

DULUTH, MINNESOTA



MAY 8-13, 1979

25th ANNUAL
INSTITUTE ON
LAKE SUPERIOR GEOLOGY



TECHNICAL SESSIONS

and

ABSTRACTS

for the

25th ANNUAL

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Sponsored by

UNIVERSITY OF MINNESOTA, DULUTH

held at

DULUTH, MINNESOTA

in Joint Session with the North Central Section
Geological Society of America

May 8 - 12, 1979

Donald M. Davidson, Jr., Program Chairman

David G. Darby, Field Trip Chairman

Carol Moss, Technical Editor

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* COVER DRAWING: The large anticline. View from the east bank of the St. Louis River, just south of the highway bridge, looking west. Thomson Dam Area, near Thomson, Minnesota.

W. Wilson, May 30, 1968

25th Annual

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Sponsored by

University of Minnesota, Duluth

at

Duluth, Minnesota

May 8 - 12, 1979

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PROGRAM

Tuesday, May 8, 1979

8 a.m. Field Trip 1 leaves Hotel Radisson Duluth

Wednesday, May 9, 1979

8 a.m. Field Trip 2 leaves Hotel Radisson Duluth

12 noon Registration opens, Superior Foyer, Hotel
Radisson Duluth

5 p.m. Field Trips 1 and 2 return Hotel Radisson Duluth

7-10 p.m. Smoker poolside, Hotel Radisson Duluth

Thursday, May 10, 1979

7:30 -
12 a.m. Registration, Superior Foyer, Hotel Radisson
Duluth

S E S S I O N 1

Morning

Thursday, May 10, 1979

Early Precambrian

Co-chairmen: Manfred Kehlenbeck, Paul Meyers

8:45	D. M. Davidson, Jr.	Opening Remarks
9:00	John Klasner and Paul Sims	Geologic Interpretation of Gravity Data in the Marinesco, Thayer and Watersmeet Quad- rangles, Michigan
9:20	K. Howard Poulsen	Polyphase Deformation of Archean Rocks at Rainy Lake, Ontario
9:40	Elizabeth Palmer and Donald Davidson	Paleostrain Analysis - Across a Shear Zone, Northwestern Marathon County, Wisconsin
10:00	Stephanie Wurdinger	Structural Geology of Amphibolitic Gneisses, Northeast Chippewa County, Wisconsin
10:20	Coffee Break	
10:40	Manfred Kehlenbeck	Structural Interpretations in the Hazelwood Lake Area, Thunder Bay, Ontario
11:00	Paul Sims and David Southwick	New evidence on the stratigraphy and structure of the Soudan area, Western Vermilion dis- trict, Minnesota
11:20	Bruce Brown	Deformational History of Archean Greenstone Terrane, Eastern Lake of the Woods, Ontario
11:40	Thomas Waggoner and Thomas Mroz	Palmer Gneiss Update
12:00	Noon, Adjourn for Lunch	

Luncheon Meeting of Board of Directors - location to be announced.

S E S S I O N 2

Afternoon

Thursday, May 10, 1979

Middle Precambrian

Co-chairmen: Ralph W. Marsden, Glen Morey

- | | | |
|------|---------------------------------------|---|
| 2:00 | David Larue and
F. William Cambray | Cross folding in the eastern part of the
Marquette Trough, Michigan |
| 2:20 | Roy Shegelski | Stratigraphy of the Gunflint Formation,
Kakabeka Falls Area, Ontario |
| 2:40 | Karen Kimball | Coexisting Amphiboles in the metamorphic
iron formation, Jackson County, Iron Mine,
Wisconsin |
| 3:00 | Mike Cummings | Phase relations of oxide-free iron formation
in the Amphibolite Facies |
| 3:20 | Coffee Break | |
| 3:40 | Mark Kirstein | Contact Metamorphism of the Virginia Forma-
tion in the Minnamax Deposit, St. Louis
County, Minnesota |
| 4:00 | Jesse Dann | Comparative major element variations within
the Emperor Igneous Complex, and the Hemlock
and Badwater Volcanic Formations, northern
Michigan |
| 4:20 | G. Bennett and
D. G. Innes | Stratigraphy and Petrochemistry of Huronian
Volcanics, North Shore of Lake Huron, Ontario |
| 4:40 | Discussion Session | |
| 5:00 | Adjourn | |

* * * * *

Evening

7:30 Banquet with North Central Section GSA - Hotel Normandy

Speaker: Dr. Vincent McKelvey
Former Director
United States Geological Survey

S E S S I O N 3

Morning

Friday, May 11, 1979

Late Precambrian

Co-chairmen: Stan Watowich, Mike Foos

9:00	William Matlack	Geology of the Duluth Complex-Virginia Formation Contact, Minnamax Deposit, Minnesota
9:20	George Lehman and Donald Davidson	Petrology Aspects of the Troctolite-Olivine Gabbro Series, Duluth Gabbro Complex (Late Precambrian), Northeast Cramer Quadrangle, Minnesota
9:40	James Hahnenberg	Petrology and Geochemistry of Keweenaw Diabase Dikes in Michigan's Western Upper Peninsula
10:00	Coffee Break	
10:20	John Green	Bedrock Geology of the Milepost 7 Area, Silver Bay, Minnesota
10:40	Stephen Guggenheim, Peter Wilkes and S. W. Bailey	The Nature of Greenalite
11:00	Discussion Session	
11:20	Adjourn for Lunch	

S E S S I O N 4

Afternoon

Friday, May 11, 1979

General Session

Co-chairmen: Cedric Iverson, Mike Mudrey

- | | | |
|------|---|--|
| 1:40 | Business Meeting of the Institute | |
| 2:00 | William Cannon and
Dennis Kostick | Ronchi Filtering - an easy, inexpensive technique for linear enhancement of many kinds of Geologic Data |
| 2:20 | Elizabeth King
and William Cannon | Results of a Truck Magnetometer Survey of the Southwestern Quarter of the Iron River 2 ⁰ sheet |
| 2:40 | Jim Trow | DOE-Bendix-Michigan Geological Survey Diamond-Drilling for Geologic Information in Marquette and Iron Counties |
| 3:00 | Coffee Break | |
| 3:20 | Maurice Brock,
Jo Kalliokoski and
Richard Ojakangas | Status of USGS Uranium Studies in Michigan's Upper Peninsula |
| 3:40 | Tom Evans | State Legislation Affecting Mineral Development in Wisconsin |
| 4:00 | End of Technical Session | |

Saturday, May 12, 1979

Field Trips 3, 4, 5, 7, 8 Depart

Leave 0800 Normandy Inn

POSTER PAPERS

Morning

Friday, May 11, 1979

9:00 to 12:00*

Explorer Room, Radisson Duluth Hotel

Glenn R. Bruck	A new Proposal for the Origin of the Horse Creek Channel, in Polk & St. Croix Counties, Wisconsin
Jeff Greenberg and Bruce Brown	Preliminary Geologic Interpretation of the Northeastern Wisconsin 1:250,000 Geologic Map
Frank Karner and John T. Ray	The Precambrian Basement of North Dakota
M. P. McKenna and L. W. Gladen	Mineral Survey and Mineral Potential of Cook County, Minnesota
Nancy Scofield and David B. Jorgenson	Pink and Green Albite Phenocrysts from the Mohawk Mine, Michigan--Indicators of Changes in Hydrothermal Fluids
D. W. Snider and B. K. Parker	The copper-sulfide potential of several igneous plugs in Michigan's Keweenaw Peninsula
G. Bennett and D. G. Innes	Huronian Volcanic Rocks, North Shore of Lake Huron, Ontario

*Authors will be present 11:00 to 12:00

HURONIAN VOLCANIC ROCKS, NORTH SHORE OF LAKE HURON, ONTARIO

G. Bennett and D. G. Innes
Ontario Ministry of Natural Resources

ABSTRACT

The distribution, petrochemical and stratigraphic relationships of volcanic and clastic formations at or near the base of the Huronian Supergroup of the Southern Structural Province of Ontario permits the following reconstruction of Middle Precambrian events in terms of rift tectonics.

1. Sands and gravels of the Livingstone Creek Formation are deposited on Archean basement.
2. Thermotectonic uplift centered east of the present Elliot Lake area (probably in the Sudbury area) causes an eastward erosional beveling of the Livingstone Creek Formation.
3. The andesitic member of the Thessalon Formation erupts from central vents and fissures in a subsiding basin or graben. The study of 110 chemical analyses indicates that in spite of local spilitization, these oldest volcanics included (tholeiitic) basaltic andesite, icelandite, rhyolite; and (mildly alkalic) hawaiiite, mugearite and ankaramitic flows.
4. The eruption of compositionally uniform tholeiitic flood basalt forms the upper (basaltic) member of the Thessalon Formation.
5. Reoccurrence of uplift in the Sudbury area results in erosion of the upper member of the Thessalon Formation east of Thessalon and its complete removal east of the Elliot Lake area.
6. In the Sudbury area the thick accumulations of tholeiitic basalt (Elsie Mountain and Stobie Formations) erupt from fissures in a subsiding basin or graben. Increasing subsidence and/or waning volcanism causes much intercalated wacke and conglomerate in the Stobie Formation; while in the Massey area (80 km to the west), basalt to rhyolite of the Salmay Lake Formation is erupted on a surface in part of exhumed, layered gabbro-anorthosite which was probably emplaced during the Thessalon volcanic event.

Coarse sands and uraniferous gravels of the Matinenda Formation are laid down on the eroded surface of the Thessalon Formation in the Elliot Lake area and westward; but are intercalated with the younger volcanics in the Massey and Sudbury areas to the east.
7. The eruption of the predominantly rhyolitic Copper Cliff Formation of the Sudbury area marks the final Huronian volcanic episode.
8. Cessation of volcanism in the Sudbury-Massey area is followed by prolonged subsidence and the deposition of the thick turbidite sequence of the McKim Formation.

STATUS OF USGS URANIUM STUDIES IN MICHIGAN'S UPPER PENINSULA

Maurice Brock, U.S. Geological Survey, Denver, Colorado 80225, Richard W. Ojakangas, University of Minnesota, Duluth, Duluth, Minnesota 55812 and U.S. Geological Survey, and J. Kalliokoski, Michigan Technological University, Houghton, Michigan 49931 and U.S. Geological Survey

ABSTRACT

The U. S. Geological Survey is conducting work related to uranium potential of Lower, Middle, and Upper Precambrian rock units. Randomly selected samples from all units are being analyzed for uranium content. In general, base-level data are being generated where such knowledge is lacking.

Possible enrichment of shear zones is one focus of the study. Mylonitic shear zones containing radioactive biotite and chlorite pods cut granitic rocks; some of these porphyritic or porphyroblastic rocks are 3-5 times more radioactive than other granites. A number of primary radioactive occurrences are present in the granitic terrane (see Kalliokoski, 1976).

All the major Middle and Upper Precambrian sedimentary units of the Cogebeic Range in Michigan and Wisconsin, and other units to the east, are in the process of being studied. Paleocurrent patterns have been determined (largely on cross-bedding) for the Sunday Quartzite (72 readings--bimodal WNW and ESE), the Palms Formation (102 readings--bimodal W and E), the Bessemer Sandstone (105 readings--bimodal ENE and W), and the Jacobsville Formation (150 readings--local variability). Field data are of primary importance, but drill core samples of the Jacobsville are also being studied. Paleogeographic-depositional models are being constructed; these should be of value in determining sources and transport directions of radioactive mineral grains and/or solutions. However, to date abnormal radioactivity has only been found in detrital monazite of the Goodrich Quartzite (Vickers, 1956) and in phosphatic zones of the Michigammi Formation (Cannon and Klasner, 1976). There are a number of minor radioactive occurrences which may be related to the sub-Jacobsville unconformity (Kalliokoski, Langford and Ojakangas, 1978).

References

- Cannon, W. F. and Klasner, J. S., 1976, Phosphorite and other apatite-bearing sedimentary rocks in the Precambrian of Northern Michigan: U.S. Geological Survey Circular 746, 6 p.
- Kalliokoski, J., (with C. Johnson), 1976, Uranium and thorium occurrences in Precambrian rocks, Upper Peninsula of Michigan and northern Wisconsin, with thoughts on other possible settings: U.S. ERDA, Grand Junction, BJX-48(76), 294 p.

Kalliokoski, J., Langford, F. F., and Ojakangas, R. W., 1978, Criteria for uranium occurrences in Saskatchewan and Australia as guides to favorability for similar deposits in the United States: U.S. D.O.E., Grand Junction, CJBX-114(78), 480 p.

Vickers, 1956, Geology and monazite content of the Goodrich Quartzite, Palmer area, Marquette County, Michigan in Contributions to the geology of uranium, 1955: U.S. Geological Survey Bulletin 1030, p. 171-185.

DEFORMATIONAL HISTORY OF AN ARCHEAN GREENSTONE TERRANE:
EASTERN LAKE OF THE WOODS, ONTARIO

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ABSTRACT

A structural and stratigraphic study has been completed in the east-central part of the Lake of the Woods region. The rocks of this area constitute a typical greenstone assemblage of volcanic and sedimentary lithologies. The greenstones occupy an east-to-west trending belt bounded on the north, south, and east by granitic batholiths in the study area. The results of this study indicate that the greenstones have undergone a complex deformational history which can be related to the diapiric emplacement of the large bordering plutons and several smaller stocks within the belt.

The earliest structural features of the area are a series of major east-west trending isoclinal folds (F_1) with horizontal to shallow plunging axes. F_1 folds have an associated axial planar foliation and are well defined by top reversals within the volcanic-sedimentary section. These folds are a regional feature and can be traced beyond the area of study. Evidence from sedimentary facies distribution as well as structure supports their early origin.

Deformation which accompanied emplacement of the granitic plutons produced folds (F_2) and a complex pattern of faults and shear zones. Axial planar cleavages, penetrative mineral lineation, and a complex set of crenulations are associated with the F_2 folds. F_2 folds and related fabrics show a consistent style throughout the area, but their orientation and degree of development is variable depending on their location relative to the deformational and metamorphic regime surrounding the plutons.

Where pluton contacts parallel the structural grain of the greenstones, F_1 folds were tightened and flattened, and shear zones developed along lithologic boundaries. Vertical displacement occurred along these zones, causing repetition of section and development of cataclastic textures. Where the structural grain met a pluton contact at a high angle, shear zones acted as detachment faults to accommodate flexural folding of bedding and F_1 axial planes around steeply plunging F_2 axes.

In the late stages of deformation, a set of northwest- and northeast-trending kink bands was overprinted on rocks with strong planar fabrics. Kinks grade into crenulation cleavage in fine grained pelitic rocks and fine grained cataclastic rocks.

The latest structures are a series of northwest-trending faults into which diabase dikes were intruded in Late Proterozoic time.

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A PROPOSED SOUTHERN SPILLWAY FOR GLACIAL LAKE GRANTSBURG

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ABSTRACT

In 1935 W. S. Cooper described Glacial Lake Grantsburg which was formed when the Mississippi and St. Croix Rivers were dammed by the glacial advance of the Grantsburg Sublobe. Lacustrine sediments indicate that the lake occupied an area of approximately 11,500 km² (4,500 mi²). The estimated geographic center of this body of water lies within Burnett County, Wisconsin. Lacustrine sediments also indicate that the lake maintained a level between 305 m (1002 ft) and 325 m (1070 ft) with a possible maximum at 335 m (1100 ft).

Cooper's description of the lake includes a southern limb of water extending to the vicinity of St. Croix Falls, Wisconsin. This limb was confined on the west by the Grantsburg Sublobe and on the east by the St. Croix Moraine, which was deposited about 1,300 years earlier by the Superior Lobe. The present investigation suggests that the lake's southern extension terminated near St. Croix Falls and Dresser, Wisconsin; this location being determined by evidence indicating that the Grantsburg Sublobe was pinned against the St. Croix Moraine in this area.

Although Cooper's study is the most detailed investigation of the lake to date, he was unable to find a drainage spillway associated with its highest level. As a result, he hypothesized that the lake, at its highest stand, might have drained over the Grantsburg Sublobe.

A topographic examination of the St. Croix Moraine near Dresser, Wisconsin, reveals a gap that lies at the 304 m (1,000 ft) level, fully 55 m (180 ft) below the morainal ridge it divides. During the glaciation, this gap was low enough so that it was penetrated by outwash from the nearby Grantsburg Sublobe. The gap also marks the beginning of a 42 km (26 mi) channel which is clearly defined by the 304 m (1,000 ft) contour. The channel trends southward and merges with the Apple River near Huntington, Wisconsin. From here it follows the Apple River to a point 6.5 km (4 mi) WNW of Sommerset, Wisconsin, where it finally joins the St. Croix River. This route describes a course which bypasses a 26 km (16 mi) stretch of the St. Croix River. The present study suggests that this bypass represents a southern spillway for Glacial Lake Grantsburg which facilitated the lake's drainage during the maximum advance of the Grantsburg Sublobe.

Evidence in support of this hypothesis consists of two major observations: First, the close correlation between the altitude of the channel and the level of Glacial Lake Grantsburg; and secondly, the outwash from the Grantsburg Sublobe found east of the gap at Dresser indicates that drainage from the ice flowed through the gap.

RONCHI FILTERING--A RAPID INEXPENSIVE TECHNIQUE TO AID IN THE
DETECTION OF LINEATIONS IN PHOTOGRAPHS, MAPS, ROCKS, AND THIN SECTIONS

William F. Cannon and Dennis Kostick
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ABSTRACT

Ronchi filtering is a simple visual technique that can aid in identifying linear trends in Landsat images, aerial photographs, geologic maps, aeromagnetic and gravity maps, and topographic maps; it can also be used to detect subtle linear features in rocks and thin sections. It may sometimes be an adequate substitute for more expensive and time-consuming computer enhancement of data.

A Ronchi filter is a type of linear diffraction grating in which parallel thin opaque stripes are arranged on a clear plastic so that the width of each opaque stripe is equal to the width of the adjacent transparent area. The filter used in our work contains 8 stripes per millimeter.

The filter is held about 10-30 cm in front of the eye, and the object to be studied, for example, a Landsat image, is viewed through the filter. Any small object when viewed in this way is seen as multiple images aligned perpendicular to the direction of stripes on the filter. For example, a dot appears as a line of several individual but closely spaced dots. This property can be used to enhance subtle linear trends. For example, by viewing a Landsat image through the filter and slowly rotating the filter through 180° , a user performs a rapid linear enhancement in all possible directions. Subtle linear trends, commonly not easily visible to the unaided eye, may become readily visible through the filter when it is oriented so that the direction of stripes on the grating is perpendicular to the trend on the image or object.

This technique has been useful in regional tectonic studies in the Lake Superior region by helping us to identify linear trends in Landsat images, aeromagnetic, and gravity maps.

PHASE RELATIONS OF OXIDE-FREE IRON FORMATION IN THE AMPHIBOLITE FACIES

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ABSTRACT

Iron formation units, up to 50 m thick, occur in the Precambrian Quinnesec Formation, west central Marinette County, Wisconsin. The iron formations are associated with basalt flows, graphitic metasediments and sub-economic massive sulfide.

The iron formation contains well-bedded gray quartz and iron silicate beds. Locally, quartz beds are fractured and in some cases fragments are separated by thin septa of iron silicates. Some sections are characterized by rounded, 1 to 2 cm, quartz nodules. Oxides and/or sulfides are disseminated in iron silicate beds or occur as thin layers interbedded with iron silicates. Ilmenite is the oxide phase, but magnetite is locally abundant. Monoclinic pyrrhotite is the main opaque phase. Sphalerite occurs as isolated grains interstitial to iron silicates or associated with pyrrhotite. Chalcopyrite occurs only in pyrrhotite-bearing beds.

The metamorphic grade of volcanic sequences can be determined by the iron silicate assemblages in oxide-free iron formation. Iron silicate assemblages in oxide-free samples from the Quinnesec Formation include grunerite/quartz, grunerite/stilpnomelane/quartz, grunerite/ferro-hornblende/stilpnomelane/quartz, grunerite/garnet/ferro-hornblende/quartz, grunerite/ferro-actinolite $\pm$ ferro-hornblende/quartz. Calcite is a common accessory mineral. Stilpnomelane, restricted to grunerite and grunerite/ferro-hornblende assemblages, is more iron-rich than associated amphiboles. Manganese is preferentially partitioned into grunerite in garnet-free samples. Magnesium is preferentially partitioned into ferro-actinolite in grunerite/ferro-actinolite assemblages. Ferro-hornblende is the silicate phase containing the highest concentration of titanium.

The iron silicates can be represented in the simplified system $\text{FeO}-\text{Al}_2\text{O}_3-\text{CaO}-\text{SiO}_2-\text{H}_2\text{O}$. K_2O and Na_2O in stilpnomelane, MgO , MnO and TiO_2 in amphiboles remove the system from the ideal simplified system. Iron silicate assemblages in the Quinnesec Formation indicate that the assemblage hornblende/grunerite/quartz is stable under metamorphic conditions, approximated from associated metasediments, at 520°C and 1.5 to 3.5 kb. Actinolite/garnet/quartz is stable at higher temperatures or in high-manganese bulk compositions.

MAJOR-ELEMENT VARIATION WITHIN THE EMPEROR IGNEOUS COMPLEX
AND THE HEMLOCK AND BADWATER VOLCANIC FORMATIONS

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ABSTRACT

Major-element variations within the Emperor Igneous Complex, and the Hemlock and Badwater volcanic formations of the Lower Proterozoic of northern Michigan were studied to determine the magma series type. Fifty-two new analyses indicate that continental tholeiite dominates and that most of the less abundant calcalkaline rocks are not really distinguishable from those associated with a Lower Proterozoic Cu-Zn massive sulfide deposit in Wisconsin.

The Emperor Igneous Complex in the East Gogebic Range consists of two distinct suites: calcalkaline volcanic rocks and tholeiitic sills. The volcanic rocks, interbedded with the Ironwood Iron-formation, consist mostly of andesite breccia with minor lava flows; they are interpreted to represent a subaqueous volcanic apron. SiO_2 increases upward from 54 to 62 percent with FeO remaining at 9 to 11 percent. The sill complex intruded the iron-formation in three stages which show a FeO increase from 12 to 19 percent.

The Hemlock Formation north of Crystal Falls displays tremendous lithologic and geochemical variety. Rhyolite lava and/or volcanoclastic deposits occur at three horizons within the formation which is dominated by basaltic lavas and volcanoclastic sediments (pillow breccia, flow breccia, hyaloclastite, and turbidites). The lowermost basalts, deposited about 2 b.y. ago, are poorly differentiated oceanic basalts, perhaps erupted in a fault-bound basin; these are overlain by slate and iron-formation. The succeeding lavas, composed of continental tholeiite basalt, display several subcycles of FeO and TiO_2 enrichment. The uppermost unit of extraordinarily high-iron basalt (up to 25 percent FeO) is immediately overlain by iron-formation. The rhyolites do not occur at the top of volcanic cycles.

The Badwater Greenstone outcropping along the north margin of the Iron River-Crystal Falls basin consists of several different sequences of dominantly tholeiitic volcanic rocks. Exposures on the south limb of the basin exhibit a close relationship between high iron tholeiite basalts and iron-rich sediments; these rocks are interpreted to belong to the Hemlock Formation.

It is clear that lavas associated with the Ironwood Iron-formation are not enriched in iron. However, there is some evidence which leads one to suspect a relationship between iron-rich lavas of the Hemlock Formation and the overlying Amasa Iron-formation.

STATE LEGISLATION AFFECTING MINERAL DEVELOPMENT IN WISCONSIN

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ABSTRACT

Proposed metallic mineral development in Wisconsin has stimulated wide-ranging legislative activity by the State of Wisconsin. The new legislation, passed in 1977 and 1978, also has impact on the two existing metal mines in Wisconsin. Metal mining operations are subject to new laws concerning (1) taxation of mineral revenues (Chapters 31, 185, and 423), (2) controls on operating procedures and environmental impacts from the exploration (drilling) phase through actual mine production (Chapters 377, 420, and 421), (3) controls on metallic mineral exploration lease terms and recording procedures (Chapter 253), and (4) submittal of metallic mineral exploration information of geologic interest to the State (Chapter 422).

Some of the background leading to the recent legislation will be reviewed with a brief discussion of the current status of each law, its impact on the mining industry, and subsequent regulatory activity. Potential modifications of the laws will also be noted.

Proposed legislation in the 1979 legislative sessions concerns long-term liability of mining companies and registration of severed mineral interests. Prospects for and ramifications of this additional legislative activity will be examined. In addition, the work of the Legislative Council Mining Committee's Subcommittee on Reclamation of Nonmetallic Mining will be reviewed.

BEDROCK GEOLOGY OF THE MILEPOST 7 AREA, SILVER BAY, MINNESOTA

John C. Green
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ABSTRACT

Reserve Mining Company's new tailings disposal area lies in the broad valley of the Thirty-nine Creek tributary to the West Branch of the Beaver River about five miles west of Silver Bay. The basin is underlain by lavas of the North Shore Volcanic Group whereas the high ridge along the southeast side is held up by diabase of the Beaver Bay complex. The more gradual slope on the northwest flank is also underlain predominantly by mafic intrusive rocks. All of the bedrock is of Keweenawan (Late Precambrian) age. During the summer of 1978 the bedrock geology of the area was studied by field mapping and examination of drill cores obtained for dam foundation testing.

The lavas in the basin and along strike to the south can be assigned to the Gooseberry River basalts of Green (1942). They dip gently (about 90°) to the southeast, and consist of roughly 700 feet of intergranular andesites and basaltic andesites overlain by about 850 feet of ophitic olivine basalts. The later tend to hold up low hills within the southeast part of the basin.

The high ridge along the east side is made predominantly of ophitic olivine diabase, but a few anorthosite xenoliths and thick screens and blocks of basaltic hornfels are also present as well as minor interflow volcanic sandstone and breccia. The main diabase intrusion appears to have been localized along a major NNE-trending fault which also divides the lava succession into two separate structural and stratigraphic blocks; the flows east of the ridge strike WNW and dip south whereas those to the west strike NE and dip SE. Some faulting has also occurred since intrusion, producing breccias and topographic cross-valleys and juxtaposing unmetamorphosed sediments next to diabase.

The intrusive rocks of the western flank are more diverse and are probably interdigitated with lavas but exposures are too poor to show contact relations. The uppermost unit is a ridge-forming, fine-grained, iron-rich trachybasalt sill, probably with two branches. The other major units along the west side of the area are mostly ophitic olivine diabase and gabbro of various types; some have highly zeolitized roof zones.

This project was supported by the Minnesota Geological Survey with the cooperation of Reserve Mining Company and Klohn Leonoff Consultants, Ltd.

INITIAL PROGRESS AND INTERPRETATION OF
GEOLOGICAL MAPPING IN NORTHEASTERN WISCONSIN

J.K. Greenberg and B.A. Brown

Wisconsin Geological and Natural History Survey
Madison, Wisconsin

ABSTRACT

Initial results from reconnaissance-scale bedrock geological mapping in northeastern Wisconsin (an area bound by 45°N, 90°W and the state border) suggest the presence of four distinct tectonic regions separated by three major boundary structures which are best defined by their geophysical signatures. Available age data indicate that most, if not all, of the observed rock units are Middle Precambrian.

The three boundaries extend approximately east to west across the map area. The northern one is nearly parallel with and just north of the southern border of Vilas County and just south of the Wisconsin-Michigan border in Forest and Florence Counties. The central boundary extends from the northern border of Lincoln County in the west, across central Forest County, and through Amberg in eastern Marinette County. The southern boundary continues from northern Marathon County east-northeast through Merrill and across southern Forest County before swinging to the south along the eastern border of Oconto County.

The northernmost tectonic region consists of Michigamme and equivalent sedimentary rocks including iron formation and small volumes of volcanic rocks, all of a wide range in metamorphic grade. The next region to the south is separated from these rocks by the northern boundary, a complex series of fault zones. This region is characterized by isolated areas of migmatitic gneisses associated with foliated granitic intrusions. These areas of felsic rocks are surrounded on the north and east by predominantly mafic volcanic rocks, including the Quinnesec Formation, and are apparently truncated on the south by the central geologic boundary. However, late to post-kinematic plutons, ranging in composition from gabbro to granite, intrude both the regions to the north and south of the boundary. Much of the region immediately to the south is typical of a "greenstone" terrane composed of metavolcanic and metasedimentary rocks which are the hosts for major massive sulfide mineralization. The southern boundary between the greenstone terrane and rocks including the McCaslin Mountain Quartzite and Wolf River Batholith intrusives to the south is expressed, at least in part, as a major shear zone. All of the tectonic features in the map area will be better understood as future work extends mapping coverage to the west and south.

THE NATURE OF GREENALITE

Stephen Guggenheim, Department of Geology, University of Illinois at Chicago, Illinois, Peter Wilkes, Department of Metallurgical and Mineral Engineering, University of Wisconsin-Madison, and S. W. Bailey, Department of Geology and Geophysics, University of Wisconsin-Madison, Madison, Wisconsin

ABSTRACT

Pure samples of greenalite, including a single crystal, have made possible a more detailed structural characterization than before. All samples studied consist of an intimate intergrowth of a predominant trigonal phase and a minor monoclinic phase, even down to the smallest particles visible in the electron microscope. Specific polytypes cannot be assigned because of absence of the diagnostic $k \neq 3n$ reflections, but the mode of layer stacking differs in the two phases. The single crystal allows the sense of the axes to be established and leads to the conclusion that the monoclinic phase is in a fixed orientation relative to the trigonal host, but with inverted layers. Tetrahedral inversion is a known mechanism for relief of the lateral misfit anticipated due to a Si-rich tetrahedral sheet and a Fe^{2+} -rich octahedral sheet. As in antigorite, it causes elimination of octahedral cations and surface OH groups at the inversion loci, thus simulating an excess of Si upon conventional allocation of chemical analyses assuming a full complement of anions. Hexagonal arrays of satellite spots around sharp $k \neq 3n$ spectra on $hk0$ electron diffraction nets are interpreted as due to multiple diffraction caused by the coherent intergrowth of the monoclinic phase scattered as islands throughout the matrix of the trigonal host. The monoclinic phase is Mn^{2+} -rich and its abundance increases with Mn^{2+} content from greenalite through the species tosalite to caryophilite, the Mn^{2+} -analogue of greenalite, where the monoclinic phase is predominant and the trigonal phase is minor.

PETROLOGY AND GEOCHEMISTRY OF KEWEENAWAN DIABASE DIKES
ONTONAGON, GOGEBIC, IRON AND DICKINSON COUNTIES, MICHIGAN

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Keweenawan diabase dikes in Michigan's Upper Peninsula are being analyzed for major and selected trace element (Rb, Sr, Ba) concentrations and bulk mineral compositions. Specifically, techniques using the petrographic microscope, x-ray fluorescence, atomic absorption spectrographic analysis and the magnetometer are being used to accurately define mineralogical and chemical trends and magnetic character of the dikes. Sample distribution is spaced as uniformly as possible on a trend roughly perpendicular to the Keweenawan "rift trend". The dikes will be compared to other Keweenawan igneous units, specifically lower Keweenawan flows in the region (the Powdermill Group, formerly the South Trap Range). Correlation with chemical trends in more recent rift systems will be attempted.

The larger dikes are composed of subophitic plagioclase and pyroxene (augite and pigeonite). Opaque minerals are a minor, but ubiquitous, constituent. Interstitial minerals are orthoclase and quartz which occur locally as micropegmatitic intergrowths associated with needles of apatite. Some dikes are only slightly altered, being uralitized and chloritized, while others consist of 15-25% secondary minerals. In small dikes, mineral grains are microcrystalline to cryptocrystalline. The larger dikes have narrow chilled margins abruptly changing to phaneritic texture toward their centers.

STRUCTURAL INTERPRETATIONS IN THE HAZELWOOD
LAKE AREA, THUNDER BAY, ONTARIO

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ABSTRACT

The Hazelwood Lake area is underlain by Archean stratified sedimentary rocks and fragmental volcanic rocks.

Primary structures, particularly graded bedding, are well preserved in most outcrops. Pillow lava flows occur sporadically interlayered with agglomerates and tuffaceous units.

All rocks possess a well developed cleavage which appears parallel to the axial surface of observed minor folds in the sedimentary sequence.

Applying the technique of structural facing to the rocks gives the sense of younging of the folded stratigraphic succession.

Results from Hazelwood Lake indicate that a significant portion of the stratigraphic sequence was upside down prior to the last folding event in the area.

COEXISTING AMPHIBOLES AT BLACK RIVER FALLS, WISCONSIN

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ABSTRACT

Extensive outcrops of iron formation are present seven miles west of Black River Falls, Wisconsin. The dominant mineral assemblages in the iron formation are:

- 1) magnetite-quartz-grunerite-ferroactinolite
- 2) magnetite-quartz-cummingtonite-biotite
- 3) magnetite-quartz-garnet-hornblende-ferroactinolite-grunerite

The amphiboles in the iron formation are products of a metamorphic event which reached lower amphibolite facies. Coexisting amphiboles occur as discrete grains in contact with each other, as coarse intergrowths, or occasionally as 20-25 micron blebs of one amphibole in another. The amphiboles are not altered and not exsolved. Individual amphibole grains are homogeneous. Multiple electron microprobe analyses show that compositional variations are less than two percent.

The amphibole assemblage hornblende-ferroactinolite-grunerite is the only three amphibole assemblage found in the iron formation. In the presence of quartz this assemblage is invariant. The chemical formulas for these amphiboles are $(\text{Na},\text{K})_{.2}\text{Ca}_{.9}(\text{Mg},\text{Fe},\text{Al})_5\text{Si}_{7.5}\text{O}_{23}$ for the hornblende, $\text{Ca}_{1.9}\text{Mg}_{1.4}\text{Fe}_4\text{Si}_{7.8}\text{O}_{23}$ for the ferroactinolite and $(\text{Mg},\text{Fe})_{6.7}\text{Si}_{7.7}\text{O}_{23}$ for the grunerite.

Amphibole pairs are abundant and include:

grunerite-hornblende $\text{Mg}_{1.4}\text{Fe}_{5.7}\text{Si}_{7.7}\text{O}_{23} - (\text{Na},\text{K})_1\text{Ca}_{1.9}\text{Mg}_3\text{Fe}_{1.1}\text{Al}_{2.9}\text{Si}_5\text{O}_{23}$

grunerite-ferroactinolite $\text{Mg}_{1.8}\text{Fe}_{5.7}\text{Si}_{7.9}\text{O}_{23} - \text{Ca}_{1.9}\text{Mg}_{1.4}\text{Fe}_{3.9}\text{Si}_{7.8}\text{O}_{23}$

cummingtonite-gedrite $\text{Mg}_{4.8}\text{Fe}_{2.1}\text{Si}_{7.8}\text{Al}_{.4}\text{O}_{23} - \text{Mg}_{1.2}\text{Fe}_{4.7}\text{Al}_2\text{Si}_{5.6}\text{Al}_{1.5}\text{O}_{23}$

cummingtonite-actinolite $\text{Mg}_{3.7}\text{Fe}_{3.8}\text{Si}_{7.9}\text{O}_{23} - \text{Ca}_{1.9}\text{Mg}_{3.2}\text{Fe}_{1.5}\text{Si}_8\text{O}_{23}$

Ferroactinolite coexisting with grunerite has higher $Mg/Mg+Fe$ and $Ca/Mg+Fe$ ratios than ferroactinolite coexisting with grunerite and hornblende. Grunerite in the two phase assemblage has lower $Mg/Mg+Fe$ ratios and higher $Ca/Mg+Fe$ ratios than in the three phase assemblage. Cummingtonite coexisting with gedrite has higher $Mg/Mg+Fe$ and lower $Ca/Mg+Fe$ ratios than cummingtonite coexisting with actinolite.

The composition of the amphiboles is related to the chemistry of the rocks. The Fe-rich amphiboles occur in magnetite deficient sections of the iron formation. The Fe-poor amphiboles occur with magnetite. The Mg-rich amphiboles occur in a transition zone surrounding a talc schist.

PRELIMINARY RESULTS OF A TRUCK-MOUNTED MAGNETOMETER
SURVEY OF THE SOUTHWEST QUARTER OF THE
IRON RIVER 1°x2° QUADRANGLE, MICHIGAN AND WISCONSIN

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ABSTRACT

In August of 1978, the U.S. Geological Survey made a survey of the southwest quarter of the Iron River 1°x2° quadrangle, Mich.-Wis., using a truck-mounted magnetometer. This work, which is part of a mapping and resource-evaluation program in the Iron River quadrangle, was done over poorly exposed Proterozoic and Archean terrane, which is covered by a thick layer of glacial alluvium.

The survey consisted of nearly 470 miles of traverses generally oriented in a north-south direction. The traverses were done over selected unpaved forest roads to minimize the effects of heavy traffic and of steel in the roadbed. The system used a fluxgate magnetometer mounted on a boom on the top of the truck, and the variations in the total magnetic field were recorded in both analog and digital form.

The purpose of the survey was to augment existing aeromagnetic coverage, which was flown at a 1/2-mile line spacing and at an elevation of 500 ft. above the surface, with ground-level magnetic data to aid in detailed geologic interpretations. A number of domal uplifts have been both mapped and inferred from sharp linear magnetic anomalies that outline them. The Archean Precambrian gneisses in the cores of these domes have relatively low magnetic relief, as do the metasedimentary rocks of the overlying Michigamme Formation, and are not readily distinguishable on the aeromagnetic map. However, there are subtle differences in the magnetic signatures between the almost magnetically featureless Michigamme slates and the more variable gneissic rocks. These differences can be observed on the detailed ground magnetic profiles and permit more accurate interpretation of the aeromagnetic map.

The area has been cut by a complex system of faults having predominant northwest and northeast trends, some with considerable horizontal and vertical displacements, which are apparent from the magnetic pattern of the contoured aeromagnetic data and the ground profiles. The magnetic profiles also detect relatively low amplitude, sharp negative magnetic anomalies associated with a series of reversely magnetized Keweenaw diabase dikes striking approximately east.

CONTACT METAMORPHISM OF THE VIRGINIA FORMATION
MINNAMAX DEPOSIT, ST. LOUIS CO., MINNESOTA

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ABSTRACT

Calc-silicate bodies occur in the Virginia Formation and as xenoliths in metadiabase dikes near the contact with the base of the Duluth Complex in the Minnamax Deposit, St. Louis County, Minnesota. The rocks of the footwall have been metamorphosed to the pyroxene hornfels facies. Later sulfide mineralization is present in all metamorphic rocks.

The calc-silicate bodies are ellipsoidal to spherical and range in length from 4 inches to 4 feet. They are generally light gray and are fine to medium grained granofels. There are three types of bodies: (a) homogenous, (b) layered, with alternating layers of leucoxene or diopside, and (c) concentric showing at least two distinct mineral layers. The most common mineral assemblages are diopside and wallastonite with either grossularite or anorthite. Accessory minerals include ilmenite, sphene, and leucoxene. Later sulfide replacement occurs with chalcopyrite, exsolved cubanite, and minor magnetite. Associated with the sulfide mineralization is the development of poikiloblastic quartz, calcite, and apophyllite with minor anhydrite, fluorite, humite, and laumontite.

The Virginia Formation, a pelitic hornfels, and later metadiabase dikes look almost identical in hand sample. They are fine grained, massive, and dark gray. Relict bedding, when seen in the hornfels, is highly contorted and discontinuous. The hornfels consists dominantly of equigranular untwinned plagioclase, cordierite, and hypersthene with minor quartz, apatite, and graphite. Biotite and orthoclase occur locally. Black "reaction" rims exist for 3 inches into the hornfels when in contact with calc-silicate bodies. The rims consist of plagioclase, hypersthene, and poikiloblastic augite. The metadiabase dikes consist primarily of lathy labradorite with interstitial hypersthene and augite. Ilmenite, quartz, and apatite occur as accessory minerals. Sulfides in the hornfels consist of pyrrhotite with exsolved pentlandite, chalcopyrite, and minor magnetite and ilmenite. Sulfides in the metadiabase are restricted to fractures and are dominantly composed of pyrrhotite.

The calc-silicate bodies show metasomatic effects with a gain of aluminum and a loss of calcium. This is responsible for the formation of the "reaction" rims. Some of the bodies may be from the top of the Biwabik Iron Formation that were brought up by the intrusion of the Duluth Complex. The majority appear to have originated as concretions in the Virginia Formation. The sulfides and associated silicates are related to a later retrograde metamorphic event.

GEOLOGIC INTERPRETATION OF GRAVITY DATA IN THE
MARENISCO-WATERSMEET AREA, NORTHERN MICHIGAN

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ABSTRACT

Geophysical studies have been conducted in the western part of northern Michigan to aid in determining the geology of the tectonic zone marking the boundary between two Archean terranes recognized in the Lake Superior region; a greenstone-granite terrane on the north and a gneiss terrane on the south. A gravity map of the area having a 2 milligal contour interval was prepared using data from approximately 310 stations. The map includes gravity readings obtained along 3 profiles with 300 m station spacing to aid in interpretation of the data.

The gravity anomalies generally are in good agreement with the mapped geology. Pronounced lows coincide with the large pluton of Archean Puritan Quartz Monzonite west of Lake Gogebic and the Archean gneiss dome near Watersmeet. Small positive anomalies coincide with synclinal basins of the lower Proterozoic Coppins and Michigamme Formations and with magnetic anomalies interpreted as being caused by lean iron-formation and associated rocks. Amphibolitic layers in both the quartz monzonite and the gneiss also have positive gravity anomalies. A relatively steep (approximately 5 milligals per km) north-sloping gradient coincides with the inferred position of the boundary zone between the Archean greenstone and gneiss terranes.

A two-dimensional gravity model consistent with mapped geologic units and measured rock densities suggests that the synclinal basin within the greenstone terrane which involves the Coppins Formation is about 2.0 km deep, whereas the basin within the gneiss terrane which includes the Michigamme Formation may be approximately 3 km deep.

A north-sloping regional gravity gradient extrapolated from data outside the study area corresponds with the boundary zone between the two basement terranes and reflects an increase in density from north to south in rocks of the upper crust and perhaps also in the lower crust and/or upper mantle.

CROSS FOLDING IN THE PRECAMBRIAN X STRATA
OF THE EASTERN MARQUETTE TROUGH, MICHIGAN

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ABSTRACT

The Precambrian X Chocelay and Menominee Group strata in the eastern Marquette trough of Michigan show evidence of two episodes of deformation. The first and major deformation (D_1) folded the strata and formed vertical E-W slaty cleavage (S_1). The second, less intense deformation (D_2) locally formed cross folds of bedding and folded cleavage.

The major synclinal fold in the trough, termed the Marquette synclinorium, was formed by the D_1 deformation. Macroscopic D_1 folds are confined to the hinge region of this synclinorium (e.g., Harvey Quarry, Marquette). Minor D_1 fold axes plunge gently to the E or W in vertical E-W axial planes.

At two localities, the Enchantment Lake Formation along U.S. 41 in Negaunee and the Kona Formation in Sec. 32, T48N, R26W, Negaunee, the quartzose beds exhibit minor folds with steeply plunging axes, F_2 , and a vertical NW-SE axial plane, S_2 . These minor folds have an S-shaped profile and can be shown to deform S_1 . Similar features of minor folds can be observed in the Siamo Slate (northeast shore of Teal Lake), in the Mesnard Quartzite (shore of Lake Superior, Marquette), and in the Negaunee Iron Formation (New Richmond Mine, Palmer, and on Jasper Knob, Negaunee). These lithologies rarely develop cleavage so it is not possible to determine the sequence of folding directly. However, minor folds showing steeply plunging fold axes are thought to have been superimposed on the already steeply dipping limbs of the Marquette synclinorium. In addition, small intrafolial folds in bedding with an E-W axial surface and steep plunge can be seen on an island in Teal Lake and are attributed to the D_2 episode.

The major folds in the Marquette synclinorium exhibit a somewhat variable fold-axis orientation from south of west to north of west, as exhibited by the Goose Lake syncline and the folds associated with the Isabella syncline in the Palmer area. These major folds may be either refolded D_1 folds or both D_1 and D_2 folds. Absence of a pervasive slaty cleavage makes assignment difficult.

The sequence of events is consistent with a north-south compression to produce D_1 structures, followed by a NE-SW compression to form the D_2 structures. The NE-SW compression could be induced by a left-lateral strike-slip movement on the Marquette trough in the late stages of D_1 compression. Such displacement would be expected if the regional directions of shortening during D_1 were not precisely orthogonal to the trough.

It is interesting to note that the regional shortening represented by D_2 has a similar orientation to that represented by the folds in the Republic trough,

PETROLOGY OF THE TROCTOLITE-OLIVINE GABBRO SERIES, DULUTH GABBRO COMPLEX (LATE PRECAMBRIAN) NORTHEASTERN CRAMER QUADRANGLE, LAKE AND COOK COUNTIES, MINNESOTA

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As observed in the northeast quarter of the Cramer quadrangle, Minnesota, rock textures, the orientation of igneous laminations, systematic variations in modal abundances of minerals as well as the chemical composition of major minerals indicate that the troctolite-olivine gabbro series in the Duluth Gabbro Complex (Keweenawan) differentiated in situ as a result of crystal settling. Here, the troctolite-olivine gabbro series is exposed as a southwest-northeast trending band of outcrops approximately two km in width which lies between two distinct terrains. The area to the northwest is dominated by rocks of the anorthosite and felsic series while the area to the southeast contains flow units of the North Shore Volcanic Group.

The general orientation of igneous laminations (N60E, 15SE) within the troctolite-olivine gabbro series is interpreted to be the result of gravity settling, suggesting that the unit has tilted approximately 15 degrees toward the southeast since solidification. The general strike of the troctolite unit is parallel to a well defined lineament which occurs along the northwestern contact of the unit.

Textures of the troctolitic and gabbroic rocks indicate that, in general, plagioclase and olivine are cumulate, while pyroxenes and oxides are interstitial. Modal analyses show that rocks of troctolitic affinity (Pl - 70%; Cpx - 10%; Ol - 16%) are abundant along the northwest boundary (base?) while olivine gabbro (Pl - 68%; Cpx - 22%; Ol - 8%) is the most abundant lithology along the southeastern contact (top?). Interstitial ilmenite is the major oxide component and occurs as 1-1.5% of the rock unit.

Electron microscope analyses of plagioclase, olivine, and pyroxene mineral grains from rocks of the troctolite series vary nearly continuously and systematically in composition upward through the column. These compositional variations are: An₇₇ to An₅₈ (plag), Fo₇₀ to Fo₅₀ (Ol), and Wo₄₁ En₄₅ Fs₁₄ to Wo₃₈ En₃₆ Fs₂₆ (Cpx).

The bulk composition of the troctolite-olivine gabbro series as calculated from modal abundance data and individual mineral compositions suggests that the series could have been derived from a magma with a composition identical to that of the chilled margin of the Pigeon Point sill. The results of this investigation support the model proposed by Weiblen which indicates that units of the Duluth Complex (other than the anorthosite and felsic series) have been derived from a late stage, high-Al magma, the composition of which is compatible with the Pigeon Point sill.

GEOLOGY OF THE DULUTH COMPLEX-VIRGINIA FORMATION CONTACT
MINNAMAX DEPOSIT, MINNESOTA

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The Minnamax Deposit, near Babbitt, Minnesota, is a large, low-grade deposit of iron-copper-nickel sulfides at the contact of the Duluth Complex and the Virginia Formation. Mineralization is primarily disseminated in troctolitic rocks of the Duluth Complex, and is locally massive at the contact and in the immediately adjacent Virginia Formation.

In the Minnamax test shaft area, the contact dips 0 to 35 degrees SE and is highly irregular. Apophyses of the Duluth Complex intrude the underlying Virginia Formation and xenoliths of the Virginia Formation, ranging upwards of 150 feet in dimension, occur in the complex. The Virginia Formation consists primarily of argillic hornfels with abundant calc-silicate concretions. Minor lithologies include graphite schist, biotite schist, and calcareous argillic hornfels. Bedding, where visible, can only be traced for a few feet and is locally contorted; concretions appear randomly oriented. Metadiabase dikes and sills, metamorphosed by the Duluth Complex, occur in the Virginia Formation. The Duluth Complex consists primarily of a mineralized phase which is characteristically troctolitic. Near the contact it is commonly noritic. Here it contains cumulus plagioclase and intercumulus hypersthene, olivine, and augite, and is highly variable in composition, texture, and sulfide content. Sulfides are primarily interstitial to silicates. Xenoliths of an unmineralized phase, ranging upwards of 100 feet in dimension, occur in the mineralized phase. These xenoliths range in composition from olivine gabbro to feldspathic peridotite, and are characterized by cumulus olivine and plagioclase. Fractures and breccia zones, both in the Virginia Formation and the Duluth Complex, commonly contain massive sulfides and granitic veins and veinlets. Sulfides locally replace hornfels, particularly at the Duluth Complex contact.

Field relationships and petrography indicate that the Virginia Formation was highly deformed and metamorphosed to pyroxene hornfels facies by the Duluth Complex. The common pelitic mineral assemblage of plagioclase-hypersthene-cordierite suggests substantial loss of SiO_2 , Na_2O , K_2O , and H_2O from the Virginia Formation (Bonnichsen, 1971). These constituents contaminated the base of the mineralized phase of the complex. Granitic vein material may have formed from a residual fluid of the mineralized phase, or by direct partial melting of the Virginia Formation. Recognition of unmineralized metadiabase dikes and sills in the Virginia Formation explains many complexities in the petrology, structure, and mineralization of the contact zone. Massive sulfides appear to have formed by: 1) migration of a sulfide-rich fluid into and along fractures, and 2) local replacement of the Virginia Formation.

MINERAL SURVEY AND MINERAL POTENTIAL
OF COOK COUNTY, MINNESOTA

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ABSTRACT

This study was conducted to obtain and compile information on the mineral potential of Cook County, Minnesota. This information will be used to assist the Minnesota Department of Natural Resources (MDNR) in making land management decisions in relation to mineral lands it administers and to provide information which may lead to further leasing and exploration of MDNR administered lands.

The study included various information gathering activities. Initially, a literature survey was conducted to determine the existence and location of reported economic mineral occurrences. This was followed by a field examination, during which outcrop samples were collected for assay and microscopic study in order to determine the nature and extent of mineralization and the host rock geology. A compendium was prepared on past mineral exploration activity in Cook County; it includes available drill logs and assays, geologic, geophysical, and geochemical data. In some cases, where drill logs and assays were not available, the cores were logged and assayed. An organic-rich lake sediment exploration geochemical reconnaissance survey was conducted concurrently with the field examination of mineral occurrences.

A report is in preparation which will contain all information derived from this study. It also describes the various models which were used in determining the mineral potential of the area. These models are based on economic mineral occurrences found in Minnesota and in similar geologic environments in other parts of the world.

Results of this study indicate that significant vanadium concentrations exist in titaniferous magnetite deposits occurring within the Duluth Complex. Disseminated low grade Cu-Ni mineralization also occurs in the more mafic units of the Duluth Complex. Ag-Cu-Zn fissure-vein mineralization occurs in the Rove Formation where the Rove is intruded by Logan sills. The lake sediment geochemical survey indicates anomalous values in certain areas which have potential for economic mineralization.

This survey did not include the Boundary Waters Canoe Area (BWCA); however, some of the highest mineral potential areas in Cook County were added to the BWCA after the field surveys were completed.

PALEOSTRAIN ANALYSIS ACROSS A "SHEAR ZONE",
NORTHWESTERN MARATHON COUNTY, WISCONSIN

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ABSTRACT

The boundary between two major northeast trending Precambrian terranes (superbelts?) is structurally concordant with geological units which trend approximately 75° through Athens, Wisconsin in northwestern Marathon County. This belt or "shear" zone, 0.75 to 4 km in width, generally, though not uniquely, separates gneissic amphibolites of the Chippewa Amphibolite Complex (Archean?) to the north from volcano-plutonic (greenstone-granite units (PG x?) on the south.

Foliations within the host rock strike $50-70^{\circ}$ and dip $50-75^{\circ}$ N while lineations trend $230-250^{\circ}$, and plunge $65-75^{\circ}$. The zone itself has gradational boundaries and is composed of cataclasized equivalent greenstone and amphibolite units showing mortar texture, feldspathic porphyroclasts, comminution and fluxion structure, and varying degrees of recrystallization. Discrete fault planes have also been recognized within the zone.

Paleostrain analysis was carried out on samples from each host unit at distances up to 9 km from the shear zone as well as on samples located within the zone itself. At least 50 strain indicators, usually deformed mineral grains or volcanic fragments, were measured from 3 sets of orthogonal faces cut on each sample as well as the angle relative to the principal directions (foliation, lineation and right angles to both) in the rock parallel to which cuts were made. Strain was analyzed using the methods of Ramsay (R_f/θ), Elliott's polar plot and the Hsu plot. A best fit strain ellipsoid was calculated for each sample using the Pase 5 program of Siddans. Error limits on the dimension and orientation of the best fit strain ellipsoid and its orientation were calculated at less than 2 percent for each sample.

Results indicate that both the gneiss and volcano-plutonic regimes are characterized by a flattened fabric ($V=+0.16, 0.19, 0.3$; $K=0.4$) with generally low strain values ($\epsilon_s=0.75, 1.29, 0.5$). As the shear zone is approached, a strong linear fabric ($V=-0.5$; $K=2.4$) is developed which is generally one order of magnitude greater in ϵ_s value than is flattening in the host rocks. This linear fabric cannot have developed from simple shear alone. The lineation appears to have developed as a result of ductile deformation which, though regional in scope, appears localized along the zone. A strong vertical stress component appears consistent with the strain pattern.

POLYPHASE DEFORMATION OF ARCHEAN ROCKS
AT RAINY LAKE, ONTARIO

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ABSTRACT

The Archean geology of the Rainy Lake area has been the subject of considerable study for nearly a century. A.C. Lawson mapped the region (1888, 1913) and interpreted the stratigraphy. He placed a sequence of metasedimentary biotite schists (the Coutchiching Group) beneath a sequence of metavolcanic schists (the Keewatin Group). He further recognized a second sequence of largely conglomeratic metasedimentary rocks (the Seine Group) which he placed unconformably above the Keewatin. Various workers have re-studied the area applying the techniques of a number of geological subdisciplines. Some have disputed the existence of the Coutchiching Group and have placed it above the Keewatin as a lateral equivalent of the Seine Group. Others have upheld Lawson's original interpretation and the conflicting points of view have become referred to as the Seine-Coutchiching problem. The present study re-examines the significance of the Keewatin-Coutchiching boundary in light of detailed structural investigation of two type localities.

At Rice Bay, lithological mapping and geometric analysis of fabric elements reveals the presence of a major antiform with moderate plunge. Observed younging information (graded bedding and pillow shapes) does not conform to this simple interpretation and part of the sequence is recognized as having a downward structural facing with respect to the major fold closure. This implies that the sequence was overturned by an episode of folding (F_1) which predated the development of the major closure (F_2).

At Bear Passage, structural elements similar to those at Rice Bay are exposed. Fold axes (F_2) and axial surfaces (S_2) no longer have systematic orientations, however, and appear to be complexly redistributed due to the intrusion of a quartz monzonite pluton. The crest of this pluton conforms to a broadly antiformal structure (F_3). The rocks of the Bear Passage area are transected by a penetrative crenulation cleavage S_4 which is axial planar to minor folds (F_4). While simple stratigraphic interpretations are precluded by this polyphase deformation, a key exposure at the Keewatin-Coutchiching contact reveals the presence of structurally overturned strata. These strata appear to have a downward structural facing with respect to each of the observed fold phases and hence overturning is assigned to F_1 .

The documentation of polyphase deformation in the Rainy Lake area makes clear the reason for previous conflicting stratigraphic interpretations. The recognition of structurally overturned strata favours the stratigraphic superposition of the Coutchiching upon the Keewatin. Fold nappes (F_1) may have been responsible for inverting part of the sequence. It is not clear whether this and subsequent deformations were unique events or merely progressive episodes in a continuous sequence of deformation.

THE PRECAMBRIAN BASEMENT OF NORTH DAKOTA

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ABSTRACT

Information on the Precambrian basement of North Dakota is based on cores and cuttings from 132 drilling tests (Lidiak, unpublished; Muehlberger and others, 1967; Moore, unpublished), 11 age determinations (Peterman and Hedge, 1964), geophysical data and correlation with surrounding areas of exposure. The North Dakota Precambrian consists of several types of Archean Superior Province and possibly younger terranes in the east, often with deep weathering profiles, and much less well known terranes in the west, including younger rocks, possibly a southern extension of the Churchill Province. The Williston basin, centered in northwestern North Dakota, is the dominant structural feature that determines the depth to the Precambrian. From a depth of approximately 200 m in eastern North Dakota, the Precambrian surface slopes 8 m/km to a depth of 5100 m in the west. The distribution of radiometric age dates and a pronounced break in the trend of geophysical features suggests that the Superior/Churchill Provincial boundary transects central North Dakota.

The Precambrian basement of eastern North Dakota has been divided into five terranes based on predominant petrographic character and regional gravity features (Lidiak, unpublished). Amphibole schist terrane is characterized by belts of low and medium grade metamorphic rocks with associated gravity highs. The predominant rock types are actinolite and hornblende schists with occurrences of retrogressive quartz-biotite-feldspar gneiss, serpentinite, stretched lithic lapilli tuff, massive and porphyritic basalt and banded iron iron formation. The Ramsey gneiss terrane consists of silicic to intermediate rocks with a persistent gneissic fabric. The characteristic lithology is layered gneiss metamorphosed to amphibolite facies and fine- to medium-grained gneiss with subordinate foliated plutonic rocks. The remaining three terranes are characterized by silicic to intermediate massive plutonic rocks with associated gravity lows of gentle gradient and are distinguished by location. The Grand Forks plutonic terrane (east-central), McIntosh granite terrane (southeast), and Towner granite terrane (north-central) all contain occurrences of amphibolite facies gneiss. The generalized pattern of large plutonic areas within gneissic terranes and intervening greenstone belts is consistent with the exposed Archean rocks to the northeast.

New information on the Precambrian of eastern North Dakota was added by the Red River Valley drilling program of 1977 (Moore, unpublished) which provided 26 cores. Preliminary petrographic results suggest that the concept of the amphibole schist terrane be retained and the distinction of the remaining terranes on the basis of rock fabric be abandoned. Amphibole schist terrane is characterized by low to medium grade metasedimentary and metavolcanic rocks and was penetrated by seven cores which included the following rock types; pillowed basalt, porphyritic basalt, stretched lithic lapilli tuff, mica schist, talc-chlorite schist, phyllite (with graded beds), and meta-graywacke. The remaining cores penetrated fine- to coarse-grained igneous rocks, gneiss, and

banded gneiss. The interpretation of the dominant igneous character of the Grand Forks plutonic terrane is revised by the occurrence of rocks with a gneissic-migmatitic fabric in six of seven cores. Accordingly, the distinction of the remaining terranes by predominant fabric may be misleading and will be eliminated. Subdivision of these gneissic and plutonic terranes is being attempted on the basis of rock chemistry and petrographic character.

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PINK AND GREEN ALBITE PHENOCRYSTS FROM THE MOHAWK
MINE, MICHIGAN - INDICATORS OF CHANGES IN HYDROTHERMAL FLUIDS

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ABSTRACT

Albite phenocrysts with green rims and pink interiors are present in samples of altered basalt taken from the Mohawk mine and known to be present in Ahmeek #3 and #4 mines. In the collected samples, phenocrysts are 5-20 mm long and 1-10 mm wide. Some of the smaller phenocrysts are green only.

Microscopically, the green portion consists primarily of pumpellyite with some white to light green remnant albite. Some of the pumpellyite extends into the pink interiors which are predominantly albite with an abundance of sericite as an alteration product. Under high power, small amounts of red iron oxide are apparent in the phenocryst interior, appearing as clouds or clots of dust-like particles. Albite twin lamellae are continuous through the green and pink portions of the phenocrysts although masked by alteration in the pink portion. Flat stage extinction angle measurements on albite twins suggest a composition of about An_5 .

X-ray diffraction analysis of the phenocrysts verifies the mixture of albite and pumpellyite in the green rims, with albite showing up as the only phase of the pink interiors. Structural differences between the pink and green albite were not detected.

Electron microprobe analyses show pumpellyite compositions in green and pink portions to be identical with total iron, calculated as FeO , about 5%. Albite compositions are near An_0 with no difference in major element composition between pink and green albite with the exception of a range of K (0-3% K_2O) in pink albite. The distribution of K suggests its presence in alteration products. Measurement of minor Mg and Fe concentrations in albite revealed that incipient pumpellyitization is common. But only pink albite showed minor Fe (up to 0.7% Fe_2O_3) unaccompanied by Mg, consistent with the red iron oxide microscopically observed as a possible source of the pink coloring.

Because pumpellyite cross-cuts albite, pumpellyite is assumed to be paragenetically later than albite. The distribution of sericite suggests control by the original calcic interior of plagioclase. But whether sericitization preceded or was contemporaneous with albitization is unclear. At least two stages of alteration by hydrothermal fluids of different composition and/or conditions are inferred.

STRATIGRAPHY OF THE GUNFLINT FORMATION, KAKABEKA FALLS AREA, ONTARIO

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ABSTRACT

A total of ten stratigraphic sections of the Gunflint Formation have been measured over a lateral distance of 3.6 kilometers in the Kaministiquia River gorge. From the study, a composite section 57 m thick was found to contain six distinct lithostratigraphic members. These members are, in ascending order: 1. basal member (3 meters) composed of conglomerate, quartzite, stromatolites, taconite or pyritic, black chert-carbonate; 2. lower shale member (7 meters) composed of fissile carbonaceous shale; 3. lapilli member (4 meters) composed of felsic quartz-feldspar lapilli-tuffs; 4. middle shale member (22 meters) composed of fissile carbonaceous shale; 5. chert-carbonate member (11 meters) composed of alternating layers and lenses of chert and siderite; 6. upper shale member (at least 10 meters; top not exposed) composed of fissile carbonaceous shale. The composite section therefore contains 70% fissile carbonaceous shale, 20% chert-carbonate, 7% lapilli-tuff and 3% diverse lithologies of the basal member.

Primary sedimentary structures are well preserved in the various strata. Well rounded, well sorted sand grains in the basal quartzites, in association with taconites and stromatolite mounds suggest a shallow, littoral environment. The presence of accretionary mudball lapilli, graded ash-fall tuffs and large scale crossbedding in the lapilli-tuffs indicate subaerial derivation and shallow water reworking and deposition. Dessication features and soft sediment slumpage and brecciation occur within chert carbonate layers and lenses. The lenticular geometry of chert carbonate beds as well as their intimate interlayered relationships with ripple-marked, and mud-cracked carbonaceous shales suggest a shallow water origin for both of these lithologies. The entire stratigraphic section is therefore considered to have been deposited in a shallow water environment at the margin of a large restricted basin.

NEW EVIDENCE ON THE STRATIGRAPHY AND STRUCTURE OF THE SOUDAN AREA,
WESTERN VERMILION DISTRICT, MINNESOTA

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ABSTRACT

Recent geologic mapping southeast of Soudan, Minnesota at scale 1:24,000 has further clarified the stratigraphy and structure of the western Vermilion district. Numerous top-indicators confirm the major structure of the area to be a broad, steep-limbed, southward-overtaken anticlinorium, the axial trace of which trends about N.70° W. The core of the anticlinorium is metabasalt belonging to the lower member of the Ely Greenstone. On the upright north limb of the fold, the stratigraphic succession above the lower member is as follows: Soudan Iron-formation Member of Ely Greenstone, upper member of Ely Greenstone, and Lake Vermilion Formation. Although the Soudan Member is characterized by the presence of cherty iron-formation, its internal stratigraphy is complex and more than half of it is composed of volcanic and volcanoclastic rocks. Felsic volcanic and volcanogenic sedimentary rocks of the Lake Vermilion Formation rest directly on the Soudan Member in the Soudan quadrangle, but pinch out toward the east beneath a tongue of pillow breccia, mafic aquagene tuff, iron-formation, and pillowed metabasalt belonging to the upper member of the Ely Greenstone. The iron-formation at Jasper Peak is a lenticular body within the lower Ely member; it is stratigraphically beneath the Soudan Iron-formation Member.

The stratigraphy of the overturned south limb of the anticlinorium is as follows: lower member of Ely Greenstone, member of Ely Greenstone near Two Rivers, upper member of Ely Greenstone, and Lake Vermilion Formation. The member near Two Rivers is a heterogeneous sequence of pillowed basalt, basalt tuff, felsic porphyry, felsic tuff, and cherty iron-formation that appears to be slightly below the stratigraphic position of the Soudan Iron-formation Member and does not connect with it.

The lower and upper members of the Ely Greenstone are distinct in terms of primary structures, textures, and bulk chemical compositions (Schulz, 1977). The lower member consists chiefly of calc-alkaline basalt in the form of massive and pillowed flows; the pillows typically are irregular in size and shape and are highly amygdaloidal, indicating deposition in shallow water. The upper member is chiefly tholeiitic basalt in the form of pillowed flows. The pillows are regular in size and shape and are generally non-amygdaloidal, indicating deposition in deep water.

The stratigraphic record clearly indicates a highly mobile volcanotectonic environment that may have been analogous on a smaller scale to the modern volcanic arc and back-arc basin.

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GEOCHEMICAL AND GEOPHYSICAL ANOMALIES
ASSOCIATED WITH THE BEAR LAKE INTRUSIVE,
SECTIONS 24 AND 25, T56N, R34W, HOUGHTON COUNTY, MICHIGAN

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ABSTRACT

The Bear Lake Intrusive is a nearly circular felsic igneous body which appears to have intruded the Freda Sandstone. The body is roughly 1.3 km in diameter and is located about 11.2 km (7 miles) north of the city of Hancock, Michigan.

The work at the Bear Lake body was part of a larger investigation that was designed to test a model based upon the copper sulfide mineralization at Mt. Bohemia (Section 29, T58N, R29W, Keweenaw Co., Michigan). Basically, the model suggests that several, isolated intrusive/extrusive bodies of Keweenawan age distributed throughout the Keweenaw Peninsula may represent exploration targets for copper sulfide mineralization. Both the soil geochemistry and the ground geophysics tend to support this idea at the Bear Lake body.

The results of the field mapping, geochemistry and geophysics indicate the following:

1. The predominantly felsic body displays an easily recognizable magnetic signature.
2. There are two relatively strong conductors (VFL-EM) associated with the body.
3. The body has potassic rock chemistry, averaging 6.43% K_2O , with a high $K_2O : Na_2O$ ratio averaging 3.4.
4. Trace element analyses indicate that the copper values for the felsic body average 190 ppm which is anomalous when compared to the published averages for that rock type (15-30ppm).
5. The results of a soil geochemistry survey indicate a pattern of anomalous copper values that appears to be associated with the location of the VLF-EM conductors.

Although the development of a model or "type" deposit based upon the Mt. Bohemia copper sulfide mineralization is still in its early stages, we hope that further rock chemistry studies as well as geophysical and case history studies from several other known areas of similar copper sulfide mineralization will confirm or refute the idea that Michigan's Copper Country may have another type of mineralization for which to explore in addition to the native copper and White Pine-type copper settings.

DOE-BENDIX-MICHIGAN GEOLOGICAL SURVEY DIAMOND-DRILLING
FOR GEOLOGIC INFORMATION IN MARQUETTE AND IRON COUNTIES, MICHIGAN

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ABSTRACT

Many Precambrian X argillites and slates are carbonaceous and pyritic, and some contain pyrrhotite, chalcopyrite, sphalerite, and galena. Precambrian W metabasalt (1059-1148') at DL-5 contains strata-bound sulfides with 130-2010 ppm Cu and 20-50 ppb Au. Maximum uranium content in holes occurs in a 2"-thick conglomerate at 3011' at DL-4, with 130 ppm U (nitric/perchloric) or 260 ppm U (hydrofluoric/nitric/perchloric acid digestion). Precambrian W metarhyolite at DL-5 (997-1059') with 72-76 ppm U is a possible source rock for uranium in Precambrian X strata.

In Marquette County, age Y diabase dikes and minor gravity faults appear in two orientations: 1) E-W, vertical, and 2) parallel to SW-dipping Precambrian X slaty cleavage. Such E-W vertical faults at DL-1 and DL-7 have downthrown north sides; SW-dipping faults at DL-3, DL-5, and DL-4 have downthrown SW sides, suggesting the possibility of age Y horst and graben structure in the region, in harmony with Cannon's north-south tension enunciated at 1978 Institute on Lake Superior Geology. Epigenetic sulfide remobilization in Precambrian X rocks appears to be structurally related to the post-Penokean faulting, which drags slaty cleavage as well as bedding. Lower dip of Penokean slaty cleavage at DL-5 is thought to reflect post-Penokean rotation of Clark Creek block.

DL-1: NW $\frac{1}{4}$, SW $\frac{1}{4}$, Section 5, T 50N, R 28W, East Baraga Basin, Marquette County
 DL-3: NW $\frac{1}{4}$, NW $\frac{1}{4}$, Section 14, T 50N, R 29W, East Baraga Basin, Marquette County
 DL-7: SW $\frac{1}{4}$, NE $\frac{1}{4}$, Section 4, T 50N, R 28W, East Baraga Basin, Marquette County
 DL-5: NW $\frac{1}{4}$, SE $\frac{1}{4}$, Section 16, T 49N, R 27W, Clark Creek Basin, Marquette County
 DL-4: NW $\frac{1}{4}$, NE $\frac{1}{4}$, Section 2, T 48N, R 28W, Dead River Basin, Marquette County
 DL-6: NE $\frac{1}{4}$, NE $\frac{1}{4}$, Section 30, T 46N, R 33W, NW of Amasa Oval, Iron County

Hole number	DL-1	DL-3	DL-7	DL-5	DL-4	DL-6
Terminal depth.....	2148'	1634'	697'	1148'	3176'	1093'
Maximum deviation from vertical.....	56 $\frac{1}{2}$ °	44°	14 $\frac{1}{2}$ °	3°	12°	4 $\frac{1}{2}$ °
Overburden.....	0-71'	0-163'	0-243'	0-320'	0-76'	0-236'
Age Y diabase.....	---	1545-1551'	---	523-602'	2286-2358' 2825-2827'	---
Age X strata						
Dip of bedding.....	30°SE- 3°NW	20°NE- 60°SW O.T.	5°-70°SW	15°-45°SW	5°-40°NE	55°S- vertical
Dip of cleavage.....	37°-65°SW	40°-55°SW	37°-65°SW	20°-40°SW	35°-65°SW	65°N
(Argillite, slate, ...	71-2148'	163-1634'	243-569'	320-523'	76-2966'	---
(turbidite, marble, (algal stromatolite Cherty carbonate,...)	---	---	569-659'	660-714'	2966-3019'	
clastics, algal)						
stromatolite,)						?
"iron-formation")						)
(Argillite and	---	---	---	714-884'	---	) 236-1903'
(graywacke						?
Quartzite.....	---	---	---	884-997'	3019-3119'	---
Age W basement.....	---	---	659-697' granite	997-1059' meta- rhyolite 1059-1148' meta- basalt	3119-3176' tonalite	---
Shallowest phosphate.....	---	---	490'	514'	2810'	421'

PALMER GNEISS UPDATE

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ABSTRACT

The Palmer Gneiss is somewhat of a misnomer for an Early Precambrian formational unit composed primarily of quartz chlorite-sericite schists. The unit contains thin beds of orthoquartzite and slate, along with a typical Archean magnetite/pyrite chert iron-formation. The gneiss has been intruded by granite with small amounts of calcite, ankerite, pyrite and chalcopyrite. The preference of the intrusive granites for foliation planes indicates deformation prior to the granitic episode.

In Sections 25, 26 and 27, T47N, R27W, the northern limit of the Palmer Gneiss is the east-west Palmer Fault that dips fairly uniformly at 58° to the north. The gneiss is in direct contact with the middle and upper portions of the Negaunee Iron-Formation. Both the Palmer Gneiss and the Negaunee Iron-Formation have been offset by northwest-trending near-vertical faults. The southern terminus of the Palmer Gneiss is gradational into the pegmatitic granite. Assimilation of the Palmer Gneiss into granite has produced compositional variations that make determination of the original rock extremely difficult. The Palmer Gneiss contains numerous east-west vertical faults that further confuse the lithologic sequence.

The foliation trends N 70° - 80° W with northerly attitudes varying between 35° to 85° . Where bedding was observed, the trending was N 72° W with a northeasterly dip of 61° .

The Palmer Gneiss is a Lower Precambrian meta-sedimentary sequence that has been intruded by Lower Precambrian pegmatitic granite whose abundance progressively increases to the south. Assimilations and post-intrusion shearing have caused extensive silicification, carbonization and sericitization.

STRUCTURAL GEOLOGY OF AMPHIBOLITIC GNEISSES,
NORTHEAST CHIPPEWA COUNTY, WISCONSIN

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ABSTRACT

Precambrian amphibolites, hornblende schists and intrusive units are exposed along the Chippewa and Fisher rivers near Holcombe, Wisconsin. These rock formations occur near the northern boundary of the Chippewa Amphibolite Complex and are judged to be Archean (?) in age. Exposures of the rocks were investigated in order to determine the stages of deformation and their relative ages.

The major rock units in the area are quartz-biotite amphibolite at Holcombe dam, and interbanded amphibolite gneiss and tonalite along the Fisher River. Intrusives into the quartz-biotite amphibolite include coarse grained granodiorite and associated dikes, and a hypabyssal andesite intrusive. The two amphibolite units are separated by a zone of mylonite at least 300 m wide.

Banded gneiss along the Fisher River displays three periods of folding. An early phase of deformation, F_1 , produced isoclinal folds in tonalite banding and a mineral lineation in zones of amphibolite. A penetrative axial planar foliation, S_1 , trending east-west was also produced. During F_1 deformation, ptygmatic folds formed in response to the development of closely spaced S_1 foliation. During a later deformation, F_2 , large folds, possibly isoclinal, refolded earlier mineral lineations and minor fold axis lineations along a great circle distribution. The axial planes of F_1 and F_2 are believed to be coplanar. A third fold deformation, F_3 , produced broad, open folds with north-south axial planes at a high angle to earlier fold axes.

At Holcombe dam the first and third fold deformations can be observed in the quartz-biotite amphibolite. Late synkinematic granitic intrusives show a faint foliation parallel to S_1 . The hypabyssal andesite intrusive exhibits a strong, steeply-plunging lineation and a faint foliation which also parallels S_1 .

The quartz-biotite amphibolite was later converted to hornblende schist along a shear zone which is exposed along the Chippewa River. A penetrative lineation plunges moderately to the west. Late movements along the zone formed small pods of brecciated mylonite along foliation planes.

All the rocks in the area were crosscut by a series of closely-spaced, steeply-dipping faults. Strike separation along the faults is dominantly right lateral, and offset does not exceed ten feet.