



18TH ANNUAL  
INSTITUTE ON  
LAKE SUPERIOR  
GEOLOGY

MAY 3-6, 1972

MICHIGAN  
TECHNOLOGICAL  
UNIVERSITY

HOUGHTON, MICHIGAN 49931

ABSTRACTS EDITED BY W. I. ROSE, JR.

18th ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY

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PART I. TECHNICAL SESSIONS

AGENDA

and

ABSTRACTS

Edited by W. I. Rose, Jr.

## AGENDA

### Tuesday May 2, 1972

8:00 a.m. Field Trip A leaves Michigan Tech Memorial Union

### Wednesday May 3, 1972

6:00 p.m. Field Trip A arrives back in Houghton.

7:00-

10:00 p.m. Institute Registration, St. Albert the Great  
Student Parish, MTU Campus

### Thursday May 4, 1972

7:30-

10:00 a.m. Registration, Fisher Hall Foyer

8:00-

12:00 noon General Session I, 135 Fisher Hall

1:30-

5:00 p.m. General Session II, 135 Fisher Hall

7:00 p.m. Banquet and Address, Onigaming Supper Club

### Friday May 5, 1972

8:00-

11:00 a.m. Penokean Session I, 135 Fisher Hall

1:30-

4:45 p.m. Penokean Session II, General Session III, 135 Fisher Hall.

5:30 p.m. Departure of Field Trips B and C. from MTU Memorial Union.

### Saturday May 6, 1972

8:00 p.m. Departure of Field Trip D from MTU Memorial Union

6:00 p.m. Field Trips B, C. and D. arrive back in Houghton.

TECHNICAL SESSIONS

135 Fisher Hall (Building #15, See Map)

MAY 4, 1972

I. GENERAL SESSION 8-12 AM Co-chairmen: Robert C. Reed and Donald M. Davidson, Jr.

| <u>Time</u> | <u>Paper No.</u> | <u>Title</u>                                                                                         | <u>Author(s)</u>                       |
|-------------|------------------|------------------------------------------------------------------------------------------------------|----------------------------------------|
| 8:00 a.m.   |                  | Introductory remarks, Announcements                                                                  |                                        |
| 8:15 a.m.   | 7                | Deposition Model for the Lower Nonsuch Shale Based on Lithologic Variation                           | R. Ehrlich<br>T. A. Vogel              |
| 8:35 a.m.   | 34               | Weathering and Metasomatism of the Presque Isle Serpentinized Peridotite, Marquette County, Michigan | M. D. Lewan                            |
| 9:00 a.m.   |                  | Break for coffee                                                                                     |                                        |
| 10:00 a.m.  | 15               | Petrologic and Structural Aspects of the Gabbro Sill on Pigeon Point, Minnesota                      | M. G. Mudrey<br>P. W. Weiblen          |
| 10:20 a.m.  | 8                | Peleomagnetic Evidence for the Extent of Lower Keweenaw Lavas in Minnesota                           | J. C. Green<br>K. G. Books             |
| 10:40 a.m.  | 10               | Petrology, Structure and Correlation of the Upper Precambrian Ely's Peak Basalts                     | J. A. Kilburg                          |
| 11:00 a.m.  | 18               | Magnetic Reversals and Polar Shifts as Markers in a Proterozoic Time Scale                           | W. A. Robertson                        |
| 11:20 a.m.  | 17               | The Eastern Terminus of the Lake Superior Syncline                                                   | E. Oray<br>W. J. Hinze<br>N. W. O'Hara |
| 11:40 a.m.  | 6                | The Labrador Trough - not a Precambrian Plate Boundary                                               | E. Dimroth                             |

II. GENERAL SESSION 1:30- 5PM Co-chairmen: Randall J. Weege and Gerald Anderson

| <u>Time</u> | <u>Paper No.</u> | <u>Title</u>                                                                                                | <u>Author(s)</u>                              |
|-------------|------------------|-------------------------------------------------------------------------------------------------------------|-----------------------------------------------|
| 1:30 p.m.   | 4                | Iron Segregation in Precambrian Iron Formations: Effects on Sedimentary Compositions                        | B. E. Brown                                   |
| 1:50 p.m.   | 13               | Morphology of Magnetite in Precambrian Iron Formations                                                      | M. S. Loughheed<br>J. J. Mancuso              |
| 2:10 p.m.   | 2                | Geologic compilation and Nonferrous Metals Potential, Precambrian Section, Upper Michigan                   | W. A. Bodwell                                 |
| 2:30 p.m.   | 9                | The Newly Compiled Geological Map of the Precambrian of Upper Michigan                                      | J. Kallio Koski<br>W. A. Bodwell              |
| 2:50 p.m.   | 11               | Precambrian Geology of a Greenstone Belt in Oconto County, Wisconsin, and Chemistry of the Waupae Volcanics | M. M. Lahr                                    |
| 3:10 p.m.   | 12               | The Geology of the Garlic River Greenstone Belt                                                             | P. J. LeAnderson                              |
| 3:30 p.m.   | 16               | Lower Precambrian Metavolcanic-Metasedimentary Sequence, Rainy River, Northernmost Minnesota                | R. W. Ojakangas                               |
| 3:50 p.m.   | 2                | The Geology of the Deer Lake Gabbro-Peridotite Complex, Itasca County, Minnesota                            | J. L. Berkley                                 |
| 4:10 p.m.   | 19               | Archean Salic Volcanic Rocks at Kakagi Lake, NW Ontario - Their Physical and Chemical Nature                | D. R. Smith<br>R. H. McNutt<br>P. M. Clifford |
| 4:30 p.m.   | 5                | Effect of a "Rigid" Ultrabasic Sill on Deformation in Adjacent Rocks, Kakagi Lake, NW Ontario               | R. G. Cuddy<br>P. M. Clifford                 |

III. BANQUET Onigaming Supper Club (U.S. 41 South, Houghton) 7:00 p.m. May 4, 1972

ADDRESS: A. J. Naldrett, University of Toronto  
"Archean Ultramafic Lavas and Their Associated Nickel Sulphide Deposits"

MAY 5, 1972

IV. PENOKEAN SESSION 1 8-11 A.M. Co-chairmen Carl E. Dutton and Stephen C. Nordeng

| <u>Time</u> | <u>Paper No.</u> | <u>Title</u>                                                                                                          | <u>Author(s)</u>                |
|-------------|------------------|-----------------------------------------------------------------------------------------------------------------------|---------------------------------|
| 8:00 a.m.   | 25               | The Penokean Orogeny                                                                                                  | S. S. Goldich                   |
| 8:30 a.m.   | 26               | Relation of Penokean Polyphase Deformation to Regional Metamorphism in the Western Marquette Range, Northern Michigan | J. S. Klasner                   |
| 8:50 a.m.   | 24               | Penokean Tectonics in Northern Michigan                                                                               | W. F. Cannon                    |
| 9:20 a.m.   | 20               | Three-phase Deformation Associated with the Penokean Orogeny, East Gogebic Range, Michigan                            | V. A. Trent                     |
| 9:40 a.m.   |                  | Short Break (10-15 minutes)                                                                                           |                                 |
| 9:55 a.m.   | 23               | Chronology of Precambrian Rocks of Iron and Dickinson Counties, Michigan, Part II                                     | P. O. Banks<br>W. R. Van Schmms |
| 10:15 a.m.  | 27               | Lineaments and Mylonite Zones in the Precambrian of Northern Wisconsin                                                | G. L. Laberge                   |
| 10:35 a.m.  | 28               | Stratigraphic and Tectonic Framework of Middle Precambrian Rocks in Minnesota                                         | G. B. Morey                     |
| 11:00 a.m.  |                  | Coffee and Discussion                                                                                                 |                                 |

V. PENOKEAN SESSION 2 and GENERAL SESSION 3 1:30-5:00 p.m.

Co-chairmen: J. W. Avery and Robert Seisor

| <u>Time</u> | <u>Paper No.</u> | <u>Title</u>                                                                                                     | <u>Author(s)</u>                 |
|-------------|------------------|------------------------------------------------------------------------------------------------------------------|----------------------------------|
| 1:30 p.m.   | 31               | Ages of Some Precambrian Rocks in East Central Minnesota                                                         | J. S. Stuckless<br>S. S. Goldich |
| 1:50 p.m.   | 29               | Granitic Plutonic Rocks of the Southern Province of the Canadian Shield                                          | J. A. Robertson                  |
| 2:10 p.m.   | 33               | Stratigraphy and Sedimentation of the Espanola Formations an Early Aphebian (Middle Precambrian) Carbonate Unit. | G. M. Young                      |
| 2:30 p.m.   | 30               | Regional Relationships in the Penokean Province                                                                  | H. B. Stonehouse                 |
| 2:50 p.m.   | 32               | Geochronology of Precambrian Rocks in the Penokean Fold Belt Subprovince of the Canadian Shield                  | W. R. Van Schmus                 |
| 3:20 p.m.   | 3                | Potential Sources of Raw Materials for the Structured Clay Products Industry, Keweenaw Peninsula, Michigan       | E. M. Booy<br>M. Haddadin.       |
| 3:40 p.m.   | 14               | Subsurface Geology of the Duluth Superior Area, Minnesota-Wisconsin                                              | J. T. Mengel                     |
| 4:00 p.m.   | 21               | Bedrock Morphology in the Vicinity of Portage Lake, Keweenaw Peninsula, Michigan                                 | E. J. Warren                     |
| 4:20 p.m.   | 22               | Glacial Drift on the Mesabi Iron Range, Minnesota, Its Characteristics, Origin and Hydrologic Significance.      | T. G. Winter                     |

THE GEOLOGY OF THE  
DEER LAKE GABBRO-PERIDOTITE COMPLEX  
ITASCA COUNTY, MINNESOTA

John L. Berkley

University of Missouri, Columbia

ABSTRACT

The Deer Lake Gabbro-Peridotite Complex is located in northern Itasca County, Minnesota, three miles southwest of Big Deer Lake. It is intruded into a terrane composed of quartzofeldspathic, tuffaceous metasedimentary rocks and pillowed metabasalts of Lower Precambrian age (Sims, et. al., 1971). In recent years the area has been investigated by several mining companies as a possible source of exploitable nickel deposits.

Detailed mapping has revealed that the complex is composed of five, separate, sheet-like, basaltic intrusions, averaging approximately 700 feet in thickness, each. Magma was supplied to the area in chronologically, widely dispersed episodes, allowing time for earlier intrusions to differentiate and lithify before the emplacement of a later sheet above those already present. Observed contacts between any two sills are characterized by chilled dolerite against a thin zone of amphibolite. The chilled dolerite is thought to represent the parent magma, while the amphibolite is probably a result of contact metamorphism by the magma. For any given sill within the complex, a sharp contact separates the chilled dolerite from the layered sequence above which consists of, from stratigraphic bottom to top, an augite-hornblende peridotite, diopsidic or augitic pyroxenite, and gabbros of varying compositions. This layered series of rocks is a result of selective crystallization and gravity settling of phases. Typical cumulate-intercumulate textural relations as described by Jackson (1961) from the Stillwater Complex of Montana may be seen in rocks from the peridotite up to and including certain lower gabbro units. Small scale layering structures may occasionally be observed in pyroxenites and lower gabbros. Figure one shows the ideal sequence of rock types for any particular intrusion within the complex and gives the expected cumulate and intercumulate phases for each unit.

The peridotite is composed of rounded to elongate olivines surrounded poikilitically by augite, hornblende, or both. Evidence of reaction rims may be seen surrounding some olivine crystals. The peridotite grades sharply into a pyroxenite, usually composed predominately of subhedral to euhedral diopside

enclosed by plagioclase, diopsidic overgrowth, or oikocrysts originally of pyroxene composition but now completely altered. With increasing cumulate plagioclase content, the pyroxenite grades gradually into an augite gabbro. Upper units may exhibit a significant quartz content and micrographic intergrowth. Micropegmatite veins cut many gabbro exposures and pegmatitic material has been observed in certain pyroxenite units as well.

Post-intrusive folding in the area has deformed the formerly horizontal sills into a sequence of tightly folded anticlines and synclines with axial traces trending N40E. The complex plunges to the southwest at an undetermined magnitude. Exposure of the intrusive units is now restricted to a narrow band six miles long and a maximum of about one and one half miles wide. Metamorphic grade does not surpass lower amphibolite or hornblende hornfels facies in the rocks of the complex with most assemblages, including those of the adjacent country rocks, falling into the greenschist facies.

#### REFERENCES CITED

- Jackson, Everett D., 1961, Primary textures and mineral associations in the ultramafic zone of the Stillwater Complex Montana, U. S. G. S. Prof. Paper 358, 106 pp.
- Sims, P. K., Morey, G. B., Ojakangas, R. W., and Viswanathan, S., 1971, Geologic Map of Minnesota, Hibbing Sheet: Minn. Geol. Survey.

| GENETIC FACIES                                 | ZONES           | MEMBERS                            | CUMULATE PHASES         | INTER-CUMULATE PHASES                 |
|------------------------------------------------|-----------------|------------------------------------|-------------------------|---------------------------------------|
| LAYERED SERIES                                 | GABBRO ZONE     | QUARTZ BEARING<br>AUGITE<br>GABBRO | NONE                    |                                       |
|                                                |                 | AUGITE<br>GABBRO                   | NONE                    |                                       |
|                                                |                 | LOWER<br>CUMULATE<br>GABBRO        | PLAGIOCLASE             | AUGITE<br>QUARTZ                      |
|                                                |                 |                                    | PLAGIOCLASE<br>PYROXENE | PYROXENE<br>OIKOCRYSTS<br>QUARTZ      |
| BORDER FACIES<br>CONTACT<br>METAMORPHIC FACIES | ULTRAMAFIC ZONE | PYROXENITE                         | DIOPSIDE<br>AUGITE      | PYROXENE<br>OIKOCRYSTS<br>PLAGIOCLASE |
|                                                |                 | PERIDOTITE                         | OLIVINE                 | AUGITE /<br>HORNBLende                |
|                                                |                 | DOLERITE<br>~~~~~<br>AMPHIBOLITE   | NONE                    |                                       |
|                                                | CONTACT ZONE    |                                    |                         |                                       |

FIGURE 1 IDEAL STRATIGRAPHIC COLUMN FOR A SINGLE INTRUSIVE SHEET, DEER LAKE COMPLEX, MINNESOTA.

GEOLOGIC COMPILATION  
AND  
NONFERROUS METALS POTENTIAL  
PRECAMBRIAN SECTION, NORTHERN MICHIGAN

W. A. Bodwell

Michigan Technological University

A B S T R A C T

The geology and nonferrous metal occurrences of the Precambrian section, Northern Michigan, have been compiled at the scale of 1:250,000. The map incorporates considerable new data which has become available since the previous regional map of 1936.

Review of the regional geology and mineral associations indicates several geologic environments or conditions considered to have potential for mineral deposition.

1) The effective coverage of past exploration drilling in the Michigan copper district was assessed. From this data, it appears that as much as 80 - 85% of presumed favorable ground is yet to be penetrated by drilling according to criteria developed herein:

a) The strata-controlled ore deposit sought has a minimum strike length of 2000 feet.

b) Maps showing drill holes were reviewed and all strike segments with 2000 feet or more between drill holes were outlined. These areas were measured by planimeter and compared to total area of the favorable strata.

c) All strike segments of greater length constitute untested ground.

2) A series of small felsic porphyry intrusives occurring near the base of Portage Lake lava series appear to have potential for copper sulfide deposits based on analogous features with mineralized felsic porphyry bodies on north limb of the Lake Superior syncline in Ontario.

3) A greenstone belt northwest of Marquette, Michigan exhibits certain characteristics of mineralized greenstone belts of the Canadian shield. The presence of numerous base metal occurrences and one small gold deposit suggest that significant base metal or precious metal deposits may yet be found.

POTENTIAL SOURCES OF RAW MATERIALS  
FOR THE STRUCTURAL CLAY PRODUCTS INDUSTRY  
KEWEENAW PENINSULA, MICHIGAN

EMMY BOOY AND MUSA S. HADDADIN

Michigan Technological University

ABSTRACT

The Keweenaw Peninsula of Michigan was explored for potential sites for the establishment of a structural clay products plant. The most favorable location for the establishment of such an industry was in Ontonagon County, in the southwestern portion of the Peninsula.

The sedimentary cover overlying the Precambrian to possibly Cambrian bedrock varies rapidly both laterally and vertically because of the conditions of deposition during the Pleistocene. In general, the average particle size decreases from North to South. Otherwise, no consistent variations were observed. Most sediments having suitable properties for raw materials for the structural clay products industry have been mapped as glacial lake sediments.

An attempt was made to identify distinctive flora which might provide a mapable criterion for distinguishing between sediments suitable for structural clay products manufacturing and those unsuitable. Although there is variation in floral assemblage with topography (e.g. well vs. poorly-drained areas) there was no distinguishable variation with sediment size.

Requirements for suitable materials for structural clay products include good workability, low drying and firing shrinkage, good dry and fired strengths, and good fired color. Most of the samples studied met all criteria for most structural clay products.

The mineralogy of the samples did not vary appreciably in major constituents throughout the area sampled. Illite, expandable vermiculite, and chlorite were the dominant clay minerals. Quartz and feldspar were ubiquitous, while minor kaolinite, calcite, and dolomite were present in many samples.

Certain fundamental soil mechanics tests were run on the materials in conjunction with the ceramic tests performed. In general, the samples tested were relatively stable clays to silty clay soils.

In the area studied the most desirable location from the viewpoints of volume of material available and ease of transportation to markets would be in the area around Ontonagon. Most of the samples studied from this area would be useful for all types of structural clay products.

# IRON SEGREGATION IN PRECAMBRIAN IRON FORMATIONS: EFFECTS ON SEDIMENTARY COMPOSITIONS

BRUCE E. BROWN

Department of Geological Sciences  
Milwaukee, Wisconsin

## A B S T R A C T

According to Ronov's (1964) estimates, cherty iron formations of the pre-Cambrian type were present in the amount of 15% of the total sedimentary rock volume during the time period around 2 b.y. ago. The segregation of iron to this degree would seem to require significant shifts in the iron contents of other types of sediments, particularly shales. A sample mass balance calculation after the manner of Garrels and Mackenzie (1971, p. 242) illustrates this. Using a present day "average igneous rock" (Brotzen, 1966) as a source for limestone, sandstone, and shale, and considering just the total iron percent we have, after Garrels and Mackenzie (1971, p. 242):

| Average igneous rock<br>Fe oxides in gms/kg | limestone | shale | sandstone |
|---------------------------------------------|-----------|-------|-----------|
| 62                                          | -         | 62    | 4         |

if one considers a situation where 15% by weight of the sediments are of iron formations containing 30% iron oxides, we must subtract 45 grams of iron oxide to supply this source, leaving only 17% to go into shales and sandstones.

The assumption is made that iron normally going into shales (such as might happen during the weathering of a basalt today) has been diverted into iron formations. If this assumption is valid, shales formed during times when iron formations were a significant portion of the sedimentary column, should contain less iron than might otherwise be expected considering possible igneous sources. Since iron is the heaviest common element this might have implication regarding the composition, density and isostatic relationships of rocks such as granitic gneiss formed by metamorphism of shale.

# EFFECT OF A "RIGID" ULTRABASIC SILL ON DEFORMATION IN ADJACENT ROCKS, KAKAGI LAKE, NW. ONTARIO

by R. G. Cuddy, P. M. Clifford

Department of Geology, McMaster University, Hamilton, Ontario

## A B S T R A C T

The greenstones of Kakagi Lake consist of about 7500 metres of basic to acid volcanic rock, and some associated sedimentary rocks. Embedded within this assemblage are "sills" of ultrabasic material.

Study of the western portion of the Kakagi Lake area shows that the ultrabasic sills have a fold form of class 1-B or 1-C (cv. Ramsay; 1967 pp. 365 ff.), as revealed by thickness, measurement and isogon plots. Petrographic study of one sill (Ridler, 1966) suggests that very little strain has occurred within the sill.

The rocks in contact with the sills are with very few exceptions, acid pyroclastic volcanics. They lack significant primary layering and, mechanically, form thick, rather homogeneous units. Cleavage density rises, as does consistency of orientation of cleavage, in the vicinity, and along axial surface continuations of tight folds in the sills. Conversely, open folds in the sills are adjacent to areas of low cleavage density and locally variable cleavage orientation. In addition, fragments in the pyroclastic rocks, though flattened to lie roughly parallel to cleavage, are poorly oriented within the cleavage, a situation which suggests rather low strains within the cleavage plane compared to the high strains across it, or alternatively, a fluctuation of pyroclast long axes over  $180^{\circ}$  in the pre-strain state. Fold axes, few in number, are everywhere of moderate to steep plunges.

These features are the product of an early phase of deformation. Subsequent deformation has produced kink folds and en echelon quartz-filled gash arrays. These suggest local orientations of principal axes of stress or strain, apparently not of regional value.

It is not clear from our data, or any other data available whether the granites surrounding these rocks are fully responsible for the deformation, or have merely modified a prior fold array whose axial surfaces were aligned east-west. What is clear is the marked effect of the sills with their low ductility compared to the pyroclastic rocks in which they occur.

Ramsay, J. G. (1967) Folding and Fracturing of Rocks.

Ridler, R. H. (1966) M.Sc. thesis (unpublished) Univ. of Toronto.

## THE LABRADOR TROUGH - NOT A PRECAMBRIAN

## PLATE BOUNDARY

Erich Dimroth,

Service d'Exploration géologique,

Ministère des Richesses naturelles, Québec

## A B S T R A C T

The boundaries between the Precambrian age provinces are the natural location where to look for Precambrian plate boundaries. This is specifically so for the junction between the Superior and Churchill Provinces, which are separated by the Circum-Ungava geosyncline.

Deep erosion has removed the whole of the original geosynclinal filling in the sector between Labrador trough and Cape Smith belt, and the relations between the geosynclinal filling and its basement can be studied. Other segments of the Labrador trough are deeply enough eroded to infer the presence of a basement.

At the level of the basement (that is between the Labrador trough and the Cape Smith belt) the contact between the Superior of Churchill Provinces appears to be gradational. The Archean gneisses are continuous to Ungava bay, but they give Hudsonian K-Ar ages east of line indicated in Wanless (1969). The Archean gneisses east of the age front appear to have suffered Hudsonian deformation, as indicated by the folded outline of the contact between the basement and the Lower Proterozoic sequence. Beall et al. (1963) noted that the Hudsonian biotite isograd intersects the basement-cover contact, and retrograde metamorphism has been noted in a few basement outcrops visited. It appears therefore that a Hudsonian tectonic, metamorphic and age (K-Ar) front, intersects a uniformly Archean terrain between the Cape Smith belt and the Labrador trough.

The northernmost Labrador-trough and the easternmost Cape Smith belt are synclinoria plunging south-south-east and west-northwest. The Lower Proterozoic sequence of both belts, which includes very voluminous oceanic tholeiites rests on the basement gneiss with an absolutely sharp contact (Hardy, 1969; Schimann, 1972).

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In the centre of the Labrador trough a very thick sequence of oceanic tholeiite rests on continental red beds and on shallow water sediments (for example sandstone with coarse current cross-bedding, stromatolitic dolomite). Units of stromatolitic dolomite, of dolitic iron formation and similar shallow-water deposits is continuously exposed across the whole trough, and, in its east, mantles domes of basement gneiss. There is not a trace of a sheeted gabbro complex, and in fact the source of the basalts is still enigmatic. Only very few and generally thin gabbroic dykes intersect the sedimentary sequence and are the only possible conduits known at present.

In the extreme east of the Labrador trough a metamorphosed meta-pelitic sequence, comprising interbeds of orthoquartzite, dolomitic sandstone (now diopside-quartzite), para-amphibolite, is exposed. Arkoses, arkosic conglomerates, are present here and there and perhaps indicate the presence of occasionally emergent source areas east of the trough. According to Wanless (1970) granitoid gneisses east of the trough give at one locality a K-Ar age of 2160 m.y., that is somewhat older than the Rb-Sr age of the Labrador trough rocks (Fryer, 1971). This seems to confirm the basement nature of at least some granitoid gneisses east of the trough.

There appears little doubt that the Labrador trough formed by differential subsidence and that it is not related to a continental margin existing at Lower Proterozoic time.

#### REFERENCES

- Beall, G. H., Hurley, P.M., Fairbairn, H.W., and Pinson, W.H., Jr. (1963), Comparison of K-Ar and Rb-Sr dating in New Quebec and Labrador. *Am. J. Sci.*, V. 261, p. 511-560.
- Fryer, B. J. (1971), Rb-Gr whole rock ages of Proterozoic Strata bordering the eastern part of the Superior Province, Canada. *Geol. Soc. Amer.*, Abs with programs, 3, p. 574-575.

-3-

Hardy, R., (1969), Géologie de la région du lac des Chefs, Thèse de maîtrise, non publiée; École Polytechnique.

Schimann, K. (1972), Wakeham Bay In: Travaux sur le terrain 1971. Department of Natural Resources, Quebec, Report S-126AF, p. 7-10.

Wanless, R. K. (1969), Isotopic age map of Canada. Geol. Surv. Canada, Map No. 1259A.

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## DEPOSITIONAL MODEL FOR THE LOWER NONESUCH

## SHALE BASED ON LITHOLOGIC VARIATION

Robert Ehrlich and Thomas A. Vogel  
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East Lansing, Michigan 48823

## ABSTRACT

The White Pine copper deposit is one of the classic strata-bound deposits. Not only is the mineralization restricted to a small lower portion of the Nonesuch Shale but the vertical succession of lithologies within the mineralized section is remarkably similar in all parts of the mine. This striking similarity in vertical succession has in the past been used as a basis for assuming wide scale lateral continuity of subunits within the Lower Nonesuch Shale. This in turn led to models of deposition, diagenesis, and ore emplacement in which the layercake aspect of the lower Nonesuch stratigraphy played a key role. The purpose of this report is to integrate the observed lithologic variation into an overall depositional model for the Lower Nonesuch Shale.

The lower fifty feet of the Nonesuch is composed of numerous textural modes such as graded, well-laminated, crudely laminated, fragmental, blebby, massive, etc. Various combinations of these textural elements can be found in varying proportions in each of the formal stratigraphic units and each of these (Domino, Brown Massive, etc.) have extensive lateral continuity whereas the individual textural elements included within each unit are not persistent. These lateral changes arise in three principal ways: (1) abrupt changes apparently resulting from slumping and sliding of plastic sediments, and (2) gradual and continuous changes in lithology within a major stratigraphic unit such as massive units becoming crudely laminated and then graded. Similar lateral variations can be seen with major elements within one formal stratigraphic unit varying laterally into a lithology which is a characteristic of an adjacent stratigraphic unit above or below.

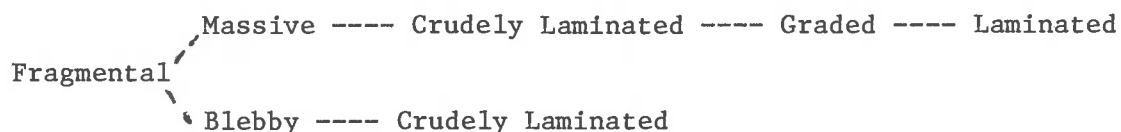
Most of the textural elements can be seen in varying proportions in the massive units. When observed in detail, it can be seen that there is a non-random juxtaposition of the elements; that is, certain elements tend to be adjacent to certain others. Figure 1 shows the most probable

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associations between textural elements. Elements adjacent in the diagram tend to be intimately associated with each other on a hand sample scale. Elements far apart on the diagram are rarely seen juxtaposed.

Figure 1 Mutual Occurrence of Textural Elements in Massive Units

Textural elements relatively closer on diagram occur together more often.



In these massive units the textural elements on the left side of the diagram (e.g., fragmental, massive, blebby) are more abundant than those on the right. Because each of these elements, except those on the extremes, is associated with two others, these inter-relationships are the basis for the pattern of vertical and lateral variation within the massive units.

A characteristic vertical succession is from bottom to top; massive, crudely-laminated, fragmental, scoured surface, massive, blebby, crudely-laminated, graded, well-laminated. A section such as this is composed of two depositional units, each beginning with a massive textural variety and terminated by a fragmental or laminated variety. Within each depositional unit there are no sharp boundaries as one proceeds from one textural element to another, indicating that the sequence of textural elements arose from a single genetic event.

The textural varieties and lateral and vertical relations observed are consistent with a depositional model involving progressive infilling of a depositional basin with coarse, denser materials being deposited over materials of low specific gravity that are mechanically weak. The pattern seen here can be understood if the effects of lateral migration and loci of sedimentation are considered as well as general infilling in the basinward direction.

In general terms, the dynamic model consists of coarse-grained material deposited on muds, triggering its accompanying flow components. In the Nonesuch two modes of deposition and transport were involved in most slumps. (1) The uppermost, least consolidated material, generally hematite-rich, moved rapidly, partially as suspended material, partially as bonafide turbidity flow, and fanned out into a roughly lobate deposit.

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(2) The slightly more consolidated material underlying this zone, in a more reduced condition, either flowed plastically, more slowly, down the depositional slope with relatively little rotation or, if it was reasonably coherent, behaved as a rotational slump with a well-developed concave upward slip surface.

Sediment that has moved further downslope is more laminar and less rotational in nature. This, coupled with longer time involved in transport, allows the previously homogenized sediment to differentiate itself with respect to grain size. The sequence, updip to downdip, is thickest, but of least lateral extent at the updip end, and thinnest (perhaps only one graded bed thick) but most laterally extensive at its downdip extremity where it fans out in an unrestricted fashion.

This process model can explain the three dimensional pattern of rock variation and provides an important framework for a discussion of the origin of the other geochemical and petrological variations in the Lower Nonesuch Shale.

PALEOMAGNETIC EVIDENCE FOR THE EXTENT OF LOWER  
KEWEENAWAN LAVAS IN MINNESOTA

by

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## A B S T R A C T

Most of the North Shore Volcanic Group of Gehman (1958), from central Duluth northeastward to the diabase complex at Hovland (Fig. 1), is now known to be middle Keweenaw on the basis of its normal magnetic polarity (Books, 1968; Palmer, 1970; new data). Beneath (north of) the Hovland diabase and the southern prong of the Duluth Gabbro Complex in Cook County is a series of lavas, approximately 8,000-10,000 feet thick (the Hovland and Grand Portage lavas of Green 1971) that were extruded during an earlier period of reversed polarity, and are therefore lower Keweenaw. These two units can be traced for at least 25 and probably 50 miles westward, where they are intruded by the Duluth Gabbro Complex. The Hovland lavas include many porphyritic basalts with platy plagioclase phenocrysts. These two lava units thus correlate with the lithically similar reversed "Traps of the South Range" in the Ironwood area, Michigan-Wisconsin, (Books, 1968) and with the Osler Series of Ontario (Palmer, 1970). The Grand Portage lavas are cut by a dike swarm of basalt and porphyritic basalt that also show reversed polarity and may have been feeders for the porphyritic Hovland lavas.

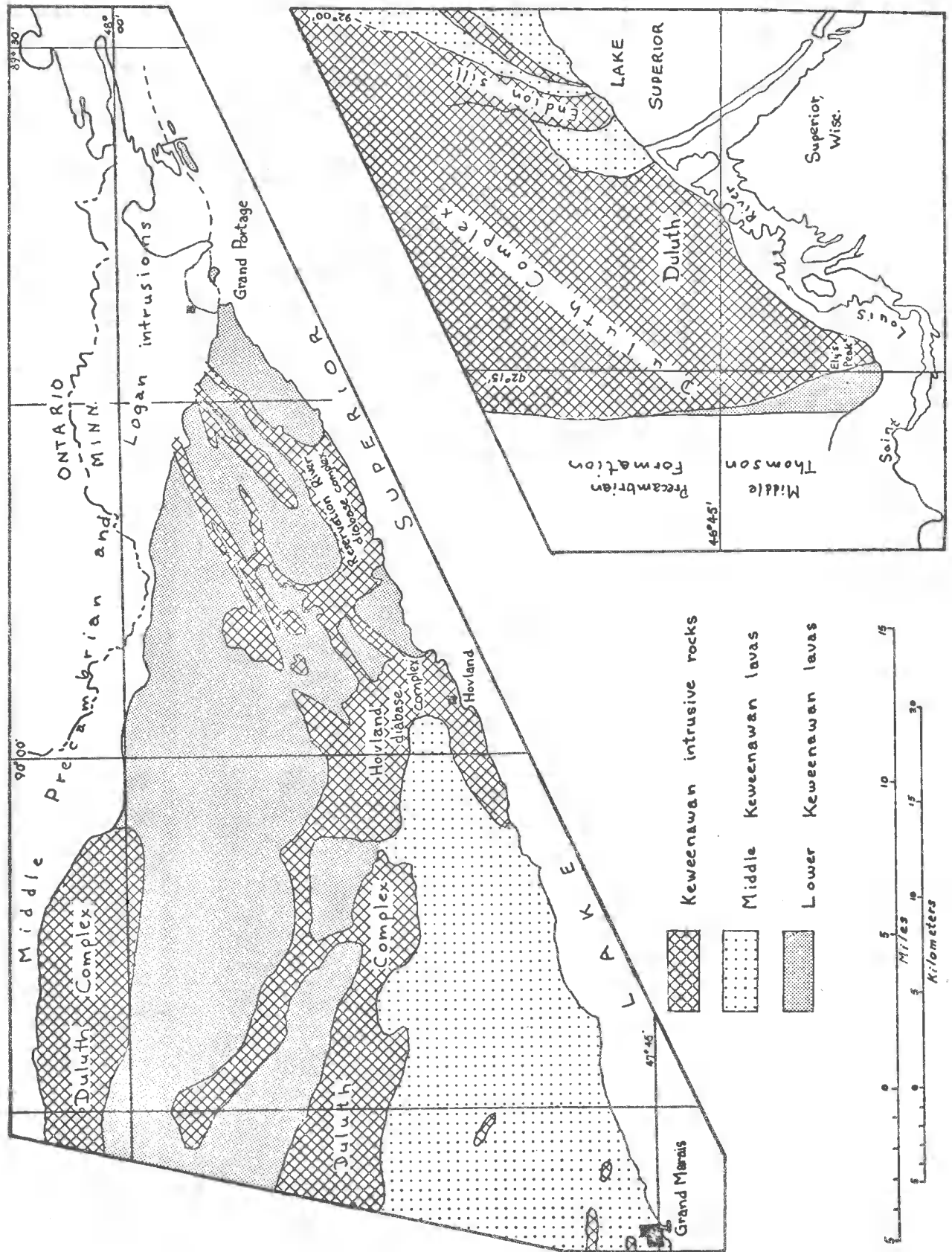
The Grand Portage lavas rest disconformably on the Puckwunge Formation of Schwartz, 1942, an orthoquartzite that overlies the middle Precambrian Rove Slate. Although the samples showed only weak magnetization, new determinations give an unequivocal reversed polarity for the Puckwunge, and support its correlation with the lithically similar Sibley Series sandstones of the Thunder Bay district, Ontario. At the southwest end of the basin also, the Duluth Gabbro Complex intruded between lavas of normal and reversed polarity, i.e. between middle and lower Keweenaw volcanic rocks. New determinations show that most or all of the basalts at Ely's Peak (the wedge of lavas that underlie the Duluth Gabbro Complex west of Duluth) have reversed polarity, and thus correlate with the flows at Ironwood and Grand Portage. The basal pyroxene-porphyritic lavas in this unit bear a very close resemblance to the basal lavas on Lucille and Magnet Islands east of Grand Portage, further supporting this correlation; such lavas are not known from anywhere else in the North Shore Volcanic Group.

Samples from the conformably underlying "Nopeming sandstone" and from the lowest flow at the "Grandview Golf Course" locality show weak magnetization and considerable scatter, but normal polarity. What is believed to be the same flow (certainly part of the same unique pyroxene-basalt flow group) 3/4 mile to the south shows reversed polarity. Although these normally polarized samples were taken at least 500 to 800 feet (structural distance) from the base of the Duluth Gabbro Complex and are not visibly recrystallized, even in thin section, it appears likely that the basalt's polarity has been inverted to

normal during contact metamorphism by the Duluth Gabbro Complex. No conclusions can yet be made regarding the original polarity of the sandstone; it may have been normal, thus correlating with the Bessemer Quartzite of Seaman, 1944, beneath the lowest Keweenawan flows at Ironwood, or it may also have been changed from an original reversed state, thus correlating with the Puckwumge and Sibley. Further investigations will be carried out.

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THE NEWLY COMPILED GEOLOGICAL MAP OF THE PRECAMBRIAN  
OF THE UPPER PENINSULA OF MICHIGAN

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With the retirement of the older staff, the Department of Geology and Geological Engineering found itself in a position of requiring a mechanism whereby it could refamiliarize itself with the Precambrian geology of the Upper Peninsula, in order to identify good field-thesis problems and to become knowledgeable about the mineral potential of the region. The most direct approach seemed to be in compiling all geological data on the most suitable scale.

With the help of the Institute of Mineral Research (M. T. U.) and the full cooperation of the Michigan Geological Survey, the U. S. Geological Survey, various mining companies, and land owners, this task has now been completed. The resulting map, "Precambrian Geology of the Upper Peninsula" (M. T. U. Press, Geological Series, Map 2, 1972) is on a scale of 1:250,000. A second map "Geology of the Marquette-L'Anse Region, Michigan", (M. T. U. Press, Geological Series, Map 1, 1972) shows the available outcrop data for the "Northern Complex" on a scale of 1:62,500. Both maps, uncolored, show the location of known base metal and precious metal showings.

The 1:250,000 map (released April, 1972) is priced at \$3.00 and the 1:62,500 map (released in late August, 1972) is \$5.00, both including postage, prepaid. They are available from the Department of Geology and Geological Engineering, Michigan Technological University, 49931.

Although the maps are complete in themselves, they represent part of the documentation for an M.S. thesis by W. Bodwell, entitled "Geologic Compilation and Non-ferrous Potential, Precambrian Section, Northern Michigan". Copies of the thesis may be obtained from the Department for the cost of reproduction.

PETROLOGY, STRUCTURE, AND CORRELATION OF THE  
UPPER PRECAMBRIAN ELY'S PEAK BASALTS

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## A B S T R A C T

The Upper Precambrian Ely's Peak basalts crop out in a north-south trending, wedge shaped belt in the area around Nopeming, southwest of Duluth, Minnesota. These Lower Keweenawan flows overlie the basal Upper Precambrian quartzite in the southwestern portion of the Lake Superior basin. There are about 18 individual flows totaling some 1,200 feet of thickness, the thickest flow being 125 feet thick while the thinnest is less than 10 feet thick. Many of the flows show lateral continuity, for example, one flow is traceable for about three miles along strike.

Petrographically, there are three main types of flows. Five of the first six that form the basal portion are dark gray, porphyritic basalts. Of these, four contain euhedral, zoned, single and glomeroporphyritic augite phenocrysts up to 5 mm in diameter. Some ilmenite phenocrysts and some olivine pseudomorphs are also present. The groundmass contains altered plagioclase, magnetite, augite, actinolite, chlorite, and sphene. The sixth flow up from the base is a dark gray, porphyritic basalt with single and glomeroporphyritic plagioclase phenocrysts up to 7 mm in diameter; there are also occasional augite phenocrysts. The groundmass contains altered plagioclase, augite, actinolite, ilmenite, sphene, epidote and chlorite. The third type of flow is a dark gray, commonly ophitic, altered basalt. It consists of plagioclase, occasional olivine pseudomorphs, actinolite after augite, augite, ilmenite, magnetite, epidote, sphene, and chlorite.

Structures within the flows include ropy surfaces, vesicular and amygdaloidal tops, straight and bent pipe vesicles, straight cylinder vesicles, columnar joints, and pillows in the basal flow. Several north-east trending basalt dikes cut the flows and have been deeply eroded leaving pronounced lineaments.

The whole sequence has undergone regional hydrothermal metamorphism to the high zeolite-low greenschist facies. Minerals present which demonstrate this are actinolite, chlorite, and epidote. The only zeolite present is wairakite which has been discovered probably for the first time in the Lake Superior region. It is the highest temperature zeolite. Intrusion of the Duluth Complex is thought to be responsible for elevating the geothermal gradient and thus, permitting the formation of wairakite. The gabbro intrusion also contact metamorphosed the lavas to a medium grained pyroxene hornfels for a distance of up to one-fifth of a mile from the contact.

Pressures of metamorphism are thought to have been around 2,000 bars, although a range of pressures between 1,500-2,500 bars seems feasible. This pressure was produced by the weight of up to 30,000 feet of overlying Upper Precambrian lavas and Duluth Complex which underlie the North Shore of Lake Superior; however, as little as about 16,000 feet of overburden could have produced the minimum pressures of about 1,500 bars needed for metamorphism.

Based on their distinctive petrology and reversed magnetic polarity (Green and Books, 1972), the Ely's Peak basalts appear to correlate with the basal flows at Grand Portage, Minnesota. This implies that the time of deposition at these localities was approximately the same, and the source area from which these lavas were derived was probably the same.

# PRECAMBRIAN GEOLOGY OF A GREENSTONE BELT IN OCONTO COUNTY, WISCONSIN, AND CHEMISTRY OF THE WAUPEE VOLCANICS.

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## A B S T R A C T

Detailed mapping has been carried out in the northern half of the Mountain Quadrangle in order to establish the geologic history and evolution of a Precambrian greenstone belt and to determine the nature of volcanism. The sequence of Precambrian events was the following (oldest to youngest):

1. Deposition of the Waupee formation, including flows, agglomerates, tuffs, volcanoclastic sediments, and sandstones.
2. Emplacement of the Macauley intrusive (granodiorite to quartz monzonite).
3. Deformation and regional metamorphism.
4. Deposition of the Baldwin conglomerate.
5. Intrusion of the Hager granite and contact metamorphism of the older rocks.

The Waupee formation trends approximately N45°E and has a steep dip. Relic graded bedding and cross-stratification indicate that tops of beds are to the northwest. Three lithologic units have been distinguished in the Waupee formation: a basal member consisting of massive flows, volcanoclastic sediments, and minor agglomerates; a middle sandstone member with a subordinate amount of massive flows; an upper thin-bedded tuff member. Pyrrhotite mineralization is concentrated along the boundary between the basal and middle members of the formation.

Sedimentary features and volcanic textures have been preserved in the Waupee formation, but recrystallization under conditions of the amphibolite facies has produced the following mineral assemblages:

basic volcanic flows: plagioclase-hornblende-clinopyroxene.  
plagioclase-hornblende-cummingtonite.  
sedimentary rocks: quartz-biotite-hornblende-plagioclase+  
epidote.  
quartz-microcline-biotite-muscovite+  
plagioclase.

Contact metamorphism due to intrusion of the Hager granite has been superimposed on the regional metamorphic assemblages, resulting in the appearance of garnet, vesuvianite, scapolite, clinopyroxene, hornblende, and plagioclase in the metavolcanic rocks. In the aluminous metasedimentary rocks the assemblage quartz-plagioclase-alkali feldspar-muscovite-biotite-andalusite+ sillimanite has developed.

Eighteen samples of massive volcanic flows from the Waupee formation were fused and analyzed for nine elements (Si, Al, Ti, Fe, Mn, Mg, Ca, Na, K) by means of an electron microprobe. The majority of samples are basalts ( $\text{SiO}_2$ , 46 to 51%) containing 15 to 20%  $\text{Al}_2\text{O}_3$  and 2.0 to 5.8%  $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ; a few samples are andesitic, containing up to 61%  $\text{SiO}_2$ .

If the chemical compositions of the massive flow rocks have not been modified during regional metamorphism, then the Waupee volcanics can be classified as high-alumina and alkalic basalts. As yet, no tholeiitic basalts have been recognized in this area.

The chemistry of the metavolcanic rocks and the nature of associated metasedimentary rocks suggest that the Waupee formation originated in an island arc environment.

## THE GEOLOGY OF THE GARLIC RIVER GREENSTONE BELT

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## ABSTRACT

The Garlic River Greenstone Belt is the Archaean greenstone belt northwest of Marquette, Michigan. It consists of a series of basalt flows, tuffs, greywackes, arkoses and iron formations formerly referred to as the "greenstone" or as Mona Schist. The belt is twenty miles wide along the southern boundary, at the contact with the Marquette Synclinorium, and extends ten miles to the north (See Fig. 1).

Discernable tectonic history indicates gentle folding of the flows and sediments, followed by intrusion of quartz monzonite pegmatites, large diabase dikes and finally granodiorite pegmatites. The flows and sediments were metamorphosed to chlorite schists and amphibolites. The chlorite and chloritic amphibole schists may represent greywackes and/or reworked or waterlain tuffs. The amphibolites are thin bedded or massive; some of the latter have pillows or relict plagioclase laths, indicating a volcanic origin.

Felsic volcanics are uncommon, but form a zone of sheared rhyolitic tuffs (?) at the east end of the Dead River Basin. Small extrusive bodies of porphyritic dacite are found throughout the chlorite and amphibole schists.

The Arkoses (Gar) occur commonly as thin units in the chlorite and amphibole schists, but are the dominant rock type in two areas near the northwestern boundary of the belt.

Iron formation (IF) consists of thin discontinuous lenses of magnetite in arkoses. Neither carbonate nor sulfide facies iron formation were found.

Two synclines have been mapped trending northwest-southeast and plunging southeast, one in the northwest corner of the belt and the other some six miles to the south in the central part. Additional detailed mapping may reveal other folds.

Two large downfaulted basins with lower (Ar) and middle and upper (Amu) Animikie Sediments, partially covered with thick deposits of Pleistocene sand, truncate the northern and western boundaries of the belt. A third smaller basin occupies the center of the belt.

In the northern part of the area two ages of felsic intrusives can be distinguished, but this distinction cannot be made southeast of the Dead River Basin. The younger intrusives are predominantly quartz monzonites, and are cut by the second set of intrusives which are weakly metamorphosed, non-porphyrific granodiorites. The felsic intrusives in the southern part are porphyritic granodiorite pegmatites.

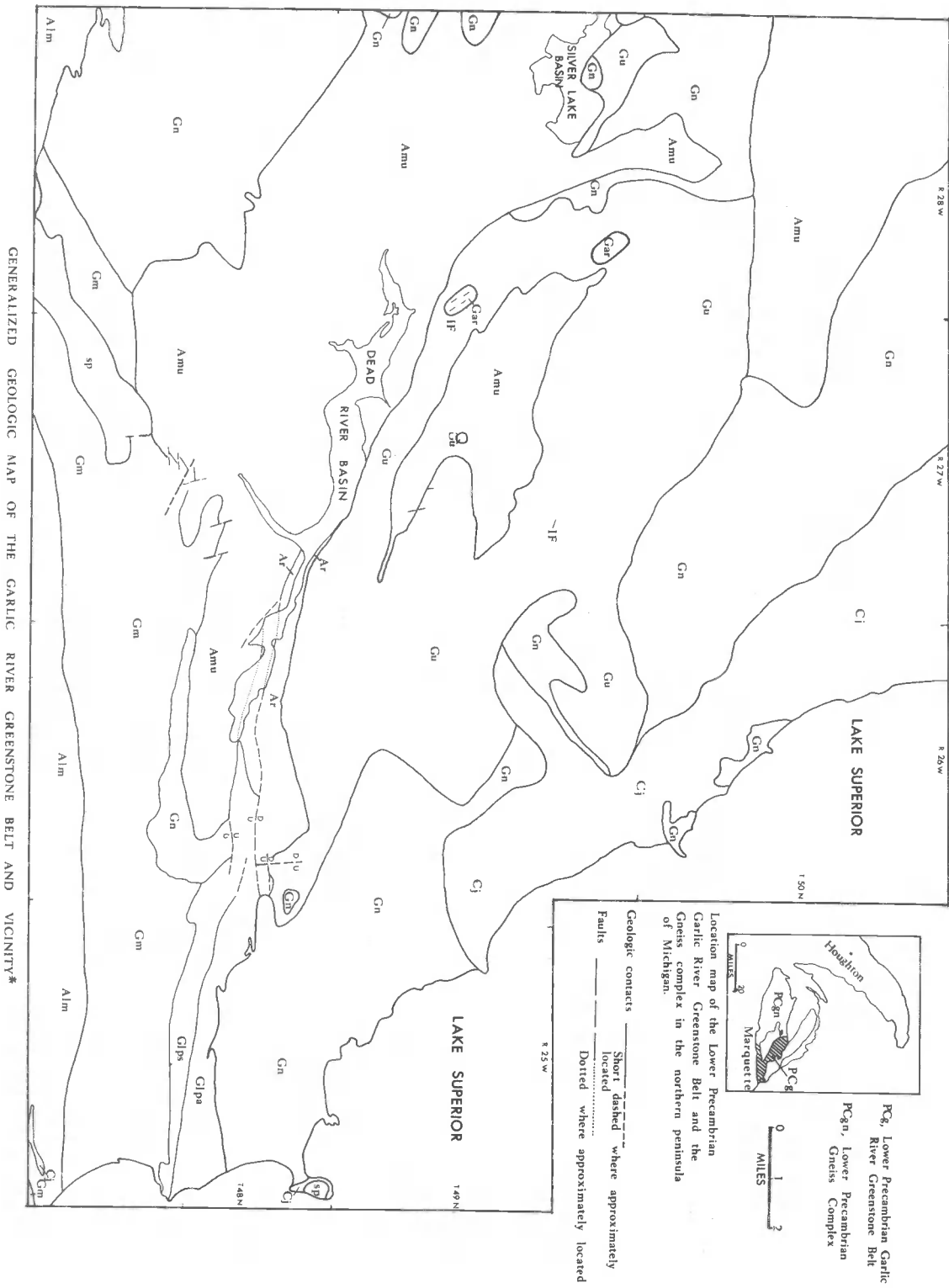
Diabase dikes consisting of unoriented subhedral hornblende and plagioclase crystals trend east-west across the regional foliation but are not folded. They appear to belong to one set, intermediate in age between the quartz monzonite and the granodiorite.

The uniformity of mineral composition of the greenstones and the ubiquitous and commonly complete alteration to chlorite and sericite, makes determination of the metamorphic grade difficult. However, the trend, from predominantly pale green amphiboles to dark blue-green amphiboles, from the center to the margins of the belt, indicates that the metamorphic grade increases in the same direction from the greenschist to the amphibolite facies.

Although stratigraphic and time relationships in the belt are unknown the following generalizations can be made, 1) the sediments, tuffs and lavas were deposited in shallow water, possibly subaerially, as indicated by the pillow lavas and oxide facies iron formations, 2) the series of thick and extensive metabasalts, tuffs, greywackes and rhyolites south of the Dead River Basin indicate continuous and voluminous outpourings of lava and pyroclastics, and 3) the thin discontinuous layers of basalt, greywackes, tuffs, dacites, arkoses and iron formations to the north, suggest local eruptions of short duration with frequent erosional breaks.

After folding of the greenstones, magma intruded and assimilated the lower units, leading in turn to first stages of development of the lit-par-lit gneisses (Gn). The magma spread further into the greenstone and formed pegmatite dikes and sills in the nose of the northwestern syncline. This was followed by the intrusion of a series of diabase dikes; at this time the metamorphic grade reached it's peak.

The area was then covered by Animikie sediments which were folded by the Penokean Event, when the structural basins were formed. The intrusion of Keweenawan dikes, followed by deposition of the Jacobsville sandstone in late Precambrian or early Cambrian times, closed the geological record, with the exception of that attributed to the Pleistocene glaciation.



# GENERALIZED GEOLOGIC COLUMN<sup>1</sup>

|                                        |                                           |                        |                                                |
|----------------------------------------|-------------------------------------------|------------------------|------------------------------------------------|
| Upper Proterozoic<br>or Lower Cambrian | Jacobsville Sandstone                     |                        |                                                |
|                                        | unconformity                              |                        |                                                |
| Middle Proterozoic                     | Keweenawan Diabase Dikes                  |                        |                                                |
| Lower Proterozoic                      | Animikie (A)                              | Middle and Upper (Amu) |                                                |
|                                        |                                           | Lower and Middle (Alm) |                                                |
|                                        |                                           | Lower                  | Reany Creek (Ar) Formation                     |
| ?                                      | Serpentinized Peridotites <sup>2</sup> sp |                        |                                                |
| ARCHEAN                                | ? Granodiorites                           |                        |                                                |
|                                        | Intrusive contact                         |                        |                                                |
|                                        | Metadiabase Dikes                         |                        |                                                |
|                                        | Intrusive contact                         |                        |                                                |
|                                        | Quartz Monzonites                         |                        |                                                |
|                                        | Intrusive contact                         |                        |                                                |
|                                        | Garlic River Greenstones <sup>3</sup> (G) |                        | Gu<br>Gar<br>— IF<br>Gr†<br>Glpa<br>Glps<br>Gm |
| Gneiss and Intrusive Complex (Gn)      |                                           |                        |                                                |

\*Based in part on maps by Case, J.E. and Gair, J.E. (1965), Gair, J.E. and Thayden, R.E. (1968), Puffett, W.P. (1969) and LeAnderson, P.J. (1969).

<sup>1</sup>Units with symbols are included on the map with descriptions in the text. Units without symbols are not included on the map due to the scale involved.

<sup>2</sup>The age is uncertain. They may be post-Anamikie and pre-Keweenaw.

<sup>3</sup>The stratigraphic succession of the units of the Garlic River Greenstone is indeterminate.

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MORPHOLOGY OF MAGNETITE  
IN PRECAMBRIAN IRON FORMATIONS

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ABSTRACT

The morphology of magnetite in all metamorphic facies of unoxidized Precambrian iron formations in the Lake Superior region is remarkably similar. Particularly noticeable are discrete symmetrical or distorted octahedral crystals of magnetite disseminated within individual lamina of chert. Several other features are noteworthy: 1) the crystal diameters range from sub-micron to over fifty microns; 2) the concentration of crystals in a particular lamina can range from a fraction of a percent to aggregates constituting the entire lamina; 3) the invariant associate of magnetite is chert; 4) the variant associates are iron carbonate and/or iron silicate minerals; 5) the minor but not uncommon associates are minute hematite crystals as disseminated spherical clusters, and pyrite as framboids, octahedra, and crystal aggregates generally within laminations of digital stromatolites or in laminations of mat algae.

The morphology of magnetite, its variation in grain size, and its relationship to chert (quartz) siderite, iron silicate minerals, pyrite and/or hematite indicate that it is primary and that no chemical interreactions took place during diagenesis or metamorphism even to extremely high grades.

SUBSURFACE GEOLOGY OF THE DULUTH-SUPERIOR AREA,  
MINNESOTA-WISCONSIN

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## ABSTRACT

Study of about 300 borehole records for the Wisconsin Geological Survey indicates that the Quaternary succession in the western end of the Superior lowland consists of glacial, lake, and river deposits which record stages in the development of Lake Superior which are not presently evident in the high-level shore deposits around the rim of the basin to the west or in deeper water lake deposits to the east. Preliminary interpretation of the sequence suggests two times of deep water red clay accumulation separated by a low water stage during which sands and gravels were laid down across an unconformity. A prominent boulder bed overlies the youngest red clay deposit, suggesting a late pulse of ice development during about Nipissing time.

The Duluth Complex forms the north wall of the lowland in the Twin Ports area and is found in borings along St. Louis and Superior Bays, where wells encounter the same lithologies known from surface exposures. Fluvial red clastics - mainly quartzose sandstones with limited amounts of conglomerate and shale - of the Bayfield group are unconformable on the Complex and subcrop beneath most of the plain. Throughout the subcrop the Bayfield Group is identified as a "sandstone" or "brownstone" and an aquifer. Similar red clastics underlie most of the western end of the Superior Basin and are the principal source from which the Quaternary sediments were derived. Along the base of the South Range the red clastics are cut off by the Douglas Fault which brings the Keweenaw basalt sequence of the St. Croix Horst upward and northward over the sandstones. Basalts crop out locally along the crest of the South Range and subcrop beneath the Quaternary succession southward to the Lake Duluth beaches (elevation about 1070) and beyond.

The most notable feature about the configuration of the erosion surface on which the Quaternary succession lies is the buried western extension of the major depression along the northerly shore of Lake Superior (cf. Farrand, 1969). Twenty-five to 50 feet of local relief is present on the bedrock surface everywhere. One local high forms a prominent outcrop along the bay front at the foot of 27th Avenue West in Duluth and a belt of subsurface bedrock highs are known in the northern half of 48N-13W, extending westward into the center of 48N-14W in Wisconsin.

A maximum thickness of about 600 feet of sediments are present along the axis of the north shore depression between Fond du Lac and Superior Bay and 100 to 300 feet are present under the plain as far south as the crest of the South Range. Less than a hundred feet of glacial drift overlain by clays and/or sands is present along the crest of the South Range.

Glacial drift everywhere overlies the bedrock of the plain. Typically about 25 feet is present except toward the bottom of the north shore depression, where as much as 200 feet is known. The drift ranges from a silty or sandy clay to an argillaceous sand and generally contains gravel and erratic boulders. Clean sand/gravel lenses are presently locally most commonly at or near the base of the drift, and are an important source of ground water when encountered.

Lake deposited stiff red clay overlies the drift and is more or less gradational with it. Along the northerly side of the St. Louis River in West Duluth, and beneath the plain to the south of Superior almost the entire Quaternary succession is medium to stiff red brown clay containing scattered ice rafted pebbles and cobbles. Silty, sandy/gravelly layers, some of which contain small amounts of water are encountered in the clays, most commonly at depths of about 20 to 50 feet below the general level of the plain. At higher elevations i.e., about 900-1000 feet the clays are gradational with sandy materials representing shore reworking of the underlying drift and materials introduced by small tributary streams. Locally the sandy materials extend to lower elevations-lying on top of the clay sequence.

Along the St. Louis River the clays are largely replaced in the stratigraphic succession by brown, poorly permeable dense argillaceous silty to sandy deposits which become coarser and cleaner and may contain gravels toward the top of the sequence. These deposits, which reach a maximum thickness of about 200 feet lie on a stiff red clay unit, which in turn rests on glacial drift deposited in the north shore depression. Deep engineering bore control is not adequate to define lateral relationships with the middle part of the clay sequence. It presently appears that there is little or no interbedding of sand and clay either in West Duluth or in Superior, suggesting the possibility of introduction of the sandy materials by ice or in part by turbidity flow or river deposition along the general trend of the north shore depression.

The coarseness of the upper part of the sandy sequence, its considerable degrees of sorting, and prominent cross bedding indicate the existence of high energy conditions at the Lakehead prior to deposition of the 15 to 50 foot thick red clay which overlies the sandy unit, forming the surface of the Superior plain. The uppermost clay layer lies on an undulating surface having up to a few tens of feet of relief. Contours on the base of the clay define the north shore depression and indicate slopes toward the depression and toward Lake Superior. The clay dips beneath present water level in Howards Bay and is known beneath the younger sands and gravels of Connors Point and the outer end of Rice's Point. Both of these points are built along

the erosional zero edge of the clay as it subcrops under St. Louis Bay, suggesting that this fact may have influenced their construction. The same red clay subcrops beneath the outer end of Minnesota Point and under Wisconsin Point. This uppermost clay rests on a thin sandy or gravelly unit which overlies the main clay sequence in West Duluth and Morgan Park and conditions are similar in Superior. Prominent development of clays to elevations of about 700 feet on the Duluth hillside may indicate flooding of the plain to this level during development of the clay layer.

A later very low water stage, perhaps Ferrand's (1969) Houghton Stage, allowed deep incision of drainage along the north shore depression, exposing the sandy sequence and initiating the present drainage system. A general rise in lake level toward a maximum of about 610 feet during the Nipissing Stage caused the deeper parts of the drainage to become aggraded with sandy materials and subjected the upper red clays to strong wave attack. The rise of the uppermost clay away from the north shore depression made it particularly subject to wave erosion, causing steep bluffs from the central part of the Superior Bay waterfront eastward to the present shore line of the lake. A prominent clay platform was developed offshore from the bluffs. This platform is the floor on which Minnesota and Wisconsin Point are built. It is presently blanketed by twenty to at least 70 feet of clean fine to coarse sand containing small amounts of gravel. A greater thickness of such sandy deposits may lie below present control depth under the central part of Rice's Point and the northerly third of Minnesota Point. A great number of large crystalline rock boulders occur at or near the base of these young sandy deposits under Superior Bay. Maximum boulder size recorded so far is 5 x 6 x 7 feet for one recovered during construction of the Cloquet water line. Large boulders are known throughout the length of the Superior Front Channel and the open lake shore to the southeast, their number, size and wide distribution, together with the existence of a higher lake level more or less following their deposition may suggest a late pulse of ice development. An alternative view is that they are developed by exposure of the top of the sandy unit beneath the upper red clay. This unit is known to contain boulders locally, as in the vicinity of the local bedrock high at the foot of 27th Avenue West in Duluth. However, the fact that boulders lying on a few feet of sand overlie the top of the young red clay under Connors Point suggest that ice transport may be involved. It is quite possible that some of the sand present on south shore beaches comes from exposure of the underlying sands. Much of the modern south shore sand is derived from reworking of the underlying till which is exposed along several drainages as the bedrock surface rises to the east of the Twin Ports. A period of declining lake levels during which water levels dropped from about 610 to perhaps 590 feet, witnessed the sequential development of the lake-head barriers of Grassy Point, Rice's-Connors Points, and Minnesota-Wisconsin Points (cf. Loy, 1963). All are built primarily from materials derived by the erosion of the sandy sequence of the north shore depression by the St. Louis River and by lake activity during the high waters of the Nipissing stage. The eventual decline in water level during the subsequent Algoma stage was low enough

to permit development of spruce woods rooted in the sands of what is now Allouez Bay.

Later flooding, which is apparently continuing at present (cf. Moore, 1948), has led to development of organic-rich mucks, locally capped by peats as the main sediments above the most recent harbor sands. The upper parts of the organic deposits often contain sawdust, wood fragments and horse manure, a legacy of late 19th century activities in the harbor. Slag, wood derivatives, etc. of more recent origin are also present. Dredging for harbor development and slip construction have largely altered the natural stratigraphic sequence of the young sands and organic materials but the natural bottom contours, sediment types, and shore features can still be studied on the excellent 1861 chart directed by Captain G. C. Meade for the Army Corps of Engineers.

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PETROLOGIC AND STRUCTURAL ASPECTS OF THE GABBRO SILL ON  
PIGEON POINT, MINNESOTA

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Detailed mapping on Pigeon Point, Cook county, Minnesota, discloses petrologic and structural complexities heretofore not reported. The sill on Pigeon Point ranges in composition from a tholeiitic olivine gabbro to ilmenite gabbro, to quartz gabbro, and to potassium feldspar-bearing gabbro. The red granitoid rock above the sill is intrusive in the upper parts of the gabbro, but the origin of these red rocks by differentiation of the gabbro or fusion of the Rove sedimentary rocks is not clear.

Analyses of coexisting phases in the gabbro indicate iron-enrichment during the differentiation history of the sill. Analysis of phases also sets limits on petrogenetic relations to the Logan Intrusive Rocks, and to the Pigeon River Intrusions of Geul. The Pigeon River Intrusions appear to have a simple direct relation; however the Logan Intrusive Rocks of Geul cannot be directly related by simple fractional crystallization to the sill on Pigeon Point.

Since emplacement and cooling of the sill, faulting and fracturing on northwest and east-west trends has occurred. The northwest faulting is marked by barite-calcite veins, and the east-west direction by late olivine diabase dikes.

Lower Precambrian metavolcanic-metasedimentary  
sequence, Rainy River, northernmost Minnesota

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A B S T R A C T

A thick metavolcanic-metasedimentary sequence is exposed in northernmost Minnesota, south of the Rainy River and about midway between International Falls and Baudette. The previously undescribed volcanic rocks range in composition from basalt to rhyodacite. Intermediate-felsic tuffs and agglomerates and dacitic flows and hypabyssal intrusions apparently are the dominant rock types.

These rocks are intermittently exposed along the edges of two younger 200-400 ft wide diorite-gabbro dikes that trend nearly perpendicular to the northeastern regional strike of the steeply dipping country rocks. Stratigraphic top determinations are limited to a few pillowed metabasalts. However, the scanty data indicate that the sequence may be as much as 25,000 feet thick.

Massive sulfides are present in prospect pits and in drill holes in the western part of the area.

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THE EASTERN TERMINUS OF  
THE LAKE SUPERIOR SYNCLINE

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ABSTRACT

A regional gravity investigation of the eastern portion of the Northern Peninsula of Michigan was conducted and combined with previously observed gravity stations in the Southern Peninsula of Michigan, Beaver Island, northern Lake Huron, northern Lake Michigan and the Sault Ste. Marie area of Canada to investigate the eastern terminus of the Lake Superior syncline.

The Bouguer gravity anomaly map of the eastern portion of the Northern Peninsula shows three major positive gravity anomalies. One of these anomalies trends southeast from Grand Island in Lake Superior and can be traced northwesterly magnetically to the Middle Keweenaw volcanics of the Keweenaw Peninsula. This anomaly represents the margin of the western limb of the Lake Superior syncline. Another positive anomaly trends south from Whitefish Point on the south shore of Lake Superior and is interpreted as a horst of basalts which can be traced magnetically to the Middle Keweenaw volcanics outcropping on Mamainse Point, Ontario. The eastern limb of the syncline near the eastern edge of the Northern Peninsula is also defined by a positive gravity anomaly. These three positive gravity anomalies which are associated with positive magnetic anomalies merge in the vicinity of Beaver Island in Lake Michigan and mark the termination of the Lake Superior syncline. South of Beaver Island, the Keweenaw basalts continue in a south-trending narrow belt and are expressed by the "Mid-Michigan gravity high". The Bouguer anomaly map indicates two local gravity minimums in the Whitefish Bay area on the south shore of Lake Superior. These are interpreted to result from a thick accumulation of Upper Keweenaw clastic sediments.

The results of two dimensional model studies suggest that the Lake Superior syncline in the eastern portion of the Northern Peninsula consists of up to 12,000 feet of basaltic flows overlain by Upper Keweenaw clastic rocks. Two geological models can be fitted to the observed anomalies of the northern tip of the Southern Peninsula of Michigan. The basalts either extend throughout the northern tip of the Southern Peninsula where they are highly faulted into a series of horsts and grabens or they are confined to the Grand Traverse Bay area in which case pre-Keweenaw extrusives and intrusives make up the basement of the northern tip of the Southern Peninsula.

# MAGNETIC REVERSALS AND POLAR SHIFTS AS MARKERS IN A PROTEROZOIC TIME SCALE

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## A B S T R A C T

The construction of a useful Precambrian time-scale presents great difficulties. Fossils are scarce. Sedimentary basins are widely separated, and deposition rates may have been different from today. Small errors in radiogenic age determinations represent many millions of years. Geologists should consider the help that is becoming available from paleomagnetic sources when attempting to divide Precambrian time into useful time units.

Difficulties using paleomagnetic methods of dating so far back in time are no greater than those of other methods, and have one unique advantage. The pattern of reversals of the earth's magnetic field is world-wide; it is not diachronous, and any identifiable marker horizon occurs at the same point in time wherever it is found. This is not true of polar-wandering curves, however, which apply only to their own continent.

The figure shows a hypothetical reversal pattern for the earth's magnetic field, with time as abacissa. Above and below it are hypothetical movement rates, on the same time scale, of two continents, EG and AS.

It is hypothetical for the Proterozoic due to lack of data, but is based on patterns emerging from Phanerozoic time. M intervals are ones of mixed polarity, whereas N and R. are of wholly normal and reversed polarity respectively. Reversal nodes marked X, between wholly normal and wholly reversed polarity intervals provide unambiguous, universal marker horizons. G nodes, where one double polarity inversion took place, give good marker horizons but may be hard to find in rock sequences. The F nodes also yield marker horizons, but may be harder to identify precisely.

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At the first and third polarity node the continents are shown as accelerating sympathetically at the time of change of reversal frequency. Further back in time they are shown as independent of each other, and more independent of the polarity rhythm. Whether there are links between motions at the earth's surface and reactions at the core-mantle boundary is still an unsolved problem. In any case, the location of a pole position on the polar wandering curve of the same continent will be a measure of its age. The accuracy will be highest for rocks formed at times of rapid polar movement: conversely if a continent is static relative to the pole for a long interval, pole positions will not differentiate ages of rocks formed in that interval.

Working out the polarity scheme for a Precambrian period is a very big task. Unconformities will leave gaps that have to be filled in from elsewhere. Nevertheless a pattern is beginning to emerge in the Hadrynian and Helikian (880-1640 m. y.) of the Canadian Shield, although large gaps remain to be filled. An older normal interval (1400 m.y.) appears to be followed by a mixed interval. Then a second normal interval is succeeded by a reversed interval about 1100 m.y. ago (a potential X node). A possibly longer normal interval then appears to be followed by one of mixed polarity.

It is still too early to use paleomagnetic nodes as boundaries to help form a Proterozoic time-scale, but new polar wandering and reversal pattern data are accumulating fast, and we would be wise to consider the possibility of using them to help to split the Precambrian into time stratigraphic units of wide application.

20-  
15-  
10-  
5-  
0-  
Continent  
EG

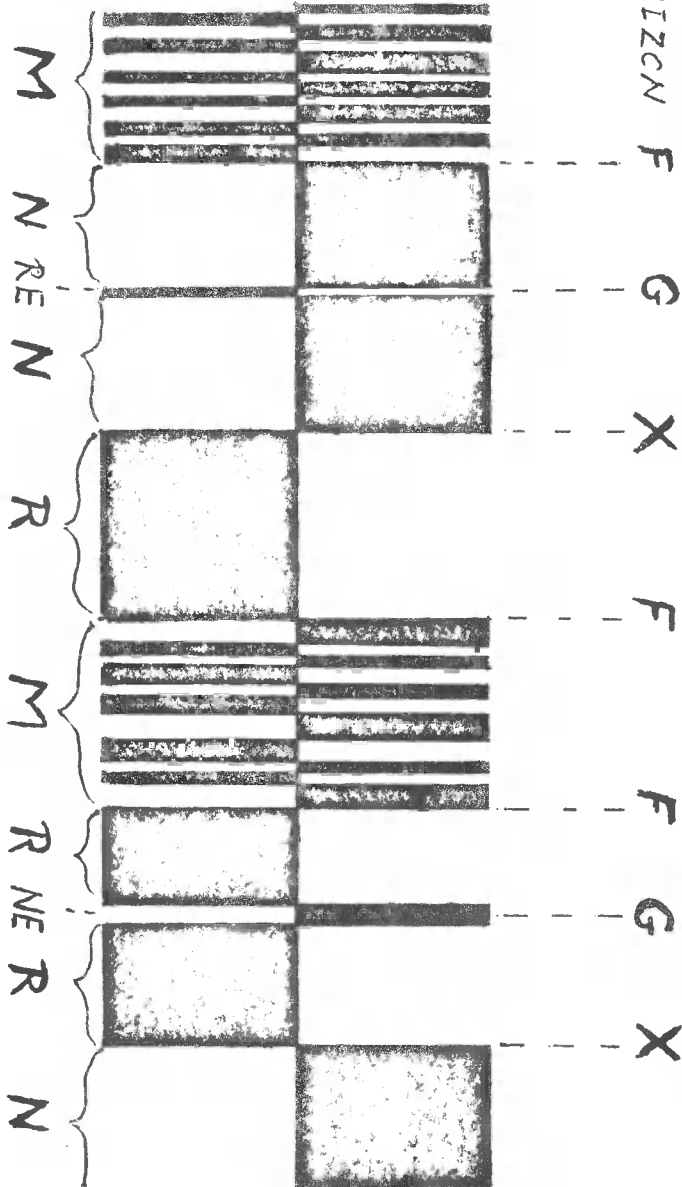


PALEOMAGNETIC  
MARKER HORIZON

NORMAL

REVERSED

WORLD-WIDE  
POLARITY



TIME

0-  
5-  
10-  
15-  
20-  
Continent  
AS



20-  
15-  
10-  
5-  
0-  
c. Continent  
EG



PALEOMAGNETIC

MARKER HORIZON F

G

X

F

F

G

X

NORMAL

WORLD-WIDE  
POLARITY

REVERSE

M

N

RE

N

R

M

R

NE

R

N

TIME

c. Continent  
AS



5-  
10-  
15-  
20-  
c. Continent

-2-

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ARCHAEAN SALIC VOLCANIC ROCKS AT KAKAGI LAKE, NW  
ONTARIO - THEIR PHYSICAL AND CHEMICAL NATUREby D.R. Smith<sup>1</sup>, R. H. McNutt<sup>2</sup>, P. M. Clifford<sup>2</sup>

## A B S T R A C T

At Kakagi Lake, and Archaean (older than ca. 2500 my) supracrustal assemblage has, for its upper portion, salic volcanic rocks, approximately two thousand metres thick. These rocks are somewhat unusual, being almost devoid of outcrop-scale layering in rhyodacitic and andesitic scoriaceous breccias and having limited or crude layering in crystal tuffs. Within the fragmental rocks, there is only poor sorting of size fractions. Moreover, in any given outcrop, the accessory fragments which make up the bulk of the framework are monolithologic.

Analysis of variation of maximum fragment size, and framework - matrix ratios reveal a "cryptic" macroscopic layering, not visible in individual outcrops. In addition, there are two, possibly three, areas having both large values of maximum fragment size, and a high framework - matrix ratio. These areas are interpreted as projections of emission centres into the present day outcrop plane.

Chemical analyses of 23 pairs of fragments and adjacent matrix show that, in general, the fragments are the richer in  $\text{SiO}_2$  and perhaps  $\text{Na}_2\text{O}$ , with matrix the richer in total Fe and  $\text{MgO}$ . Discriminant function analysis of our data, using the four oxides mentioned, properly identifies fragments from the matrix in 80% of the samples. These pyroclastic rocks have rather strong calc-alkaline affinities, and tend to be normal or low in  $\text{K}_2\text{O}$ . Normatively, matrix is: 33% basaltic, 48% andesitic, 19% dacitic; fragments are: 29% basaltic, 29% andesitic, 42% dacitic. These chemical differences are echoed in thin sections. Fragments commonly have polycrystalline quartz aggregates and feldspar phenocryst in a felsic background: matrix is markedly chloritic. Alteration is ubiquitous.

There are no discernible chemical trends along "strike" or upwards through the volcanic pile. This reinforces the evidence from physical properties-considerable thickness, lack of layering, poor sorting, monolithologic fragment

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character locally - which indicate a pyroclastic flow origin for these rocks. Presence of a fabric possibly pseudomorphic after shard structure is further support for this interpretation.

Three-phase deformation associated with the Penokean  
orogeny, east Gogebic Range, Michigan—/

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Abstract

Three phases of deformation in the east Gogebic area resulted in tight folding of Precambrian X (Marquette Range Supergroup) strata followed by folding and block tilting of the Precambrian Y (lower Keweenawan) and Precambrian X (Animikie) sections during the last phase of orogeny. The deformational periods are marked by coeval volcanism and by three angular unconformities. Although the deformations may be widely spaced in time, lithology and structural morphology suggest that they are separate phases of a single orogenic episode.

Near the east end of the Gogebic Range, Precambrian X (Marquette Range Supergroup) strata lie between tilted metamorphosed Precambrian Y volcanic rocks (lower Keweenawan) to the north and strongly metamorphosed Precambrian W or X gneiss complex, Algoman Granite of Lawson (1914), and volcanic rocks (Keewatin) to the south. Three deformational phases can be identified in Precambrian X rocks of the eastern Gogebic Range:

—/Work done in cooperation with the Geological Survey Division of the Michigan Department of Natural Resources.

- 1) The earliest was folding of the Sunday Lake Quartzite, Bad River Dolomite, Palms Formation, and Ironwood Iron-Formation. Mafic lava flows intercalated with the Ironwood Iron-Formation indicate that extrusive volcanic activity preceded folding. The large Wolf Mountain anticline began to form, followed by erosion and unconformable deposition of the Copps Group of Allen and Barrett (1915) and the Tyler Formation.
- 2) The strongest deformational phase, the Penokean orogeny, as defined by Goldich and others (1961, p. 120-122, 156-160), took place at the end of Precambrian X ("Animikie") time. The Wolf Mountain anticline was more tightly folded during this event. Mafic sills, also intercalated with the Ironwood Iron-Formation were intruded syntectonically. The northernmost thick sill truncated by the pre-Keweenawan unconformity (Prinz, 1967), appears to be genetically related to flow breccia cropping out along its eastern margin. Erosion of these volcanic rocks, parts of the Tyler and Copps, and older rocks preceded the unconformable deposition of the oldest Keweenawan strata.
- 3) Post-lower Keweenawan deformation, upon which Blackwelder (1914, p. 638) based his original definition of the Penokean orogeny, warped and tilted the whole Precambrian succession except for the Jacobsville Sandstone. The last phase of folding seems to mimic major trends of the preceding Penokean folding, especially in the area close to Lake Gogebic. Torsional basement movements related to block tilting probably contributed to the asymmetry of the Wolf Mountain anticline.

A large flat-lying mass of ellipsoidal basalt north of Wolf Mountain (T. 47 N., R. 44 W.) may be the youngest volcanic rock in the area. It lies athwart the Precambrian X (Animikie) structural trend and has not been blocktilted. The youngest major fracture in the area passes nearby, and to the southwest the fracture is filled by a thick mafic dike which I interpret to be the feeder. Two miles to the northeast, this fracture truncates the lower Keweenawan ridge. This field evidence suggests that these ellipsoidal lavas were extruded in post-early Keweenawan time and were perhaps associated with the terminal phase of folding.

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BEDROCK MORPHOLOGY IN THE VICINITY OF  
PORTAGE LAKE, KEWEENAW PENINSULA, MICHIGAN

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ABSTRACT

Portage Lake stretches across the Keweenaw Peninsula of Michigan between Keweenaw Bay and Lake Superior. This circumstance was put to good use by the Indians and later by French voyageurs and Jesuits who used the long sinuous lake as a shortcut in their travels along the south shore of Lake Superior. Modern shipping uses the same shortcut, now known as the Keweenaw Waterway.

Portage Lake has a maximum depth of about 50 feet located in the main body of the lake. On the other hand, Torch Lake, which is connected to Portage Lake by Torch Bay and a dredged ship channel, was once 170 feet deep before it was partially filled by mill tailings from various copper recovery operations.

Several geologists have speculated about the origin of these unusual lakes (Martin, 1911; Scott, 1921; Hughes, 1963). However, they were handicapped by their lack of knowledge of the bedrock morphology around and under the lakes.

The bedrock morphology was determined from water well and diamond drill logs and by geophysical methods. Seismic refraction profiles were run on land and on the mill tailings in Torch Lake. On the lakes, sparker and air-gun surveys were performed. Unfortunately the sparker survey lacked penetration and the air-gun profiles were rendered nearly useless by excessive reverberation. Gravity profiles were then run over Portage Lake, on ice, in an attempt to extrapolate the land based information. Interpretation of the gravity surveys, now being performed, is hampered by the large regional gravity gradient due to the Keweenaw fault (Bacon, 1966).

Preliminary results indicate that both Portage and Torch Lakes lie in a complicated network of buried bedrock valleys. A water well next to the narrow northwest arm of Portage Lake reaches a depth about 380 feet below lake level and a diamond drill hole east of Hancock Michigan reaches bedrock about 280 feet below lake level. Of course, there is no assurance that either of those wells have reached the deepest part of the bedrock valley.

Torch Lake lies in a bedrock valley with a floor 250 feet below present lake level. This valley underlies the present Traprock River valley to the north and continues south of Torch Lake into Portage Lake under Torch Bay. The bedrock valley under Torch Lake is also connected to Portage Lake by a bedrock valley 200 feet below lake level which parallels the Keweenaw fault and passes under the town of Dollar Bay.

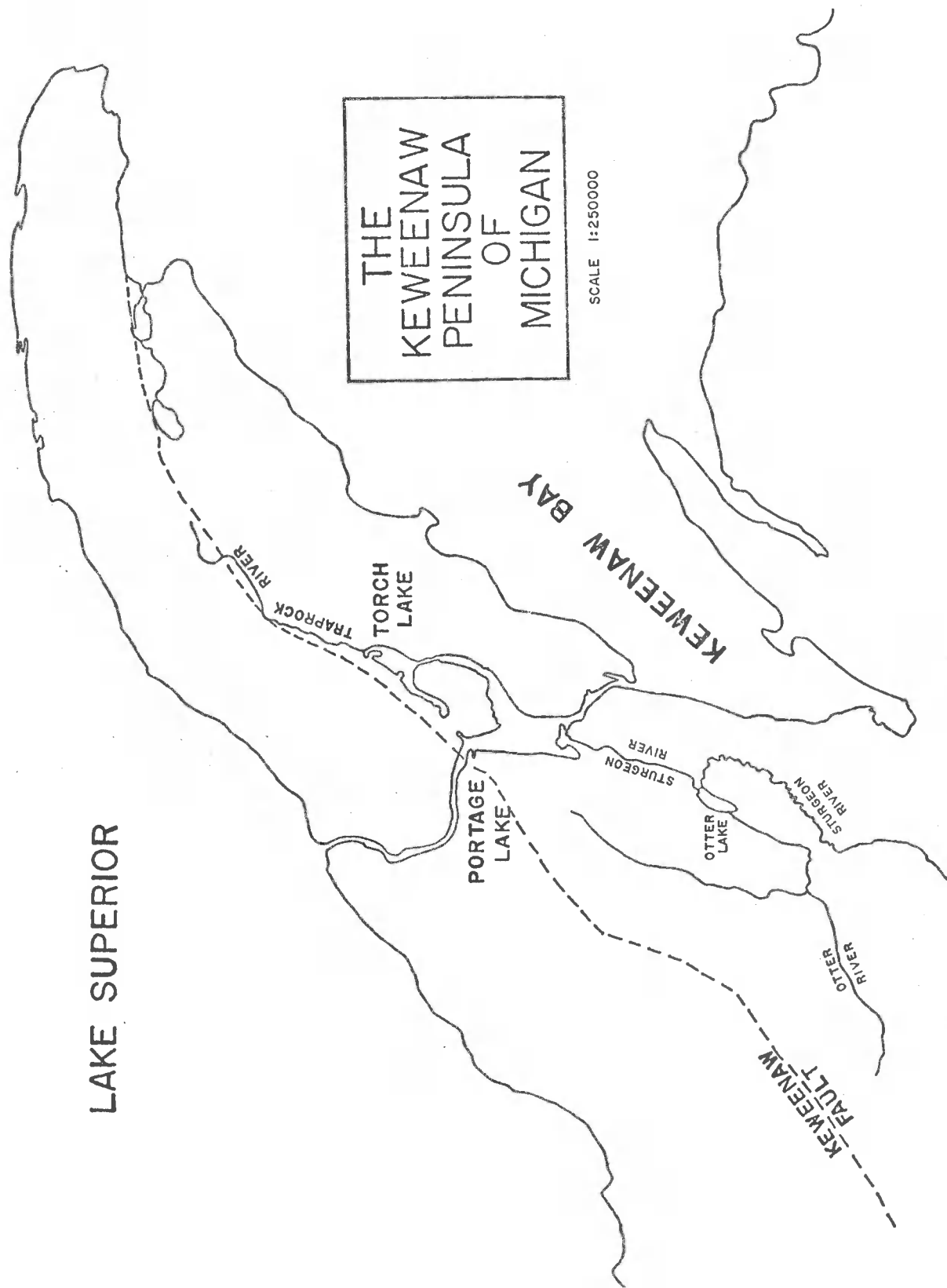
A bedrock valley about 150 feet below lake level extends from the southeast part of the main body of Portage Lake out through Portage Entry, curving to the east of the present channel.

The deepest bedrock valley, however, extends south of the main body of Portage Lake under the present Sturgeon River valley where a depth 450 feet below present Lake Superior level was found. The southern extension of this deep valley still remains to be explored. It is interesting that this valley has bedrock depths on the same order as the depth of Keweenaw Bay. A bedrock valley 200 feet below lake level branches off the west side of the Sturgeon valley and passes under Otter Lake.

It is probable that these buried bedrock valleys were originally a product of stream erosion. It is possible that some glacial overdeepening has taken place also, but this cannot be determined until all the data is compiled and a contour map of bedrock elevations is completed. At any rate, it is apparent that the base level for stream erosion was once considerably lower than the present Lake Superior level. This discovery may have some bearing on the controversy about whether Lake Superior is mainly a result of subaerial erosion, of glacial scour, or of some combination of the two.

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GLACIAL DRIFT ON THE MESABI IRON RANGE, MINNESOTA  
ITS CHARACTERISTICS, ORIGIN, AND HYDROLOGIC SIGNIFICANCE<sup>1/</sup>

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A B S T R A C T

Glacial deposits in the Mesabi Iron Range area consist of three major till units and associated glaciofluvial sediments. The basal till occurs in only a small number of mines, but they are scattered across the entire Iron Range. The till is dark gray to dark greenish gray and brownish gray, sandy, silty, and is calcareous. The middle till unit, a bouldery till, is the thickest and most widespread of the three tills. It is grey, yellow, red, orange or brown, sandy, silty, contains abundant cobbles and boulders, and is non-calcareous. The till was deposited by the Rainy lobe, which has a minimum age of 14,000 to 16,000 years before present. The surficial till was deposited contemporaneously by two minor sublobes of the same ice lobe about 12,000 years ago. The brown silty till occurs in the western and north-central part of the area. It is light to medium brown, sandy, silty, and calcareous. Red clayey till in the south-central part of the area is red to reddish brown, clayey, silty, and calcareous.

Stratified fluvial sediments occur within the glacial drift at many places in the Mesabi Iron Range area. These sediments, which are important aquifers, occur extensively between the three main till units. The thickest and most extensive aquifer consists of glaciofluvial sediments that lie between the surficial till and the bouldery till. The thickness of the glaciofluvial sediments is greater than 50 feet in much of the area, and the transmissivity is greater than 100,000 gallons per day per foot at a number of localities. Glaciofluvial sediments underlying the bouldery till occur largely in the western half of the area. These sediments are generally less than 50 feet thick and their transmissivity is generally less than 50,000 gallons per day per foot. Surficial glaciofluvial sediments are a source of ground water for high yield wells only in the eastern part of the area in the general vicinity of the Biwabik bedrock valley. Thickness of these sediments is greater than 100 feet in some places, but their transmissivity is generally less than 50,000 gallons per day per foot.

-2-

The glacial drift aquifers can yield as much as 40 mgd (million gallons per day). Assuming that the ratio of area underlain by aquifer to total area is constant for the study area (about 20 percent where mapped in detail), it is concluded that as much as 80 million gallons per day could be developed from glacial drift aquifers without causing excessive water declines and depleting streamflow.

1/ Publication authorized by the Director, U.S. Geological Survey

CHRONOLOGY OF PRECAMBRIAN ROCKS OF  
IRON AND DICKINSON COUNTIES, MICHIGAN  
PART II

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Extensive K-Ar, Rb-Sr, and U-Pb data available for the Precambrian rocks of Iron and Dickinson Counties, Michigan, permit considerable clarification of the chronologic development of this area. The following ages are considered well established (rounded to nearest 25 m.y.): Peavy complex 1900 m.y., Hemlock volcanics 1950 m.y., and Porphyritic Red Granite 2100 m.y. A U-Pb concordia intercept age of 2375 m.y. for the Norway Lake gneiss is considered minimal for this unit because of probable multiple secondary events. The pre-Animikie post-Dickinson Granite Bluffs gneiss gives an apparent Rb-Sr whole rock age of ca. 2700 m.y. whereas its apparent zircon U-Pb concordia intercept age is ca. 2100 m.y. This anomaly can be explained either by unusual migration of radiogenic Sr or by multi-stage Pb loss. Additional mineral analyses are in progress to resolve the issue. Our previous conclusion (Banks and Van Schmus, ILSG 1971) remains unchanged that the Animikie Series of James et al. is bracketed between 1900 and 2100 m.y. and therefore is not correlatable with the original Huronian of Ontario. Resolving the age of the Granite Bluffs gneiss will determine whether the Dickinson Group is or is not a candidate for correlation with the original Huronian.

Additional data of interest include a Pb/Pb age of 2900 m.y. for detrital zircon from the East Branch arkose, and a suggestion from K-Ar hornblende and U-Pb apatite and sphene data that the last major metamorphism in the area occurred 1500-1600 m.y. ago.

## PENOKEAN TECTONICS IN NORTHERN MICHIGAN

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## A B S T R A C T

The major Penokean deformation in northern Michigan <sup>1/</sup> occurred between 1.9 and 2.0 b.y. ago. Lower and middle Precambrian rocks were deformed independently of, and mostly before, regional metamorphism; the deformation took place at low temperatures. The subsequent metamorphism was a low-pressure type in which andalusite was stable over a wide temperature range. The maximum confining pressure is set by the aluminosilicate triple point at about 5 kilobars (about 13 miles burial depth), but the true pressure may have been much less.

Structural interpretations must be consonant with mechanisms of rock deformation possible at low temperatures and low to moderate confining pressures. Lower Precambrian granitic rocks form the basement for the Marquette Range Supergroup in much of northern Michigan. Experimental rock deformation indicates that granitic rocks have very high strength and very low ductility under probable conditions of Penokean deformation, and kinematic interpretations of Penokean deformation must consider the probability of a strong nonductile basement; interpretations requiring a weak ductile basement are difficult to reconcile with the probable physical environment of deformation.

The first-order regional structures in northern Michigan are uplifts of lower Precambrian rocks with middle Precambrian rocks of the Marquette Range Supergroup in intervening synclinal basins. A wide divergence of trends for these structures suggests vertical tectonism rather than regional horizontal compression. The lower Precambrian cores of many uplifts are cut by diabase dikes. These dikes are older than the Penokean orogeny, and many are probably associated with mafic intrusive and extrusive rocks in the middle Precambrian section, yet these dikes were not externally deformed during Penokean folding; they remain planar and largely massive. These relationships substantiate inferences from experimental rock deformation of a strong nonductile basement and strongly suggest that the lower Precambrian rocks remained rigid and were not penetratively deformed during Penokean deformation. The uplifts are interpreted as fault-bounded blocks of lower Precambrian rocks which were uplifted

<sup>1/</sup>  
The Gogebic Range is excluded from this discussion because of complications introduced by younger deformation.

along steep faults, many of which are steep reverse faults. The blocks may have moved either as single units or, more likely, with internal adjustments occurring along relatively narrow shear zones and parallel to dike margins. During this phase of deformation, middle Precambrian rocks were passively draped over the fault blocks, forming the presently preserved synclinal structures which occupy the relatively downfaulted segments of the basement.

Second-order and smaller folds in middle Precambrian rocks indicate that these rocks have undergone substantial horizontal shortening, whereas the underlying lower Precambrian rocks have not. Furthermore, the trends of second-order and smaller folds are mostly in west and west-northwest directions and are much more uniform than trends of first-order structures (block uplifts). In some areas, second-order folds cross the trends of first-order structures at high angles. Many of these smaller folds seem to have formed independently of first-order structures, and their geometry requires a thin-skinned compressive deformation which has affected only the middle Precambrian rocks and not the lower Precambrian basement. Many of these folds may be due to gravity sliding or spreading which, because of relatively uniform fold trends, appears to have occurred in response to a region-wide gradient. This phase of deformation must have occurred before block faulting produced substantial structural relief on the contact of lower and middle Precambrian rocks.

The suggested sequence of events is:

- 1) Regional gravity sliding which produced folds in middle Precambrian rocks with west and west-northwest trends but did not deform the lower Precambrian basement rocks. This event was probably associated with early uplift of the depositional basin.

- 2) Uplift of fault-bounded basement blocks with widely divergent trends, accompanied by passive draping of middle Precambrian rocks and earlier gravity folds into basins or tight synclines between the uplifts. A second set of folds formed in middle Precambrian rocks in areas marginal to the uplifts.

## THE PENOKEAN OROGENY

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## ABSTRACT

The Penokean orogeny (Blackwelder, 1914) was redefined by Goldich and others (1961) as Middle to Late Precambrian event that involved the Animikie Group of Minnesota and Ontario and similar rocks that were formerly assigned to the Huronian in Wisconsin and Michigan. Time limits from 1600 to 1800 m.y. were set for the orogeny; however, Peterman (1966) showed that the metasedimentary rocks of the Cuyuna district were folded 1850 m.y. ago. New data for the Thomson Formation of east-central Minnesota give a minimum age of the folding and metamorphism of 1900 m.y. ago (Stuckless and Goldich, 1972). Thus, the Penokean orogeny is a Middle Precambrian event, using 1800 m.y. as the time boundary between the Middle and Late Precambrian (Goldich, 1968).

Limiting ages have been placed on the type Huronian rocks by dating of the Nipissing Diabase in the Blind River-Bruce Mine area (Van Schmus, 1965) and of the Nipissing Diabase and Gowganda Formation at Gowganda (Fairbairn and others, 1969). The type Huronian rocks are at least as old as 2280 m.y. (Gowganda Formation), and were folded at least 2160 m.y. ago (Nipissing Diabase).

Fryer (1971) has reported ages of 1800, 1870, and 1790 m.y. for volcanic and metasedimentary rocks from the Belcher Fold Belt, the Labrador Trough, and the Mistassini Lake area. Rb-Sr ages, however, must be used with caution. They do not necessarily date the time of deposition or of a specific metamorphic event. In Minnesota, for example, isochron ages on Animikian rocks range from 1900 to 1660 m.y., but all were probably deposited at essentially the same time.

Considerable radiometric dating of Middle Precambrian rocks is now in progress. Until the new data from a number of laboratories are published and can be assessed, it is premature to correlate the rocks of widely separated areas of North America.

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# RELATION OF PENOKEAN POLYPHASE DEFORMATION TO REGIONAL METAMORPHISM IN THE WESTERN MARQUETTE RANGE, NORTHERN MICHIGAN

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## ABSTRACT

Recent work at Lake Michigamme at the western end of the Marquette Trough suggests that some metamorphic minerals began to form during the early stages of Penocean deformation contrary to previous studies (Powell 1970) that suggest that regional metamorphism almost completely postdates deformation. The new studies indicate that metamorphism peaked late in the deformational sequence as shown on figure 1.

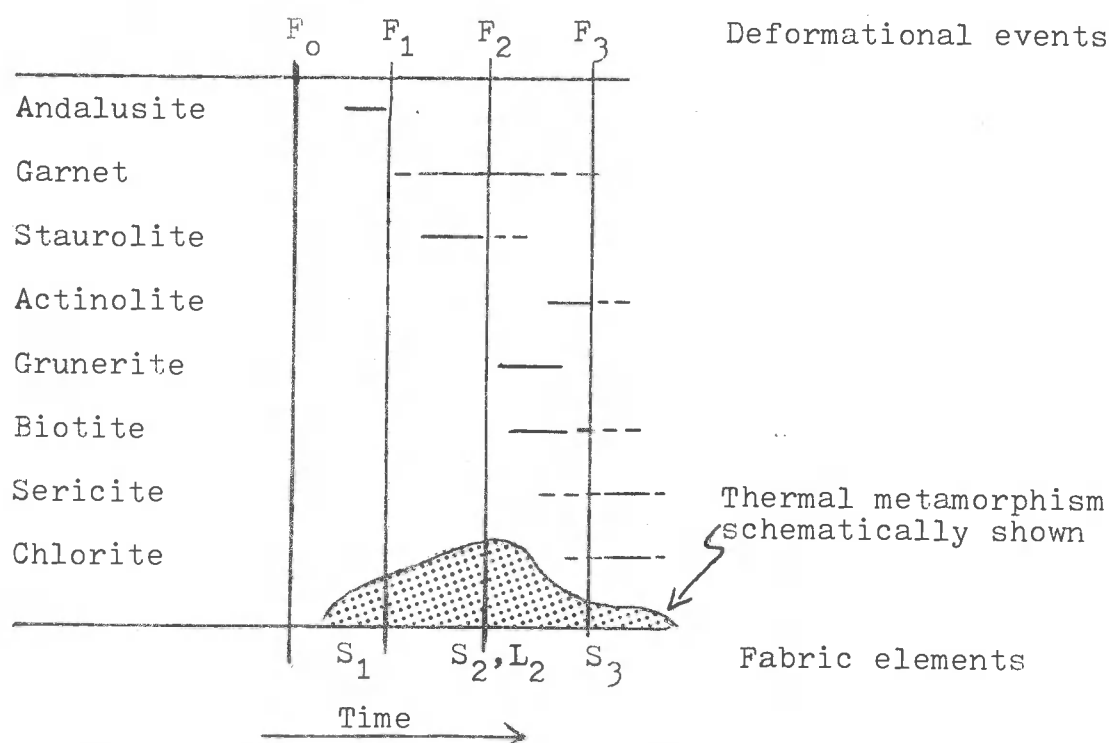


Figure 1, Kinematic relationship of metamorphism to deformation.

The deformational sequence, characterized by four phases, started with regional soft sediment deformation (F<sub>0</sub>) that produced a penetrative N 75° W trending foliation, the early stages of which can be identified as slaty cleavage (S<sub>1</sub>). Selective migration of silica (Williams 1972) during continued deformation (F<sub>1</sub>) along the early formed slaty cleavage enhanced this cleavage and formed the numerous quartz veins. The F<sub>0</sub>-F<sub>1</sub> deformational couplet produced the regional S<sub>1</sub> foliation.

Crenulation folding ( $F_2$ ) of  $S_1$  foliation resulted in the formation of  $S_2$  fracture cleavage and formation of lineations ( $L_2$ ) due to the intersection of  $S_1$  and  $S_2$ . The  $L_2$  lineations are flat lying because the strike of  $S_2$  and  $S_1$  are nearly parallel. Kink-banding ( $S_3$ ) that affects  $S_0$ ,  $S_1$ ,  $S_2$  and  $L_2$  characterizes the last deformational event in the area.

Regional thermal metamorphism accompanied the sequence of deformation. The growth of pre- $F_1$  andalusite porphyroblasts (figure 1) indicates that metamorphism started early in the deformational sequence. It probably peaked between  $F_2$  and  $F_3$  deformation as indicated by the growth of post- $F_1$ , pre- $F_2$  staurolite porphyroblasts and post- $F_2$  brown biotite and grunerite. Abundant retrograde metamorphism is shown by andalusite and staurolite porphyroblasts that have been replaced by sericite, and by garnet porphyroblasts that have been replaced by chlorite.

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LINEAMENTS AND MYLONITE ZONES IN THE  
PRECAMBRIAN OF NORTHERN WISCONSIN

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## A B S T R A C T

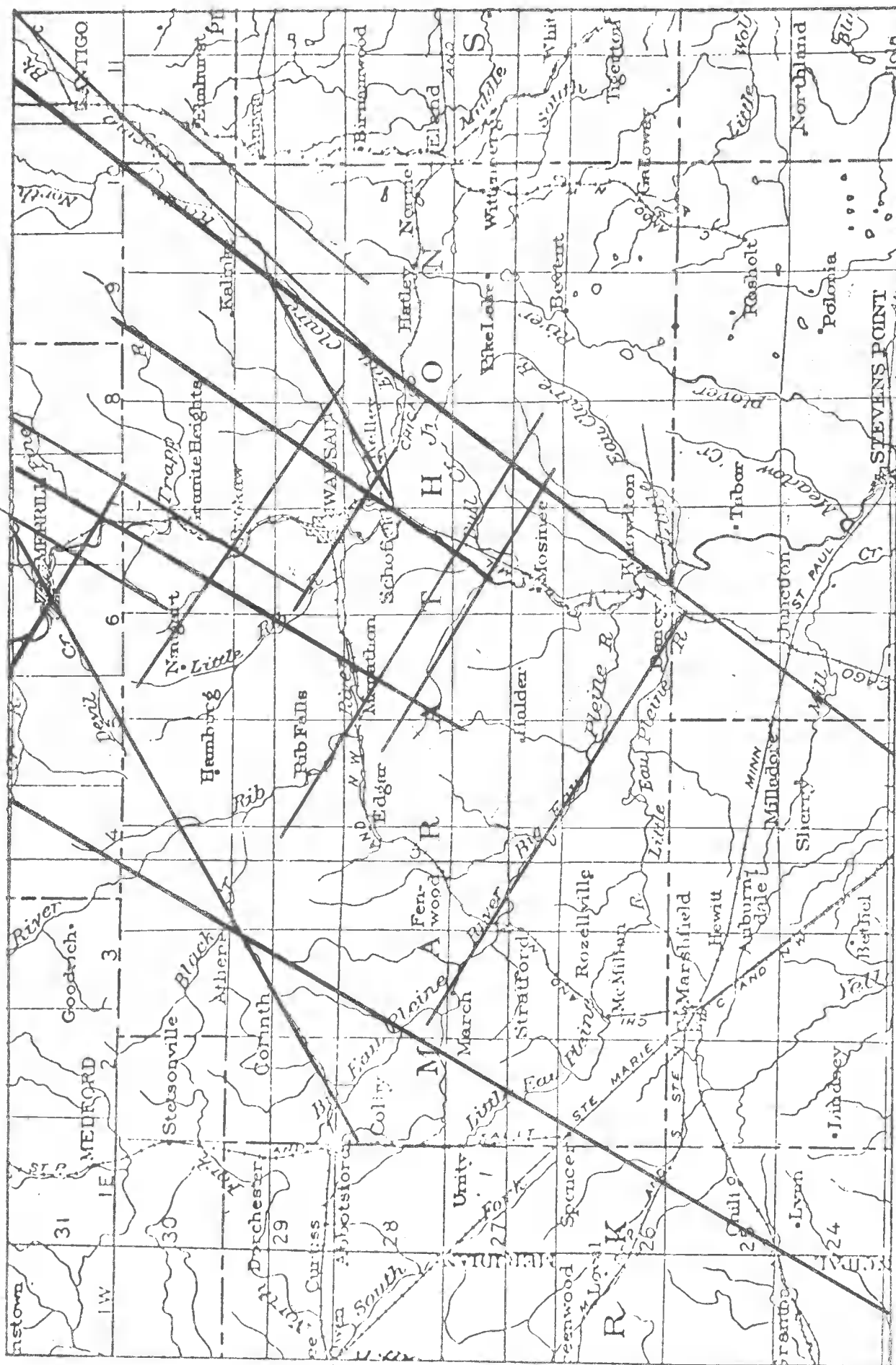
Recent geological mapping in Marathon County by the Wisconsin Geological and Natural History Survey has shown that a number of major zones of shearing cross central Wisconsin. At least 3 directions of major shearing have been recognized: N30°-35°E, N60°E, and N80°E. The N30°-35°E trend is best developed in the area mapped, but reconnaissance indicates that other directions are important in other parts of the county.

The major shear zones are represented by zones of mylonite and variously sheared rocks up to a mile wide. Because a number of different rock types, ranging in composition from granite to greenstone, have been granulated, mixed, and recrystallized to varying degrees to form the mylonite, the zones are lithologically variable both along and across the strike. However, they are structurally rather uniform, displaying a lensoidal structure on all scales from map scale to thin section. Indeed they seem to be composed of a myriad of overlapping lenses which show different degrees of flattening. Excellent examples of the progressive shearing of a granitic rock to produce a mylonite were observed along several of the shear zones.

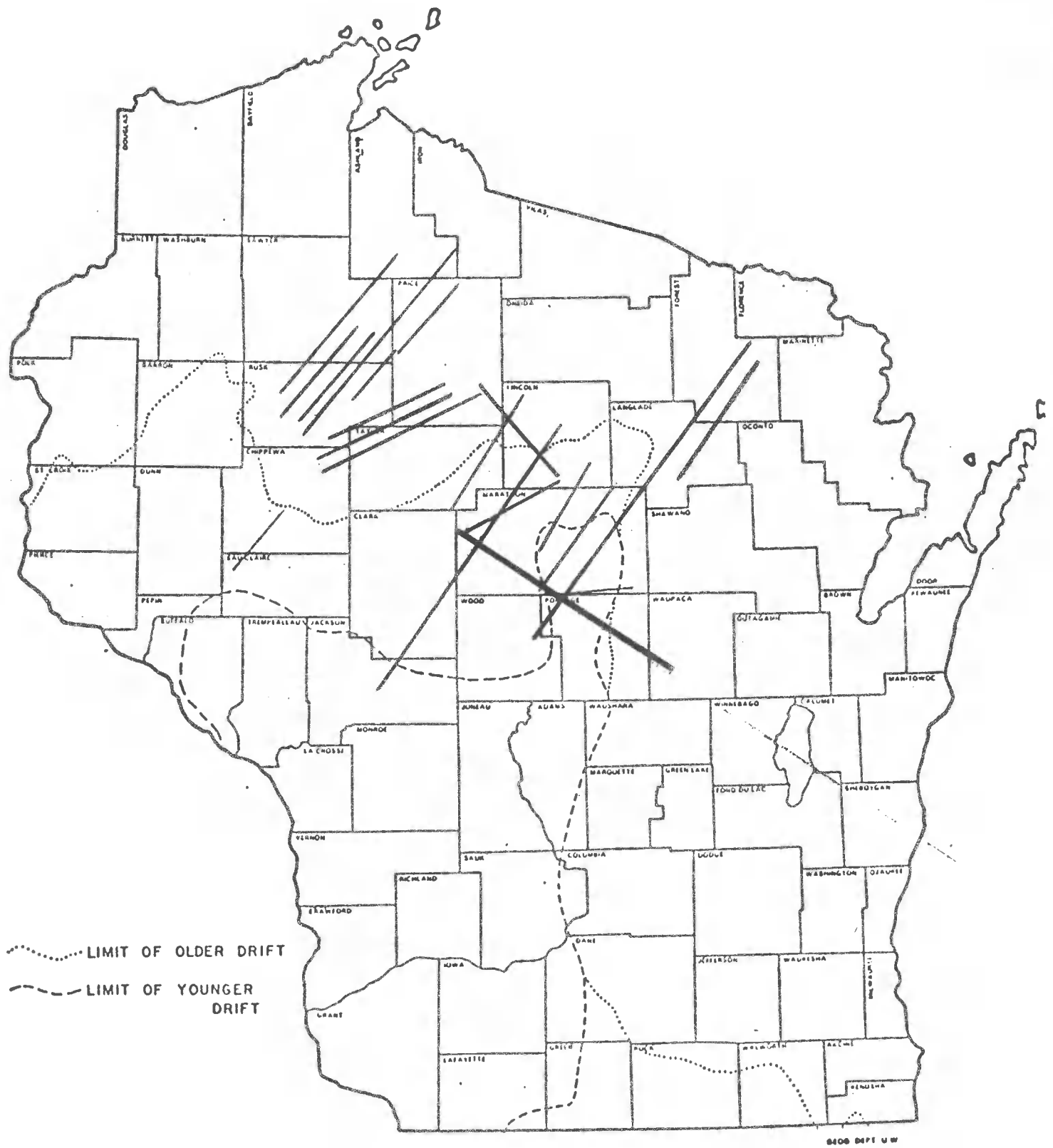
The best example of a mylonite zone mapped is that along the Eau Claire River in northeastern Marathon County. It has been mapped for a distance of approximately 20 miles, and almost certainly continues an additional 15 miles across the county. Furthermore, it is on a topographic lineament which can be traced across Wisconsin for at least 120 miles. At least 4 other major N30°-35°E shear zones cross Marathon County, and some of these also occur on topographic lineaments 100 miles or more long. Numerous stream valleys and other topographic lineaments in northern Wisconsin are oriented approximately N30°E, and these may also represent shear zones. Significantly, the N60°E and N80°E directions of shearing are also common trends of topographic lineaments.

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The origin of these major shear zones is not yet certain; however, the lithologic associations in the area mapped coupled with the major shearing suggest that northern Wisconsin may be part of a Precambrian subduction zone. Whatever the explanation of the shear zone, it is evident that they represent a major feature in the Precambrian of the Lake Superior region which has not previously been recognized.



LINEAMENTS AND POSSIBLE SHEAR ZONES IN MARATHON COUNTY



LINEAMENTS AND POSSIBLE SHEAR ZONES IN NORTHERN WISCONSIN

# STRATIGRAPHIC AND TECTONIC FRAMEWORK OF MIDDLE PRECAMBRIAN ROCKS IN MINNESOTA

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## ABSTRACT

Sedimentary strata of Middle Precambrian age in Minnesota predominantly consist of argillite and graywacke with lesser amounts of iron-formation, quartzite, quartzose siltstone, limestone, and dolomite. These strata unconformably overlie folded metasedimentary and igneous rocks approximately 2,700 m.y. old; locally they also appear to unconformably overlie diabasic gabbro or diorite dikes that may be approximately 2,000 m.y. old (Hanson and Malhotra, 1971).

Except for an older unnamed dolomite unit in east-central Minnesota, all the sedimentary rocks are assigned to the Animikie Group, a wedge-shaped body that thickens from less than 100 feet in the northern part of the State to at least 15,000 feet in areas 100 miles to the south. The Animikie Group comprises a single depositional event that began with well-sorted clastic detritus characteristic of a stable shelf -- Kakabeka, Pokegama, and Mahnomen Formations --, passed through a phase of iron-formation deposition -- Gunflint, Biwabik, and Trommald Formations --, and ended with deposition of fine sand and mud characteristic of a "deep" basin with poor circulation -- Rove, Virginia, Rabbit Lake, and Thomson Formations. Locally, the "deeper" water clastic rocks contain intercalated lava flows, thin to thick beds of pyroclastic material, and layers of carbonate- to sulfide-facies iron-formation.

During or subsequent to the time of deposition, the sedimentary rocks in east-central Minnesota were folded -- perhaps more than once -- into numerous large anticlines and synclines that have many second-order folds on their limbs. The major folds are asymmetric, with steeply-dipping to locally overturned north limbs and more gently-dipping south limbs. Fold axes trend within  $30^\circ$  of east, and plunge from horizontal to  $30^\circ$  east. In addition, a part of the Thomson Formation was regionally metamorphosed to at least the lower range (staurolite and garnet) of metamorphic grade in the amphibolite facies; however, definable metamorphic isograds are not everywhere parallel to recognizable structural trends, suggesting that deformation and metamorphism were independent variables in the orogenic scheme for this region. The time of folding is unknown, but the metamorphism on the Cuyuna range has been dated at 1,850 m.y. ago (Peterman, 1966). The Animikie strata in northern Minnesota also were deformed about northeast-trending axes, although the degree of deformation and the metamorphic grade is less pronounced. In addition, these rocks appear to have been subsequently folded about north-northwest-trending axes. Available isotopic data cluster around an age of 1,650 m.y. and these data may reflect a period of mild deformation and metamorphism at that time.

A variety of igneous rocks also were intruded into the sedimentary pile in east-central Minnesota. Several discrete events can be recognized, which together with the deformation and metamorphism comprise the Penokean Orogeny. These include (Woyski, 1949; Goldich and others, 1961): (1) pre-tectonic emplacement of small mafic intrusions; (2) syntectonic emplacement (1.78 - 1.63 b.y.) of intermediate-size intrusions of tonalitic to granodioritic composition -- the quartz monzonites at Warman, Isle, and Pierz, the tonalites near Hillman and Freedhem, and the gray granodiorite at St. Cloud; and (3) late-tectonic to post-tectonic emplacement (1.73 - 1.68 b.y.) of Woyski's "Stearns Magma Series" consisting of the augite-hornblende (red) granite at St. Cloud, the porphyritic quartz monzonite at Rockville, and other similar intermediate to silicic rocks. Lastly, rocks of the Stearns Magma Series are cut by basalt dikes which may have been emplaced during a single period, at least 1,570 m.y. ago (Hanson, 1968).

GRANITIC PLUTONIC ROCKS OF THE SOUTHERN PROVINCE OF THE  
CANADIAN SHIELD

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\*Paper presented by permission of the Director, Geological Branch.

ABSTRACT

In Ontario granitic rocks associated with the eastern portion of the Penokean fold belt comprise: (1) Archean basement; (2) early post-Huronian intrusives (= Penokean of Church, 1968), and (3) late post-Huronian intrusive (= Hudsonian of Church). Other authors eg. Stockwell (1964) have used Hudsonian and Penokean interchangeably and have not named the earlier orogenic event.

The individual granitic bodies are named on Figure 1.

1) Algoman = Archean (Robertson, 1960) granitic rocks may be divided into massive quartz monzonite and gneissic to migmatitic terranes. Bodies of quartz monzonite were formed during the Kenoran orogeny circa 2,500 MY. Early workers placed these bodies with the "young" post-Huronian granites. Overprinting of age dates becomes pronounced as the Penokean fold belt is approached (Van Schmus, 1965).

2) The Creighton and Murray Granites (Card, 1968; Ginn, 1958) lie south of the Sudbury Irruptive. They were intruded prior to the irruptive and local anomalous cutting relationships reflect remobilisation of the granite (Hawley, 1962). The granites pre-date the regional metamorphism and deformation. Gibbins et al (1971) have obtained 2,200 MY, which suggests that they are earlier than the Nipissing Diabase (2,155 MY Van Schmus, 1965). Whether they are synchronous with the earlier post-Huronian orogenic cycle or with early Huronian volcanism remains an open question (Card et al, 1972).

3) The Cutler Batholith (Robertson, 1969; 1970a; Cannon, 1970) lies some eighty miles west of Sudbury and intrudes folded and metamorphosed Huronian sediments and Nipissing Diabase and is itself foliated. Age-dates (Wetherill et al, 1960; Van Schmus, 1965) indicate a minimum age of 1,750 MY with some thermal resetting at 1,350 MY. The Cutler granite is clearly synchronous with the Hudsonian orogeny. The granite is intrusive but may have been derived from Huronian rocks at depth and metasomatism may have been an important factor (Cannon, 1970).

4) The Croker Island Complex (Card, 1965; Robertson, 1970) lies some twelve miles southeast of Cutler and comprises a circular complex of comagmatic mafic to granitic rocks accompanied by a marked magnetic anomaly. The complex post-dates regional metamorphism and folding. Age-dates (Van Schmus, 1965) and paleomagnetism studies (Palmer, 1969) indicate 1,445 MY. The complex is clearly late Hudsonian. Similar magnetic anomalies under Manitoulin Island were drilled by Union Carbide. Core of granitic rock resembling that at Killarney was obtained and submitted to Van Schmus for dating.

5) Grenville Front Granites (Card et al, 1971; Frarey and Cannon, 1969; Henderson, 1967; Quirke and Collins, 1930) are intrusive bodies in the Southern Province adjacent to the Grenville Front. To the northwest these bodies are intrusive but to the southeast they become strongly mylonitised passing into the deeper crustal granite-gneiss complex of the Grenville Province. The mylonite zone marks the Grenville Front.

5a\*) The Killarney batholith featured in the classical work of Quirke and Collins (1930) with a minimum age of 1,585 MY comprises porphyritic quartz monzonite.

5b\*) The Lake Panache and Eden Lake Intrusives, (Card et al, 1971) range in composition from gabbro-granite with a minimum age of 1,430 M.Y. from mica.

5c\*) The Chief Lake Batholith comprises quartz diorite to quartz monzonite marking the northeast continuation of the Killarney granite. Near Coniston, Phemister (in Grant et al, 1962) interpreted the rock as feldspathised sediment. Krogh (1971) indicates an initial age of 1,730 MY with some granites at 1,590 MY - 1,460 MY reflecting early movement on the Grenville Front.

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\*Individual bodies not shown on Figure 1.

## Conclusion

The granitic rocks of the Ontario Sector at the Southern Province may be classified with respect to petrography, mineralogy, chemistry, isotopic composition and they can be fitted into the historical and structural scheme established by regional mapping (Robertson et al, 1969; Card et al, 1972). However, much detailed work on individual bodies remains to be done.

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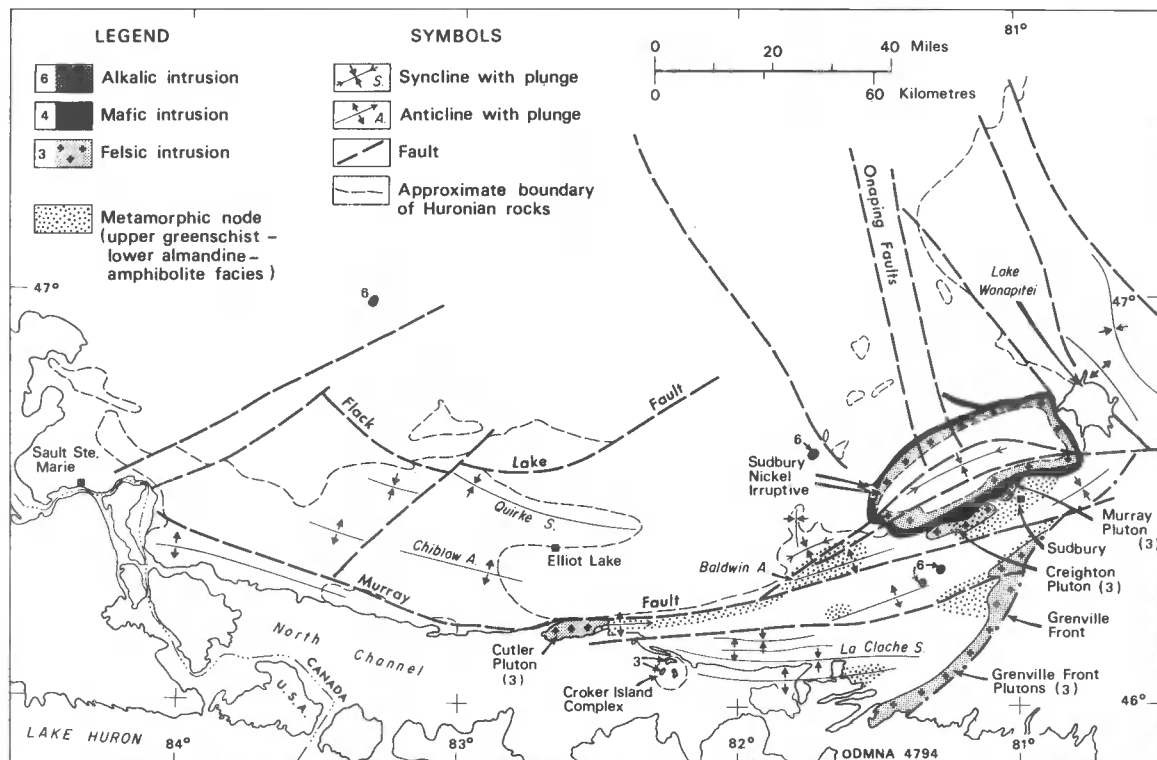
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Fig. 1. Structure, metamorphism and Post-Huronian granitic intrusions of the eastern Southern Province.



REGIONAL RELATIONSHIPS IN THE PENOKEAN PROVINCE

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A B S T R A C T

Investigations over the last few years in that area of the Southern Province of the North American Shield known as the Penokean Fold-Belt Subprovince, allow some of the following conclusions to be made:-

1. Similar sequences of sediments deposited over a period of about 600 my (roughly 2.2 by to 1.6 by ago) are of predominantly shallow water origin.
2. Local tectonic activity occurred during deposition of these sediments.
3. Intrusive igneous activity during this period resulted in basic dikes and/or sills; acid intrusives are minor.
4. The regional E-W folding increases in intensity to the south.
5. Older geological events tend to occur in the eastern part of the region and younger ones in the west.
6. Regional tectonism was most intense at some time before the end of the period.

Events which took place within this region during this time period are put into the context of cause-effect relationships and a regional-time pattern; a better geological understanding results.

The evidence strongly suggests that the area be re-designated as "The Penokean Province" and that the term "Penokean Orogeny" be replaced by "Penokean Tectonic Sequence".

AGES OF SOME PRECAMBRIAN ROCKS IN EAST-CENTRAL MINNESOTA

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ABSTRACT

The McGrath Gneiss, formerly assigned to the Penokean orogeny, 1600-1800 m.y. ago, was actually emplaced in a Lower Precambrian terrane during the Algoman orogeny, approximately 2700 m.y. ago. Locally the gneiss is intensively sheared. This phase of the deformation is related to epeirogeny that followed the regional metamorphism of the Middle Precambrian formations.

Rb-Sr isochron studies of igneous rocks that were emplaced following folding and regional metamorphism place a minimum age of 1900 m.y. on the Middle Precambrian Thomson Formation. This age is somewhat older than the 1850 m.y. age obtained by Z. E. Peterman for the metasedimentary rocks of the Cuyuna district and is considerably older than the previous K-Ar and Rb-Sr mica age determinations.

The McGrath Gneiss appears to be extensive in east-central Minnesota; hence, it is likely that the Middle Precambrian rocks of Minnesota were all deposited on an erosion surface developed on an Archean continental crust rather than on oceanic crust.

GEOCHRONOLOGY OF PRECAMBRIAN ROCKS IN THE PENOKEAN  
FOLD BELT SUBPROVINCE OF THE CANADIAN SHIELD

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A B S T R A C T

The Penokean Fold Belt subprovince is that part of the Southern Province consisting of the folded and metamorphosed Middle Precambrian rocks which occur in an E-W trending belt running south of Lake Superior and north of Lake Huron. Included within this belt are strata of the Huronian, Marquette Range, and Animikie supergroups and associated economic deposits. For many years these rocks have been considered possible correlatives, and the folding, metamorphism, and intrusive activity have been referred to as the Penokean Orogeny.

Recent and current field and laboratory studies now show that the orogenic history of this region can not be represented by a single major orogenic episode. Instead, this portion of the North American continental plate was affected by a succession of events over the interval 2.7 to 1.1 b.y. ago.

The oldest Proterozoic rocks are apparently those in Ontario, north of Lake Huron. In this area Huronian strata overlie a 2.7 b.y. old basement and are intruded by the 2.16 b.y. old Nipissing Diabase. To the west, in Upper Michigan, the Proterozoic sedimentary and volcanic rocks, the Marquette Range supergroup, are apparently younger, being between 1.90 and 2.05 b.y. old, and thus not correlative with true Huronian rocks. Farther west, in Minnesota, the Animikie rocks may be partly correlative with and partly younger than those in Michigan and Wisconsin.

There have been multiple periods of intrusive, metamorphic, and tectonic activity. The oldest Proterozoic deformation apparently occurred about 2.15 b.y. ago in Ontario, affecting the Nipissing Diabase and Huronian rocks. A major episode of igneous, metamorphic, and tectonic activity occurred about 1.9  $\pm$  0.1 b.y. ago, affecting most, if not all, of the E-W trending belt from Minnesota to Ontario. This event would appear to be the one most representative of a "Penokean Orogeny."

Subsequent to the main orogenic activity several intrusive and/or metamorphic episodes have occurred, about 1.65, 1.5, and 1.3 b.y. ago. Several of these younger events may be correlated with the Middle Precambrian history of Wisconsin and the rest of the Midcontinent. Finally, much of the area was affected by Keweenawan igneous activity and associated metamorphism 0.9 to 1.2 b.y. ago.

-2-

On the basis of present geologic and geochronologic data, it appears reasonable to interpret the Penokean Fold Belt as an orogenic belt developed along the southern edge of the Superior craton about 1.9 billion years ago. The exact nature of this structural belt and its possible relation to arc-trench sequences of present models of plate tectonics must await further work.

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STRATIGRAPHY AND SEDIMENTATION OF THE ESPANOLA FORMATION,  
AN EARLY APHEBIAN (MIDDLE PRECAMBRIAN)  
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ABSTRACT

The Espanola Formation is unique among Huronian formations in its high carbonate content. It forms part of the Quirke Lake Group, lying between the Bruce Formation (beneath) and the stratigraphically higher Serpent Formation. The Bruce Formation is mainly unstratified sandy polymictic paraconglomerate (tillite) whereas the Serpent Formation consists mainly of cross bedded feldspathic quartzites. In the Quirke Lake area the Espanola Formation is divisible into three units, here called, in ascending order, limestone member, siltstone member and dolostone member. Some fifty miles to the southeast these three members can still be recognised but the central, dominantly terrigenous clastic unit, is much thicker. In the southern area there is also an additional thick upper member which displays fining upwards cycles (from conglomerate to mudstone) similar to those attributed to fluvial deposition.

In the Quirke Lake area the Espanola Formation contains both intra-formational and intrusive breccias. The intrusive breccias are later than some faulting and transect clastic dykes. They are considered to be downward intrusions caused by release of high pore pressure in water-saturated sediments along fissures in the already lithified Espanola Formation. The triggering mechanism for the breccias may have been earth tremors associated with early (pre-Gowganda) earth movements for the breccias appear to be spatially related to areas where there is evidence of disconformable/unconformable relations between the Gowganda Formation and older Huronian rocks.

Cross bedding studies, mainly from the highest member of the Espanola Formation in the southern part of the Huronian outcrop belt, reveal a bimodal pattern with dominant modes in the south-west quadrant and towards the E.S.E.

Microprobe analyses of the carbonates of the dolostone member showed that the rusty-weathering dolostones are composed of ferruginous dolomite.

The Espanola Formation is interpreted as a post-glacial transgressive-regressive cycle (Fig. 1). The limestone and dolostone members are thought to be shallow water deposits while the siltstone member represents a deeper water facies (involving some turbidite transportation). The sandstone member of the southern region is thought to have been laid down from meandering streams which initiated sedimentation of the thick prograding fluvial sequence of the Serpent Formation.

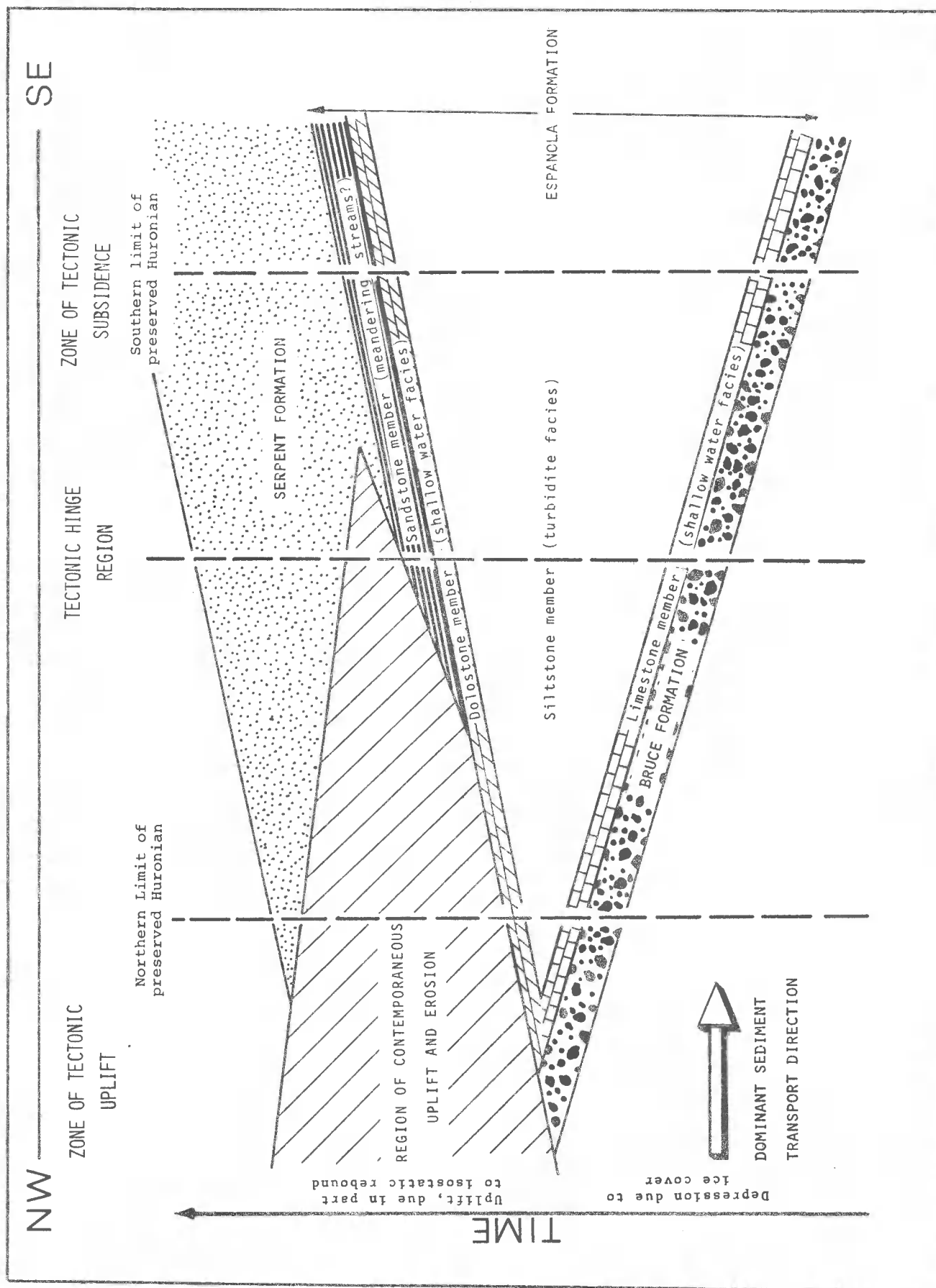


FIG. 1. SPACE - TIME RELATIONSHIPS DURING SEDIMENTATION OF THE ESPANOIA FORMATION

# WEATHERING AND METASOMATISM OF THE PRESQUE ISLE SERPENTINIZED PERIDOTITE, MARQUETTE COUNTY, MICHIGAN

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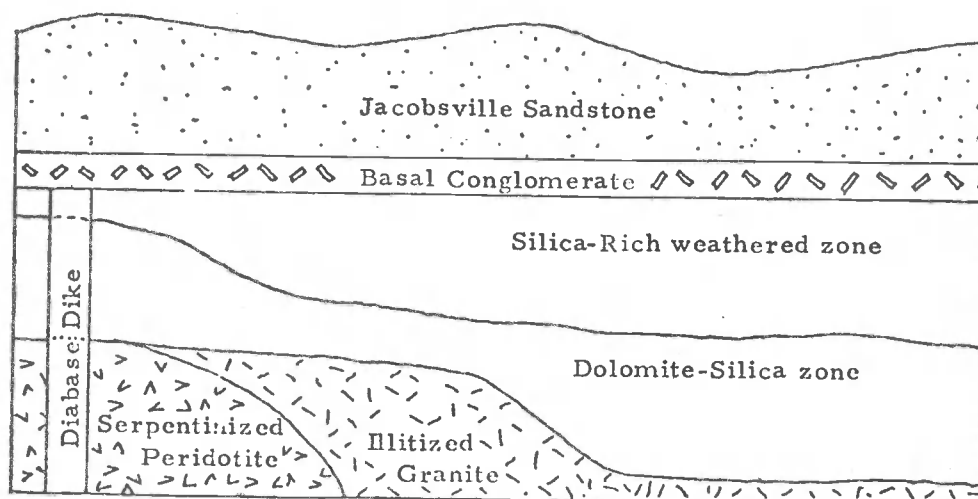
## ABSTRACT

Presque Isle Park, Marquette, Michigan is underlain by a mass of peridotite, probably cut by Archean granite and definitely cut by a diabase dike of probable Keweenawan age. The three rock types grade upward into a complex altered zone that has variable thickness and mineralogy, depending upon the rock type it occurs on. This zone is comprised of a lower zone of dolomite-silica and an upper zone rich in silica, which in turn is unconformably overlain by Jacobsville Sandstone.

Data from major element analysis of 42 rocks, qualitative mineralogy determinations by X-ray diffraction, and field observations indicate that the peridotite has undergone three periods of alteration; 1)early serpentization, 2)carbon dioxide metasomatism after emplacement, and 3)weathering after the area was exposed to surface conditions. The granite has also undergone the same sequence of alteration with the exception that the first period of alteration was illitization. On geological and geochemical grounds the serpentization and illitization processes could not have been contemporaneous.

The forming of the silica rich weathered zone, which is best developed over the granite, is the result of weak acidic meteoric waters dissolving dolomite out of the dolomite-silica zone. Chemical and mineralogical profiles show that the removal of dolomite results in the upward concentration of residual minerals such as quartz, rutile, hematite, chlorite, and illite. The weathered zone was searched for nickel concentrations such as garnierite, but none were found.

Field evidence indicates that the weathering and metasomatic alteration post-dates the intrusion of the probable Keweenawan dike and pre-dates the deposition of the Jacobsville Sandstone.



Diagrammatical sketch(not to scale) showing the relationship between the rock units on Presque Isle.