processes, including the development of granodiorite from amphibolite.

METAMORPHISM OF THE BIWABIK IRON FORMATION,
DUNKA RIVER AREA, MINNESOTA

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The Dunka River area is at the eastern end of the Mesabi range where the Biwabik Iron Formation lies unconformably on older granitic rocks and is overlain conformably by the Virginia Formation. The iron formation was intruded and metamorphosed to the pyroxene hornfels facies by mafic rocks of the overlying Duluth Complex. The iron formation is 175-300 feet thick and dips 15° - 35° SE., beneath the Duluth Complex. The Upper Cherty and portions of adjacent members are mined for their magnetite content for three miles along strike by Erie Mining Company.

The iron formation is composed dominantly of quartz, magnetite, pyroxenes, fayalite, and amphiboles; these are accompanied by local quantities of garnets, plagioclase, biotite, pyrrhotite, apatite, graphite, calcite, wollastonite, talc, serpentine and other minerals.

The magnetite content did not change during the metamorphism and much of the magnetite retains its original grain size, especially where it is poikilitically enclosed by ferrohypersthene. Quartz is the most abundant mineral and was entirely recrystallized; its grain size is related to abundance approximately by: $\log(\text{average diameter}) = A(\text{percent quartz}) + B$, where A and B are constants. The O^{18}/O^{16} ratios of coexisting quartz and magnetite from the iron formation imply that 700° - 750° C. was the maximum metamorphic temperature attained beneath the Duluth Complex.

Orthopyroxene is the most abundant ferromagnesian silicate; most is ferrohypersthene with an atomic $\text{Fe}/(\text{Mg} + \text{Fe})$ ratio of greater than 50 percent. The maximum $\text{Fe}/(\text{Mg} + \text{Fe})$ ratio of orthopyroxene, occurring in rocks that contain quartz and fayalite, is approximately 76.7 percent. A portion of the ferrohypersthene, occurring in rocks that contain sufficient iron, crystallized initially as pigeonite and inverted to orthopyroxene during cooling.

Calcium pyroxene is abundant in parts of the iron formation, generally where quartz predominates. Most is hedenbergite with a $\text{Fe}/(\text{Mg} + \text{Fe})$ ratio between 50 and 70 percent. Fayalite is locally abundant, generally where Ca pyroxene is sparse. It commonly occurs with quartz and has an average $\text{Fe}/(\text{Mg} + \text{Fe})$ ratio of approximately 90.7 percent; locally, where quartz is absent, fayalite has a lower $\text{Fe}/(\text{Mg} + \text{Fe})$ ratio.

Cummingtonite is common throughout the iron formation; most has a $\text{Fe}/(\text{Mg} + \text{Fe})$ ratio of 50 to 80 percent. Most cummingtonite is texturally late; it replaces ferrohypersthene mainly, and fayalite. The $\text{Fe}/(\text{Mg} + \text{Fe})$ ratio of the minor amount of early cummingtonite is 60 percent and less.

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Small amounts of hornblende are present throughout the iron formation; some formed during prograde metamorphism but most replaces hedenbergite. The $\text{Fe}/(\text{Mg} + \text{Fe})$ ratios encountered in hornblende range from 25 to 75 percent; Fe generally predominates over Mg. The weight percent of Al_2O_3 in hornblende ranges from 2.4 to 10.2 percent.

The iron formation originally contained abundant iron carbonates and hydrous iron phyllosilicates; these were converted to pyroxenes and fayalite during prograde metamorphism. The metamorphism was isochemical, except for loss of the original H_2O and CO_2 . Locally, fayalite and pyroxenes constitute quartz-free layers; these imply that the original siderite-rich and ankerite-rich layers were converted directly to fayalite and pyroxenes rather than progressing through an intermediate amphibole step.

Prior to metamorphism the iron formation contained several percent of H_2O and CO_2 , with CO_2 predominating. Most of this was expelled during metamorphism; however, a small proportion (probably dominated by H_2O) remained along grain boundaries and fractures. This residual H_2O combined with the pyroxenes and fayalite to form amphiboles and other hydrous minerals as the rocks cooled. Numerous hairline fractures, filled with cummingtonite and oriented perpendicular to the layering, are the probable escape route for a portion of the volatiles. Similar cummingtonite-filled veins are conspicuously developed in the overlying Virginia Formation. These thin veins, along with locally abundant biotite in the basal part of the Duluth Complex, suggest that a substantial portion of the volatiles which escaped from the iron formation and the Virginia Formation during metamorphism migrated into the overlying Duluth Complex.

DIFFERENTIATION SEQUENCE OF THE GREAT LAKES NICKEL INTRUSION

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The Great Lakes Nickel intrusion is a cross-cutting body of gabbro in the Keweenaw shales of the Ft. William area, Ontario. The intrusion is at least 1 1/2 miles in length, 1500 feet in width and plunges approximately 20 degrees toward the east. In north-south section it is funnel-shaped, but no direct evidence of a feeder has been found. Rock types consist mainly of olivine gabbro, troctolite and anorthositic gabbro. Within the lower olivine gabbro is a broad horizon of Ni-Cu sulfide enrichment which has become the focus of attention for several mining companies with property in the area. Chromian spinel is scattered throughout the sulfide horizon and particularly concentrated in a remarkably extensive and conformable thin layer of chromitite above the sulfide horizon.

Compositions of the major mineral phases were traced by means of the electron microprobe for samples from various localities, but particularly from one complete drill core intersection. An average trend toward less mafic composition with increasing distance upward from the base is apparent, but within any one short section the pattern is considerably mixed.

On the basis of chemical variations, textural relationships and mineral associations it is concluded that at the time of injection the magma had an unusually large crystalline component.

SULFIDE ASSEMBLAGES OF THE GREAT LAKES NICKEL INTRUSION

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The Great Lakes Nickel intrusion is located in the south-central part of Pardee township, Thunder Bay district, Ontario.

The intrusion is one of a great number of mafic sills and dikes in the area. This particular intrusion is interesting because of its differentiated nature and the sulfide horizon located within it.

Sulfide assemblages were examined optically in order to determine the nature and mutual relations of the sulfides and silicates. Certain of these assemblages were then studied with the aid of the electron microprobe.

The sulfides were found to be of two kinds: primary and secondary. The primary magmatic assemblage consists of high temperature sulfide phases belonging to the Cu-Ni-Fe-S system. These include two phases of pyrrhotite, pentlandite, chalcopyrite, and cubanite. The secondary assemblage consists of mackinawite, marcasite, and nickeloan pyrite.

Mackinawite appears to have exsolved from chalcopyrite and pentlandite at a very low temperature (Chamberlain and Delabio, 1965; Clark, 1966).

On the basis of textural and mineralogical evidence, it appears that the sulfides crystallized from an immiscible sulfide liquid. Sulfide droplets surrounded by oxide rims are common. These may represent closed sulfide systems in miniature (Chamberlain, 1966).

Several ideas attempting to explain the origin and development of the sulfide minerals are considered.

INTERDISCIPLINARY STUDY OF A SELECTED AREA OF LAKE
SUPERIOR: PROGRESS REPORT

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An interdisciplinary group from Wisconsin State University, Superior, comprised of members from the departments of biology, chemistry, geography and geology have completed a pilot baseline study of a selected area along the south shore of Lake Superior. The area of study is a two-mile stretch of shoreline from the base of Wisconsin Point to a point east of the mouth of Morrison Creek, in Sections 35 and 36 of T49N and R13W.

Parameters selected for study were: sediment sieving analysis, turbidity, pH, electrical conductivity, dissolved oxygen, total dissolved solids as well as qualitative analyses for certain selected ions dissolved in the lake water. Data were obtained along a set of five traverses spaced one-half mile apart along and at right angles to the shoreline. Samples were taken along these traverses at water depth intervals of ten (10) feet, from surface to bottom, to a maximum depth of thirty (30) feet, resulting in a set of ten samples of water and four sediment samples per traverse.

At each traverse station, lake bottom samples were caught with a Peterson dredge. One hundred (100) grams of each sample were oven-dried and size sorted employing a 10-unit sieve nest. The median size ranged from a negative 2.70 ϕ (small pebbles) to a positive 3.05 ϕ (very fine sand) value. Along the typical traverse, medium sand was found high on the beach and in the littoral zone. Fine sand was recorded at the ten (10) foot and the twenty (20) foot depths and very fine sand was dredged at the thirty (30) foot depth. Using Trask (1932¹) statistics, the q_2 quartile deviation (coefficient of sorting) varied from 1.51 to 0.69². These results indicate well sorted clastics. The skewness (symmetry) ranged from a negative 2.21 to a positive 1.09², while the kurtosis (peakedness) ranged from a negative 0.42 to a negative 0.21².

These statistics indicate a standard distribution of the Lake Superior clastics within the area studied. This is not unusual considering the high energy conditions of the lake within the six-fathom mark. The few anomolous zones which are recorded are attributed to small lake floor surface pockets of clay which are slowly being transported into deeper water. These clays, derived from gravity slumping along the

1. Trask, P. D., Origin and Environment of Source Sediments in Petroleum, pp. 71-72, Gulf Publishing Company, 1932.
2. All calculations based on phi scale ($-\log_2$)

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south shore line, were initially deposited in the region as lacustrine sediments during the Wisconsin sub-epoch in Lake Duluth, the ancestral glacial high water mark of Lake Superior.

The turbidity of the water was determined by means of a Secchi disk. Sightings on the disk ranged from a depth of 5' 6" (1.67 meters) to a depth of 12' (3.66 meters). The average value was 2.95 meters. Sunlight was approximately of the same intensity during all determinations. These data indicate that at the depths where water transparency was determined, wave action and shoreline currents held an amount of sediment in suspension to increase the turbidity above that as determined in mid-lake.

The pH of the water samples was obtained by means of a Beckman Model G pH meter with Sargent No. S-30072-15 combination electrode. pH ranged from a low value of 7.84 to a high of 8.02. The average value was 7.90. The higher values, as compared with those taken at Silver Bay, Minnesota,³ may be due to increased leaching of alkaline earths from the red clays along the south shore of Lake Superior.

Freas type conductivity cells with cell constants of approximately 0.3 reciprocal ohm were used in conjunction with a Model RC conductivity bridge from Industrial Instruments Inc., operating at 1000 Hz, to determine the electrical conductivity⁴. Specific conductance ($k \times 10^6$ at 25°C) had an average value of 104.5, with a standard deviation + 1.2. Homogeneity was within reasonable limits, according to conductivity and indicated that samples down to thirty (30) feet depths were still within the active mixing zone.

Dissolved oxygen, as measured by the Winkler method, ranged from an average of 10.8 parts per million at the surface layer to 10.5 parts per million at the ten (10) and twenty (20) foot levels, and to 10.6 parts per million at the thirty (30) foot level. Thus there was no significant variation in the parts per million from one depth to another, and apparently the samples were all taken from the mixing zone.

Total solids, determined by evaporation at 100°C, averaged 71.5 parts per million.

Qualitative determination of dissolved ions involved the use of a Fisher Duo-Spectral Model 80 and a Vreeland Direct Reading Spectroscope. While a detailed analysis was not performed, ions so far found are sodium, potassium, calcium, magnesium and iron.

3. Swain, F. M., and Prokopovich, N., Stratigraphy of Upper Part of Sediments of Silver Bay Area, Lake Superior, Bull. Geol. Soc. Amer., 68, 527 (1957).

4. American Public Health Association, Standard Methods for the Examination of Water and Waste Water, twelfth edition, American Public Health Assoc., Inc., 1790 Broadway, New York, N.Y. 10089, (1965) .

The quality of the water samples showed only small variations from site to site, and thus, within the area sampled, it is concluded that wave action and long-shore currents have produced a fairly homogeneous region within the study area.

These data, assumed to be normal considering the near pristine condition of the lake, could be employed on a quantitative evaluation of possible future pollution of western Lake Superior.

THE FEDERAL - PROVINCIAL COMMITTEE ON HURONIAN STRATIGRAPHY
PROGRESS REPORT

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This paper (a) reviews the history of geological work in the Sault Ste. Marie - Elliot Lake - Sudbury area, (b) summarizes the terms of reference of the Federal-Provincial Committee on Huronian Stratigraphy, (c) summarizes the recommendations of the committee, to date, and (d) outlines the anticipated further work of the committee and specific problems requiring further research.

1. The Huronian to be defined as:

"The assemblage of sedimentary and volcanic rocks occurring in the vicinity of the North Shore of Lake Huron, Cobalt, and adjacent areas and lying with marked unconformity on the Archean and intruded by the Nipissing diabase".

2. Recommended Huronian Stratigraphic Nomenclature:

Nipissing Diabase
Intrusive Contact

Huronian Super Group

Cobalt Group	(Top not seen)
Bar River Formation	(Top not seen)
Gordon Lake Formation	
Lorrain Formation	(Local Members)
Gowganda Formation	(Local Members)

Unconformable to disconformable contact

Quirke Lake Group

Serpent Formation	
Espanola Formation	(Local Members)
Bruce Formation	

Local Disconformable Contact

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Hough Lake Group

Mississagi Formation
Pecors Formation
Ramsay Lake Formation

Local Disconformable Contact

Elliot Lake Group	McKim Formation	(Local volcanic assemblages to be individually named)
	Matinenda Formation	(Uranium deposits lie at base of Matinenda Formation)

Unconformity

Archean

3. The Principal Reference Sections and Formations listed of three areas:

- (a) The "Original Huronian"
- (b) The Blind River - Elliot
- (c) The "Southern Huronian"

1 Reference Sections for the to define the Huronian in each.

- the Mines area.
- um Mining area.
- anola - Sudbury belt.

A composite section in the Elliot Lake area will contain reference sections for the individual formations and principle reference sections for the groups. It is recommended that this composite section becomes the principal reference section for the Huronian Supergroup.

4. These principal reference sections and reference sections to be measured, described, and marked during the next two years.

STRATIGRAPHIC RELATIONSHIPS OF SOME KEWEENAWAN ROCKS
OF MICHIGAN AND WISCONSIN*

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Identification of an extensive pre-Portage Lake volcanic formation requires re-evaluation of the stratigraphy and structure of northern Michigan and Wisconsin, and perhaps over an even larger area. Previous workers have assigned all of the Keweenaw volcanic rocks to the same lava sequence, but the traps of the South Range differ lithologically, magnetically, and in areal distribution from the Portage Lake Lava Series. Unconformities appear to separate the traps of the South Range from overlying formations.

The Portage Lake Lava Series thins westward and pinches out east of Mellen, Wisconsin. Magnetic anomalies suggest that the higher flows extend farther west than the lower flows. West of the pinchout, on the Bad River, steeply dipping but otherwise undisturbed conglomeratic sandstone of the Copper Harbor Conglomerate is disconformable on partly eroded felsite of the traps of the South Range. The Portage Lake Lava Series thins by more than a third between the mouths of the Black and Montreal Rivers, a distance of about 15 miles, and the Bad River thrust is not now needed to explain the absence of the Portage Lake Lava Series on the Bad River.

West of Mellen, near Davis Hill (T44N, Bayfield Co., Wisconsin), an angular unconformity appears to separate the traps of the South Range and the Northern Flow Series of Aldrich (1923, p. 563) of uncertain relative age. Aldrich correlated the conglomerate at Davis Hill with the "Great Conglomerate" of Keweenaw Point and he used this correlation as proof of repetition of strata due to thrust faulting. The conglomerate at Davis Hill is conformable with the traps of the South Range (Aldrich, 1929, p. 125-126), resembles some conglomerates of the traps of the South Range, contains similar interbedded fragmental andesites, and contains similar felsite. The Southern Flow Series of Aldrich (1923) and the conformable overlying conglomerate at Davis Hill together have a magnetic pattern similar to that of the traps of the South Range in Michigan. The conglomerate at Davis Hill has little matrix material whereas pebbles are set in a matrix of smaller fragments in the Copper Harbor Conglomerate. Thus, the conglomerate at Davis Hill appears to be part of the traps of the South Range. The existence of the Lake Owens fault, required by Aldrich's correlation, should be considered as not yet demonstrated.

The Jacobsville Sandstone is unconformable on the lower member of the South Range traps east of Lake Gogebic and at Sturgeon Falls, Michigan. This unconformity has been used by nearly all writers to demonstrate that the Jacobsville Sandstone is younger than the Portage Lake Lava Series.

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*Work done in cooperation with the Geological Survey Division of the Michigan Dept. of Conservation. Publication authorized by the Director, U. S. Geological Survey.

The unconformity at the top of the traps of the South Range may be regional in extent. On the northern Minnesota shore, South Range type rocks have the same paleomagnetic field direction as the traps of the South Range, whereas the higher volcanic rocks differ in lithology and paleomagnetic field direction. An unconformity can be inferred along the St. Croix River near Pine City, Minnesota from the aeromagnetic maps of Sims and Zietz (1967), and some of the volcanic rocks at nearby Taylors Falls appear to be similar to the traps of the South Range (Hall, 1901).

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TABLE OF NOMENCLATURE

KEWENAWAN	Upper	Nonsuch and younger formations Copper Harbor Conglomerate (including Great Conglomerate as used by Butler and Burbank) Sediments include abundant pebbles of volcanic rocks derived from traps of the South Range
	Middle	Portage Lake Lava Series Interbedded sediments include abundant pebbles of volcanic rocks derived from traps of the South Range _____ unconformity _____
	Lower	Traps of the South Range Upper Member: basaltic andesite flows, fragmental rock; felsites; conglomerate including the conglomerate at Davis Hill Lower Member: Andesitic basalt flows Quartz sandstone

NOTE: Aldrich's (1923) Southern Flow Series is equivalent to part of the traps of the South Range in Michigan. His Northern Flow Series may be equivalent to the Portage Lake Lava Series.

DISTRIBUTION PATTERNS OF POSTGLACIAL SEDIMENTS IN LAKE SUPERIOR

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Based on some 100 cores now available for study, a distinct pattern of sediment distribution in the deeper parts of the lake is emerging. We have no cores in shallow water, that is, from 0 to 400-foot depths. From 400 to about 800 feet brown mud, which is gritty in some places, is the uppermost sediment. This brown mud averages 82 cm. in thickness and 44 per cent smaller than 1 micron; it appears to be massive or not weakly stratified and contains moderate amounts of hydrotroilite.

Underlying the brown mud is a very fine-grained gray clay which, in water depths greater than 800 feet where the brown mud is lacking, becomes the topmost sediment. This gray clay is massive; it averages 98 cm. in thickness and attains a maximum known thickness of 445 cm; and 85 per cent of this clay is finer than 1 micron. The lower contact of the massive gray clay is marked by the abrupt appearance of varve laminations. The varved clay appears to be identical to the overlying gray clay except for the presence of the distinct laminations.

Pollen and geochemical studies, as well as the stratigraphy of these sediments, suggest that very little or no sedimentation is occurring at present in the central parts of Lake Superior deeper than 800 feet. The massive gray clay is apparently a late-glacial deposit which is still exposed on the lake bottom.

PALYNOLOGICAL STUDY OF POST-GLACIAL BOTTOM SEDIMENTS FROM
DEEP-WATER LOCALITIES IN LAKE SUPERIOR

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Palynological investigations of long cores taken from deep-water areas of Lake Superior in 1961 and 1962 by Zumberge and Farrand revealed a surprising paucity of microfossils, even in the youngest sediment layers, and steep gradients in distributional anomalies (Benninghoff, Taylor, and Dole, 1968). Need for further inquiry was suggested by: (a) the general absence of plankton remains, (b) the general scarcity but local abundance of fossil pollen and spores, (c) the variation in arboreal to non-arboreal pollen ratios at equivalent levels in cores from different locations and different water depths, and (d) the widespread occurrence and local scarcity of degraded fossil bi-saccate conifer pollen grains that resemble certain early Tertiary forms rather than Quaternary forms. Opportunity to explore these problems by means of greater sampling flexibility came in 1967 when the University of Michigan Glacial Geology and Polar Research Laboratory was given 92 bottom sediment cores, each 3 to 5 meters long, by the geothermal research team of the Carnegie Institution of Washington Terrestrial Magnetism Laboratory. The cores were split, photographed, and logged stratigraphically. Cores were then selected according to their location, water-depth, or bottom physiographic setting to be analyzed for their microfossils. The study was supported in large part by National Science Foundation Grant GA-1122 and aided by an NSF Summer Research Participation Grant.

Microscopic planktonic organisms in the waters and airborne particles such as pollen and spores falling onto the lake surface would be expected to contribute more or less evenly to accumulating bottom sediments. Near absence of plankton forms and scarcity of pollen and spores in the sediments implied redistribution before deposition on the bottom. To test the assumption of lateral transport and greater sedimentation nearer the shore, analyses were made of selected cores along lines normal to adjacent shores. For a series of 8 cores the concentration gradients of pollen and spores at 0.05 m core depth show an increase from nearshore areas (1,000 to 3,000 m from shore) to offshore (25,000 m) locations. There are indications, however, that this relation is not oriented the same in all areas. Even where pollen and spores were relatively abundant, the only plankton microfossils found were diatom frustules and simple spicules (megascleres) of fresh-water sponges, and these in concentrations two to three orders of magnitude less than those for the pollen and spores.

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The relative abundance of pollen and spores in given stratigraphic levels could not be correlated even within groups of cores taken within a few miles of each other, nor could the abundance be correlated with a given matrix lithology or size grade. Some small promise is indicated for correlation of pollen and spore abundance with bottom topography, however, but considerably more sampling will be needed for adequate testing.

Shift in the ratio of non-arboreal to arboreal pollen within groups of cores may have significance for differentiating between nearby sources of pollen (more NAP present) and distant sources (only long-range AP present, such as pine, spruce, and oak), although differential placering of pollen and spores by bottom currents remains a possible cause.

All the cores examined have degraded fossil bi-saccate conifer pollen resembling early Tertiary forms. These must have been exhumed from geologically older deposits and then re-deposited. There are small variations in the absolute densities of the ancient conifer pollen populations, but much greater variation in the ratio of ancient conifer pollen to pollen definitely referable to Quaternary age. It is possible that these variations are indications of transport and sedimentation along depositional gradients in certain bottom topographic depressions. But the greatest mystery is the source or sources of the ancient grains that were evidently reworked by glacial action.

Microfossil analysis of bottom sediments has contributed little to the post-glacial history of organisms in Lake Superior and its biotic province, but more to knowledge of sedimentation in the lake. Suspended particles in the upper levels of the water in offshore areas are evidently transported laterally to inshore areas with shallow water. Pollen and spores are probably moved also in bottom flocculant material by bottom currents and gravity flows of sediments. The wide variation from place to place in pollen and spore accumulation densities and in proportions of different categories within that class of particulates indicates strongly that the sedimentation process for particles of the nature of these microfossils is not one of simple vertical descent to the bottom.

NEW LIGHT ON ANIMIKIE ALGAL STRUCTURES THROUGH DARKFIELD
ILLUMINATION

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Algal filaments and other structures are preserved in some Animikie cherts as lines of inclusions of minerals such as hematite, of organic matter or of fluids. Such inclusions may be quite unimpressive in ordinary illumination, and yet acquire a three-dimensional character, and even an appearance of greater continuity, in darkfield illumination. Grain boundaries and cracks, which in darkfield may simulate filaments, reveal their true nature in phase-contrast, available with the same equipment as darkfield.

It is possible that replacement (diagenetic) cherts can be distinguished from cherts deposited in cavities by the character of their inclusions. Neither darkfield nor phase contrast appears to be of much value in interpreting microstructures in carbonate or silicate rocks, because the strong contrasts in index of refraction emphasize the existing grain boundaries and texture, at the expense of the more subtle traces of organic remains.

POSSIBLE GLACIAL ORIGIN FOR THREE PRECAMBRIAN
(HURONIAN) CONGLOMERATES, NORTH SHORE OF
LAKE ~~MICHIGAN~~ HURON

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For more than fifty years a glacial origin has been suggested for the Gowganda Formation of Ontario. Recent work has confirmed the opinion of early workers. The Gowganda Formation includes a wide variety of rock types including polymictic paraconglomerates, orthoconglomerates, sandstones, siltstones and massive and laminated argillites. The laminated argillites commonly contain large dropped clasts. The Gowganda Formation has a maximum thickness of about 3,000 ft. (in the southern part of the outcrop belt) and the present areal extent is of the order of 8,000 square miles.

Regional paleocurrent investigations (Lindsey, 1967, Young, 1968) indicate that the Gowganda Formation was derived from a northerly source. Results of 30 new chemical analyses of argillites and matrix materials from the Gowganda conglomerates indicate chemical differences between the eastern and western parts of the Gowganda outcrop belt. These differences are consistent with differences in the hinterland as indicated by paleocurrent studies. Glacial deposits of similar age were described by Pettijohn (1943) and Puffett (1967) from areas in Michigan.

Polymictic conglomerates also occur lower in the Huronian succession of Ontario. The most extensive of these form part of the Bruce and Whiskey Formations (Roscoe, 1957). The conglomerates of the Bruce and Whiskey Formations contain successively larger amounts of sand-size material. The Bruce conglomerate has a present minimum extent of about 1,700 sq. miles and a maximum thickness of the order of 600 ft. The Whiskey conglomerate is known to cover an area of the order of 1,000 sq. miles and has a maximum thickness of about 600 ft.

Although many geologists mentioned the possibility of glacial origin for these conglomerates they were formerly interpreted as mudflows related to tectonic uplift. Dropped clasts have been found in bedded sediments above both conglomerates. Together with this new evidence the following points support a glacial origin for these conglomerates:

1. The widespread occurrence and homogeneous nature of the conglomerates.
2. The polymictic nature of the conglomerates, with many plutonic rock fragments.
3. Chemical immaturity of the conglomerate matrix materials.

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4. The absence of evidence of significant topographic relief or tectonic activity in the source area.
5. The conglomerates vary in thickness from place to place, but there is a gradual thickening away from source.
6. Elongate megaclasts of all three conglomerates exhibit a regional preferred azimuthal orientation.
7. Most of the associated sediments were deposited in shallow water.

Glacial interpretation of these conglomerates is in keeping with recent paleomagnetic investigations, both in the Animikie of the Lake Superior region (Symons, 1966) and in the Gowganda Formation of Ontario (Symons, 1967) which indicate high latitudes in these regions in Early Proterozoic times.

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ICE-STAGNATION FEATURES OF THE BLOOMER MORaine, NORTHWEST WISCONSIN*

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The outer part of the Chippewa Lobe of Late-Woodfordian (Cary) age stagnated in situ, leaving behind a striking and characteristic assemblage of glacial forms. The ice-stagnation or dead-ice features partly are the result of melting out of buried ice blocks. The moraine northeast of Bloomer is characterized by small kettle lakes (commonly less than 1/4 mile across, although a few larger ones are present), of kettle swamps, of dry kettles, and of intervening irregular knobs of dark red, sandy, stony till and small kame deposits. Numerous genetically-related, large mounds grew during deglaciation as surface water and debris plunged through the ice. These mounds include conical moulin kames, straight to sinuous eskers and crevasse fills of different sizes, and large "butte" - like deposits from formerly ice-walled lakes. Generally, relief is only 20 to 60 feet in the knob and swale topography, but some of the kames and ice-walled lake deposits exceed 200 feet. The largest mounds are one mile in diameter. Several are aligned northeasterly and northwesterly, parallel and perpendicular to the former ice movement.

The present geometry of the ice-walled lake deposits and exposures of the material show them to have been large openings with ponded water much of the time the deposits were being laid down. Debris was supplied at various places around the periphery of the openings, building deltas and slump ridges. Much of the material is bedded; most is poorly-sorted, fine-grained clastics unsuited for construction aggregates. Locally, poorly-sorted, coarse-textured clastics are interstratified with till and other sediment. Small kettles dot the tops of some of the large ice-walled lake deposits, and large kettle lakes adjoin them. Views from the top of several mounds are excellent. Some are now in Chippewa County Park, but the best are outside it. A larger area should be set aside to preserve some of the better representative features not now protected.

*Field work leading to this abstract was supported by the National Park Service.

THE SEAMAN METHOD OF MINERAL IDENTIFICATION AS USED
AT LAKE SUPERIOR STATE COLLEGE

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At Michigan Technological University a unique method of mineral identification has been taught for over forty years. This method, the Seaman method, has many advantages as a useful approach to macroscopic, nondestructive mineral identification, besides being a useful tool for teaching the fundamentals of, and an appreciation for, mineralogy. At Lake Superior State College, a branch of MTU, the same method has been adopted but with modifications. The system is based on cleavage as the primary property. Because cleavage is directly related to crystal structure and has not been intensively studied, it is believed this method can be developed further and should be more widely adopted. The paper will attempt to show how the method has been applied, its advantages and weaknesses and how it could be improved.

CURRENT INVESTIGATIONS OF METEORITE IMPACT STRUCTURES IN THE CANADIAN SHIELD

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Scientific investigations of possible large ancient meteorite craters in the Canadian Shield began in 1950 with the study of the Pleistocene New Quebec Crater by V. B. Meen and the discovery of the Ordovician Brent Crater in 1951. By 1955 a systematic search of aerial photographs and maps for other craters was underway. Several dozen approximately circular structures have been studied, of which 16 are known to show positive evidence of meteorite impact.

Early investigations were based on the analysis of topography and surface structural data taking Barringer crater, Arizona and lunar craters as models. The use of gravity, magnetic and seismic methods to probe promising structures at depth was begun at Brent in 1953, and was followed in 1955 by diamond drilling at the same crater. These methods have continued in use, so that geophysical data are available for most craters and drilling has been carried out at seven sites for a total of thirty two holes and over 35,000 feet of rock core.

Detailed petrographic and mineralogic study of drill core and surface samples began in 1961. At first efforts were concentrated on a search for meteorite fragments and the shock-produced, high pressure polymorphs of quartz, coesite and stishovite, as recorded at Barringer Crater. This search continues but has proved elusive, largely due to the abundant alteration and recrystallization in these old, deeply eroded craters. Thus attention has turned to other criteria of shock metamorphism known from meteorites, recent meteorite craters, underground nuclear tests and laboratory shock experiments. These include the development of kinking in mica and other mafic minerals, of planar features with distinctive crystal orientations in quartz and feldspars and of peculiar isotropic (thetomorphic) phases, particularly in the framework silicates. Well-preserved examples are found at the 16 Canadian craters.

In the analysis of Canadian craters particular attention has been given to the relationships between grades of shock metamorphism and crater structure. The extensively drilled Brent (3.7 km diameter) and West Hawk Lake (2.7 km) craters are representative of simple craters with a lens of breccia containing fragments of altered glass and rocks at various grades of shock metamorphism, underlain by fractured autochthonous rocks, in which shock zones waken downwards. Larger craters, such as at Clearwater Lake (14 and 32 km), at La Malbaie (35 km) and Manicouagan (60 km), have central peaks in which shock zoning similar

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to that in the autochthone at Brent is developed. The central region is surrounded by an annulus of breccia, and massive, probably shock melted igneous rocks. They have a peripheral depression instead of an elevated rim. This crater form has been produced at the Suffield Research Station, Alberta in alluvial materials by a surface explosion of 500 tons of TNT, and has been recognized at many cryptoexplosion structures. These studies suggest a mechanical rather than volcanic origin for central peaks in Lunar craters.

PETROGRAPHIC EVIDENCE FOR A METEORITE IMPACT ORIGIN
OF THE SUDBURY STRUCTURE, ONTARIO

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Recently, studies of rock specimens subjected to hypervelocity shock waves generated by artificial explosions and by meteorite impacts have established some petrographic and mineralogical criteria which appear to be unique indicators of such processes (El Goresy, 1965; Short, 1966; Chao, 1967a, 1967b). These effects, which appear distinctly different from those produced by normal geological deformation, include: (1) formation of high-pressure polymorphs such as coesite and stishovite; (2) unusual fusion and decomposition reactions indicating temperatures in excess of 1500°C ; (3) widespread development of cleavage in quartz; (4) multiple sets of planar lamellae in quartz, oriented parallel to specific planes, (notably $\{0001\}$ and $\{10\bar{1}3\}$, together with development of analogous planar features in associated feldspar; (5) intense disordering of single crystals of quartz and feldspar, often producing glasslike phases which preserve original grain boundaries and structures.

Dietz (1964) argued that a meteorite impact origin explained some of the structural peculiarities associated with the Sudbury basin, chiefly the overturning of metasediments on the South Range and the widespread development of Sudbury breccia. Dietz viewed the Nickel Irruptive as derived internally and emplaced in the Sudbury basin as an "extrusive lopolith". He felt that the overlying Onaping Formation represented a "chill zone" of ash-flow tuffs, in which evidence of impact-produced shock metamorphism might be found. This view was supported by his prediction and discovery of the widespread development of shatter cones in older rocks around the Sudbury basin, and it was thought desirable to examine inclusions of older basement rocks in the Onaping Formation.

The Onaping Formation, approximately 4000 feet thick, is the lowest member of the Whitewater series which occupies the center of the Sudbury basin. The formation overlies the upper (micropegmatite) unit of the Sudbury Nickel Irruptive, and is separated from it by a "quartzite breccia" composed of large blocks of quartzite and interstitial melt material. Previous workers have considered the Onaping formation to be a complicated series of extrusive fragmental volcanic rocks and flows, but its exact origin and relation to the Nickel Irruptive have not been definitely established.

It has been previously accepted that the Onaping formation: (1) contains numerous fragments of devitrified glassy material; (2) also contains numerous inclusions of various "basement" rocks up to tens of feet in size; (3) exhibits a gradation in fragment size, from large blocks at the base to fine material at the upper contact; (4) exhibits a concentric zoning in rock types with respect to the basin margin; (5) cannot be definitely correlated with formations outside the Sudbury basin; (6) was apparently deposited as a single

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unit during a brief period of time.

Preliminary petrographic investigations (French, 1967a, 1967b) provide evidence that quartzofeldspathic inclusions of basement rocks in the Onaping Formation show microscopic textures typical of rocks subjected to shock pressures generated by meteorite impact or by artificial explosions. These include: (1) planar features in quartz, concentrated at or near the $\{0001\}$ and $\{10\bar{1}3\}$ planes; (2) intense deformation and development of planar features in associated feldspar; (3) unusual deformational "flow textures" that may be the result of selective "melting" by shock. These features are also rarely observed in smaller fragments that constitute the matrix of the inclusions.

Subsequent studies of additional inclusions have allowed the tentative recognition of five types or grades of deformation which may reflect increasing original shock intensities. The petrographic textures observed can be qualitatively compared with material from Meteor Crater, Arizona, the Ries Kessel, Germany, and the Brent Crater, Ontario. Boundaries between the groups are gradational and several "grades" may be observed in a single thin section. The different "grades" are characterized by: (1) development of multiple sets of planar features in quartz and feldspar; (2) preferential destruction and recrystallization of feldspar; (3) strong deformation of feldspar and complete recrystallization of associated quartz; (4) development of local "eutectic" melting in strongly deformed inclusions; (5) incipient melting of the whole inclusion to an aggregate of heterogeneous glasses showing incipient flow texture; (6) complete fusion and strong development of flow structure, with admixtures of shocked and unshocked rock and mineral fragments into the molten material.

Recent collateral evidence for meteorite impact, predicted by the impact theory, includes: (1) the recognition of high-temperature fusion (melting of sphene) in one inclusion, and (2) the discovery of weakly-developed shock criteria (planar features in quartz) in inclusions and wallrock in the footwall Levack breccia and related breccias along the North Range of the Sudbury basin.

These observations establish a strong similarity between Sudbury and other structures for which a meteorite impact origin is either proven or strongly indicated. Acceptance of an impact origin for the Sudbury structure would also imply: (1) that shock-induced petrographic features can be preserved for periods in excess of 1.5 billion years; (2) that shatter cones, which are common at Sudbury, may constitute a definite criterion for meteorite impact; and (3) that meteorite impacts may produce or trigger igneous processes involving large volumes of magma and economic ore deposits.

The theory of meteorite impact origin helps to explain the peculiarities of the Sudbury structure and the nature of the Onaping Formation. There is, however, no unit analogous to the Nickel Irruptive at any of the larger known impact structures, and the impact theory can contribute little to the long-standing problem of the origin and emplacement of this body and its associated ore deposits.

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At the present state of knowledge, it seems unlikely that the Nickel Irruptive could be the direct result of the impact which formed the basin, but such an impact could have exercised structural control in directing igneous processes already in motion. This view of the importance of meteorite impact in the history of the Sudbury structure does not contradict any of the theories proposed to account for the Nickel Irruptive. Resolution of the terrestrial and extraterrestrial components of Sudbury history will depend on future detailed studies of the structure of the basin and the character and subsurface extent of the Nickel Irruptive itself.

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PROGRESS OF GEOLOGIC INVESTIGATION OF THE MELLEN GRANITE,
ASHLAND COUNTY, WISCONSIN

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The Mellen Granite is located west and north of the City of Mellen, Ashland County, Wisconsin. The main granite body, encompassing some 13 square miles, lies in the southern half of T 45 N, R 3 W and the northern portion of T 44 N, R 3 W.

Middle Keweenawan gabbros and basalts unconformably overlay the Animikian Tyler formation and are unconformably overlain by the Upper Keweenawan Oronto Group. The granite is intrusive into the Middle Keweenawan gabbros and basalts and intrudes and abuts against the Animikian Tyler formation; the granite is older than the Oronto Group. Controls for emplacement appear to be the northwest trending strike slip 'cross faults' in the area.

The Mellen Granite is composed of three mineralogically and texturally distinctive phases; (1) a coarse grained porphyritic granite, (2) a medium grained, equigranular to porphyritic quartz monzonite, and (3) a fine to medium grained, porphyritic to equigranular granodiorite. The quartz monzonite and granodiorite phases, which occur only at the southern boundary of the body, are transitional. The contact between the quartz monzonite and porphyritic granite, on the other hand, varies considerably; in places this contact is sharp with no apparent gradation, while elsewhere the contact is transitional. The coarse grained porphyritic granite is the predominant phase. The intrusive apparently occupies a sill-like position generally concordant to the surrounding rocks.

The granite is not an immediate differentiate of the surrounding gabbros but may have developed by anatexis or granitization of Animikian sediments, with subsequent mobilization, or from a deep-seated parent magma.

VARIETIES OF FLOWS IN THE NORTH SHORE VOLCANIC GROUP, MINNESOTA

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The North Shore Volcanic Group of Keweenawan age, once considered to be exclusively basalt and rhyolite, has been found during the course of recent detailed mapping of 58 miles of lakeshore, wide sampling, and chemical analysis of 22 specimens, to include representatives of a nearly complete series ranging from both olivine tholeiite and alkali-olivine basalt through trachybasalt and mafic quartz latite or dellenite to felsic quartz latite. So far the alkali basalts are not known to be widespread, but the other compositional types, from preliminary information, appear to be well intermixed throughout the stratigraphic and geographic extent of the sequence. The only clear exception is that at least the uppermost 1500 feet that are exposed in Minnesota are composed entirely of tholeiite.

An outline of the characteristics of the different compositional classes of flows is given in the accompanying table.

Older terminology in this district can be roughly equated compositionally as follows: "ophites" are tholeiites; "melaphyres" are siliceous tholeiites, andesitic basalts to trachybasalts, "porphyrites" are trachybasalts, alkali-basalts, and mafic quartz-latites; and both "felsites" and "rhyolites" are quartz latites.

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TABLE 1. Generalized Characteristics of Lavas of the North Shore Volcanic Group

Alkali basalt Tholeiite Trachybasalt Mafic quartz latite Quartz latite

SiO ₂ wt. % K ₂ O wt. %	47 1 - 2.5	46-51 < 1	51-56 1 - 2	62-65 2.5 - 5	72-74 3.5 - 5.5
Textures	generally porphyritic (plagioclase) interstitial K-feldspar	only chilled margins are porphyritic (plag.) Ophitic Plag.-augite micrographic intergrowths in medium-grained thick flows	aphanitic some porphyritic (plagioclase, augite) Interstitial K-feldspar; fine banding in some	porphyritic (plagioclase, augite, rare olivine, K-feldspar)	mostly porphyritic (plagioclase, quartz, rarer orthoclase, augite); flow-banding common
Thickness Range, feet common	15-100	< 1 to > 100 10-50	up to 250 20-100	up to 200	up to 1000 100-600
Relative viscosity	more viscous than tholeiites	very fluid	rather viscous	viscous	viscous
Structures flow tops jointing	roughly corrugated	ropy or smooth sheeted top zones; big columns in medium thick flows	scoriaceous rubble lower massive part: small columns stretched at base and top	highly vesicular, some breccia sub-horizontal, platy	highly vesicular, breccia platy, subhorizontal columns in thick flows stretched, irregular, round
vesicles	stretched	round or irregular		round or stretched	
Other	least well known	olivine common; mostly crystallized after flow; Calcic zeolites common	quartz, agate common in amygdules; one thick flow traceable over 5 miles	top zones poorly exposed	pyroclastic evidence rare; top zones poorly exposed.

STRUCTURE AND SIGNIFICANCE OF INTRUSIVE SANDSTONE DYKES IN THE
SIAMO SLATE OF THE MARQUETTE TROUGH,
UPPER PENINSULA, MICHIGAN

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Sandstone dykes up to 15 cms wide and more than three meters long transect the bedding, and are essentially parallel to the cleavage in the Siamo Slate of the Marquette trough. These clastic dykes are common in the zeolite-facies slates east of Negaunee, and are composed of fine- to very fine-grained sandstones commonly containing up to 60% dolomitic carbonate. Detailed study of large thin-sections (up to 7 x 16 cms) has shown that pelitic ribbons lie along the cleavage in both the slates and the interbedded psammities. Individual cleavage ribbons which are refracted in the psammite can be traced from one pelitic band through a psammitic layer into the next pelitic band. Microstructures in the disrupted sandy laminations within the slate indicate that the dykes were formed penecontemporaneously with the cleavage, and were emplaced by forceful intrusion upwards. Both the cleavage and the dykes may have been produced by tectonic dewatering of the Siamo Slate during either late diagenesis of very low-grade metamorphism.

THE SEDIMENTOLOGY OF THE MIDDLE PRECAMBRIAN
THOMSON FORMATION*

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The Thomson Formation is exposed in parts of Carlton, Pine, and southern St. Louis counties of northeastern Minnesota. The formation was folded and metamorphosed during the Penokean orogeny (1,700 million years old), but primary sedimentary textures and structures are well preserved in the Cloquet-Carlton area, making it an excellent area to study sedimentologic features.

The stratigraphy and structure of the Thomson Formation in the Cloquet-Carlton area has been described by L. A. Mattson (1958). Mattson estimated that approximately 3,000 feet of the formation is exposed along a north-south section, three miles long, that is composed of three major synclines and two anticlines with many minor folds on their limbs. Most folds are open and symmetrical, strike nearly east-west, and plunge 10° - 20° east or west.

The formation is characterized in this area by intercalated slate, siltstone, and graywacke. Detailed analyses of two measured sections, aggregating 565 feet in thickness at the type locality near Carlton indicate that graywacke comprises about 34 per cent, siltstone 34-42 per cent, and slate 23-31 per cent of the formation. Although individual graywacke or siltstone beds (defined as the interval between slate interbeds) may be more than 10 feet thick, most are thin. Seventy-two per cent of the graywacke beds and 83 per cent of the siltstone beds are less than one foot thick and more than 80 per cent of the slate interbeds are less than half a foot thick. Because of such features as (1) pronounced lateral continuity of individual beds, (2) sharp bottom contacts and gradational tops, (3) well-defined internal structures common to other turbidite-deposited sequences, and (4) sedimentary features that exhibit consistent directional properties, the graywacke and siltstone beds are interpreted as individual sedimentation units, apparently deposited by waning sediment laden turbidity currents.

A detailed analysis of cross-bedding and of slump structures indicate that much of the sedimentary material was deposited by currents flowing southward down a regional slope. However, the presence of structures tentatively interpreted as flute and groove casts, which trend east-west, implies that some currents probably flowed perpendicular to

*Work done on behalf of the Minnesota Geological Survey.

the direction of dip of the inferred paleoslope.

X-ray and thin section studies reveal that the graywackes are composed of 4-35 percent quartz, 2-28 percent feldspar, 1-10 percent rock fragments, 19-85 percent matrix material consisting of quartz, muscovite, and chlorite, and 1-17 percent calcite. Mineralogically, the siltstones are fine-grained equivalents of the graywackes.

The correlation of the Thomson Formation with other similar rocks in the Lake Superior region has been debated since Irving first suggested a Middle Precambrian age in 1883, but the formation's physical isolation has left all correlation in doubt. The marked similarity of the mineralogic and sedimentologic aspects of the Thomson Formation with those observed in the Middle Precambrian Rove Formation implies that both formations were derived from a similar source terrain and were deposited by similar processes.

THE SEQUENCE OF GEOLOGICAL EVENTS IN THE MARQUETTE IRON RANGE
DURING THE PENOKEAN OROGENIC/METAMORPHIC CYCLE

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Four Penokean (post-Animikian, pre-Keweenawan) deformational phases are discernable on the basis of photo-lineament and regional field studies. The chronological sequence of deformational events, respective major compressional axis trend, and apparent regional intensity of each phase are listed below:

- D₁ (N82-84°W) - Moderate to strong
- D₂ (N43-45°E) - Very weak
- D₃ (N6-8°E) - Weak
- D₄ (N12-14°W) - Very strong

This sequence indicates that an approximate 90° counterclockwise rotation of the major compressional stress occurred from early to late Penokean time. Post-D₄ regional thermal metamorphism has been described by James.

Pre-Animikian granites, banded granitic gneiss, and migmatites flank a porphyritic granite "core" in the complex south of the Marquette synclinorium. Included within the core region are roof pendants, migmatite belts, and partially assimilated Animikian sediments. Porphyritic granite is synkinematic with D₂. Intense D₂ folding of the Republic Trough appears to have been a localized basement event, which had negligible effect on adjacent structures. The Republic Trough acted tectonically as a portion of the southern complex during later deformational phases.

Events which occurred between phases D₂ and D₄ include district-wide mafic dike intrusion, minor D₃ folding and stress-releasing fracturing, and increased regional uplift.

Conjugate sets which trend NNE and WNW, NNW and ENE, and EW and NS were developed during the early Pre-Cambrian and acted as sites of renewed fracturing until late Keweenawan time. The foci of nine regional lineament fans, trending N16-30°E and N60-74°W, define a line which is congruent to the present major dimensional axes of the southern complex and porphyritic granite core. These three axes trend N82-84°W and suggest a zone of major regional uplift.

(continued on next page)

The Animikian sediments present in the Marquette synclinorium may have been deposited in an elongated basin on the site of an ancient wrench-fault system which displaced the northern and southern complexes. The postulated wrench-fault/structural basin and present major axis of the Marquette synclinorium trend N32-34°W.

The southern portion of the Superior Province was subjected to a major north-south compressional stress during late Penokean time. Intense D₃₋₄ east-west folding of the Marquette synclinorium is attributable to both increased uplift in the southern complex and major north-south compression.

The portion of the northern complex immediately adjacent to the Marquette synclinorium acted as a stable block during the Penokean orogenic cycle.

Prior to late Penokean regional thermal metamorphism, dynamic and dynamo-thermal effects were relatively insignificant. Superposition of the major D₁ and D₄ deformational phases is manifested by N52°W fault zones, northwest-plunging fold structures, and N45-48°W macrolineaments. Portions of the biotite, garnet, and staurolite isograds shown by James are congruent to northwest trending macrolineaments.

Reference

James, H. L., 1955, Zones of Regional Metamorphism in the Precambrian of Northern Michigan, Bull. G. S. A., v. 66, pt. 1, pp. 1455-1488.

CHERT BED CHARACTERISTICS IN THE LAKE SUPERIOR IRON FORMATIONS

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Six thousand bed thickness measurements establish the similarity of the non-granular cherts throughout the Lake Superior region regardless of the age, metamorphic rank or associated iron mineralogy. The typical chert bed is about 1 cm. thick. Bed thicknesses are log normal, in common with those of younger detrital sediments.

Thicker chert beds are composite structures composed of smaller lenses. Some lenses exhibit cross bedding; oscillation ripple marks are present locally. No lense or bed coalesces with vertically adjacent layers.

The evidence argues against a secondary origin for the typical chert bed and indicates comparability to detrital beds found in and adjacent to the iron formation. Enigmatic amoeboid layers suggest that not all chert is of the same origin.

ANNUAL MEETINGS
of
INSTITUTE ON LAKE SUPERIOR GEOLOGY

<u>Number</u>	<u>Year</u>	<u>Place</u>	<u>Sponsor</u>
First	1955	Minneapolis, Minnesota	University of Minnesota
Second	1956	Houghton, Michigan	Michigan College of Mining and Technology
Third	1957	East Lansing, Michigan	Michigan State University
Fourth	1958	Duluth, Minnesota	University of Minnesota Duluth
Fifth	1959	Minneapolis, Minnesota	University of Minnesota
Sixth	1960	Madison, Wisconsin	Geology Department, University of Wisconsin and Wisconsin Geological and Natural History Survey
Seventh	1961	Port Arthur, Ontario	Canadian Institute of Mining and Metallurgy, Lakehead Branch, and Ontario Department of Mines
Eighth	1962	Houghton, Michigan	Michigan College of Mining and Technology
Ninth	1963	Duluth, Minnesota	University of Minnesota Duluth
Tenth	1964	Ishpeming, Michigan	Mining Companies: Inland Steel, Cleveland-Cliffs Iron, Jones and Laughlin, North Range
Eleventh	1965	St. Paul, Minnesota	Minnesota Geological Survey and University of Minnesota
Twelfth	1966	Sault Ste. Marie, Michigan	Michigan Technological University
Thirteenth	1967	East Lansing, Michigan	Michigan State University and Michigan Geological Survey
Fourteenth	1968	Superior, Wisconsin	Department of Geology Wisconsin State University and Minnesota Geological Survey

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