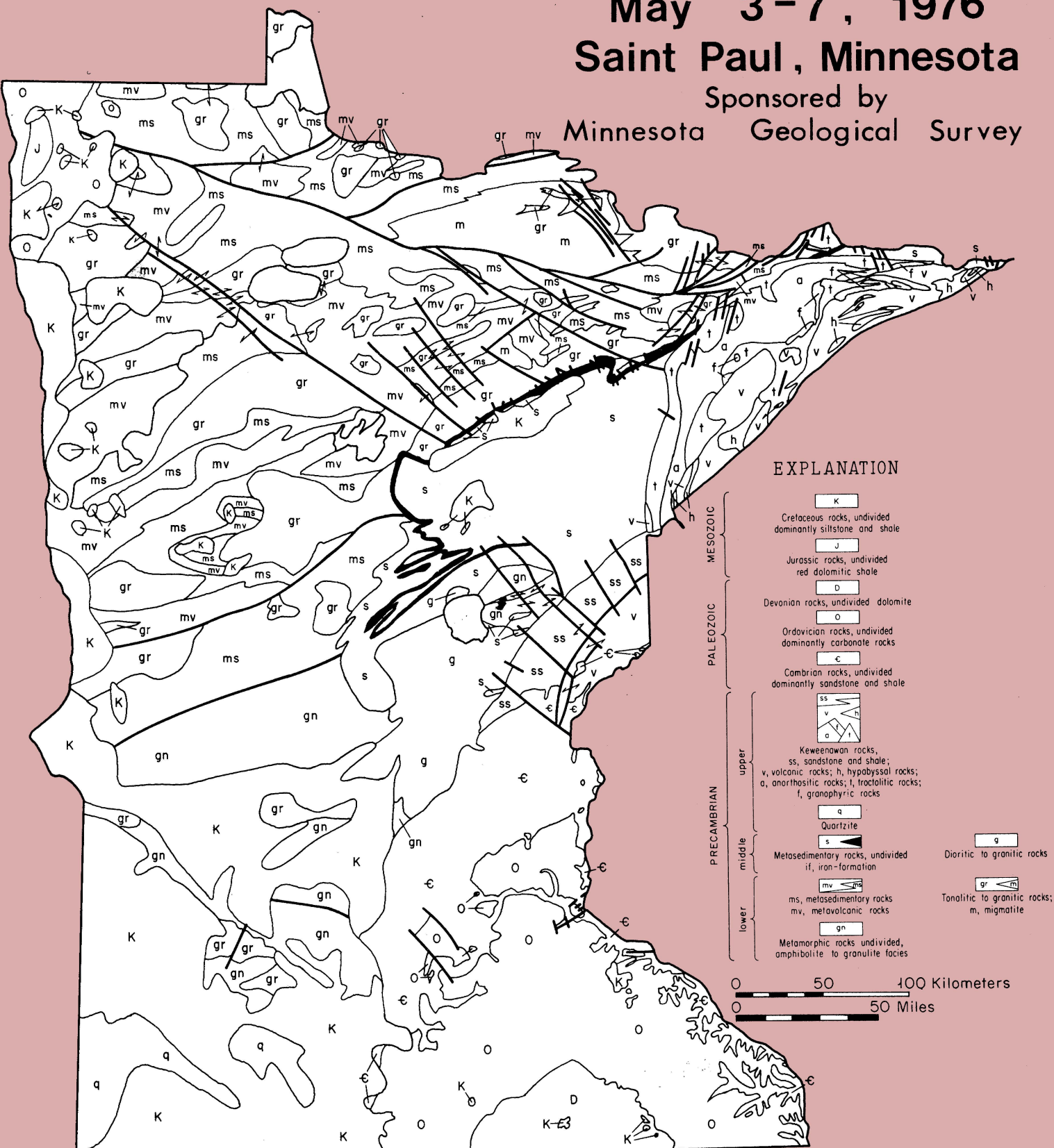


Twenty Second Annual Institute on Lake Superior Geology

May 3-7, 1976
Saint Paul, Minnesota

Sponsored by
Minnesota Geological Survey



PROCEEDINGS
TWENTY - SECOND ANNUAL
INSTITUTE ON LAKE SUPERIOR
GEOLOGY

held at

RADISSON ST. PAUL

11 East Kellogg Boulevard

St. Paul, Minnesota 55101

May 3-7, 1976

under the sponsorship of

Minnesota Geological Survey

 University of Minnesota

1633 Eustis Street

St. Paul, Minnesota 55108

G.B. Morey and R.F. Beltrame

General Editors



SALES

Please order from: Publications Sales, Minnesota Geological Survey, 1633 Eustis St., St. Paul, Minnesota 55108. Price \$5.00 (U.S.), plus 4% sales tax where applicable. Make checks payable to Minnesota Geological Survey.

Printed at:

University of Minnesota

Minneapolis, Minnesota 55455

TABLE OF CONTENTS

GENERAL INFORMATION	v
INSTITUTE BOARD OF DIRECTORS	v
LOCAL COMMITTEE	vi
SESSIONS CHAIRMEN	vii
ANNUAL BANQUET SPEAKER	vii
ACKNOWLEDGEMENTS	vii
CALENDAR OF EVENTS AND PROGRAM	viii
ABSTRACTS	3
FIELD TRIPS	71
A. MINNESOTA RIVER VALLEY FIELD CONFERENCE	73
B. ENGINEERING AND PLEISTOCENE GEOLOGY IN THE TWIN CITIES AREA	75

GENERAL INFORMATION

22nd Annual

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Radisson St. Paul

St. Paul, Minnesota 55101

May 3-7, 1976

Sponsored by

Minnesota Geological Survey

University of Minnesota

1633 Eustis

St. Paul, Minnesota 55108

INSTITUTE BOARD OF DIRECTORS

P.E. Giblin, Ontario Division of Mines, Ministry of Natural Resources, Sault Ste. Marie, Ontario

J.D. Hughes, Department of Geography, Earth Science and Conservation, Northern Michigan University, Marquette, Michigan

M.E. Ostrom, Wisconsin Geological and Natural History Survey, Madison, Wisconsin

*R.C. Reed (Secretary-Treasurer), Geological Survey Division, Department of Natural Resources, Lansing, Michigan

M.S. Walton, Minnesota Geological Survey, University of Minnesota, St. Paul, Minnesota

*Permanent Member

LOCAL COMMITTEE

Conference Chairman

Matt Walton, Minnesota Geological Survey, University of Minnesota, 1633
Eustis St., St. Paul, Minnesota 55108

Technical Program

G.B. Morey, Minnesota Geological Survey, University of Minnesota, 1633
Eustis St., St. Paul, Minnesota 55108

P.W. Weiblen, Department of Geology and Geophysics, University of Minnesota,
Minneapolis, Minnesota 55455

Field Trips

Stanley E. Chernicoff, Department of Geology and Geophysics, University
of Minnesota, Minneapolis, Minnesota 55455

S.S. Goldich, Department of Geology, Northern Illinois University, DeKalb, Illinois
60115

G.B. Morey, Minnesota Geological Survey, University of Minnesota, St. Paul,
Minnesota 55108

V.R. Murthy, Department of Geology and Geophysics, University of Minnesota,
Minneapolis, Minnesota 55455

C.R. Nelson, Department of Civil and Mineral Engineering, University of
Minnesota, Minneapolis, Minnesota 55455

D.H. Yardley, Department of Civil and Mineral Engineering, University
of Minnesota, Minneapolis, Minnesota 55455

Physical Arrangements

Gordon J. Amundson, Department of Conferences, Nolte Center for Continuing
Education, University of Minnesota, Minneapolis, Minnesota 55455

SESSION CHAIRMEN

D.M. Davidson, Jr., Department of Geology, University of Minnesota, Duluth,
Duluth, Minnesota 55802

S.S. Goldich, Department of Geology, University of Northern Illinois, DeKalb,
Illinois 60115

Clare Goldsmith, Geology Department, 3M, Bldg. 526-2, St. Paul, Minnesota.

Alan M. Goodwin, Department of Geology, University of Toronto, Toronto,
Ontario, Canada.

J.C. Green, Department of Geology, University of Minnesota, Duluth, Duluth, Minnesota 55802

R.W. Marsden, Department of Geology, University of Minnesota, Duluth, Duluth, Minnesota 55802

Z.E. Peterman, U.S. Geological Survey, Denver, Colorado 80225

F.J. Sawkins, Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota 55455

P.W. Weiblen, Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota 55455

D.M. Yardley, Department of Civil and Mineral Engineering, University of Minnesota, Minneapolis, Minnesota 55455

ANNUAL BANQUET GUEST SPEAKER

Prof. Eugene M. Shoemaker, Geology Department, California Institute of Technology, Pasadena, California.

ACKNOWLEDGEMENTS

The organizing committee of the 1976 Institute on Lake Superior Geology gratefully acknowledge the work of Jo Behm in typing the final manuscript for the Proceedings. Richard Darling prepared the cover illustration.

CALENDER OF EVENTS AND PROGRAM

MONDAY, May 5, 1976

3:30 p.m. Pre-Institute field trip A, 1976 Minnesota River Valley Field Trip and Conference departs from the Radisson St. Paul for Donovan's Motel, Redwood Falls, Minnesota.

TUESDAY, May 6, 1976

8:00 a.m. Minnesota River Valley Field Trip departs from Redwood Falls to Granite Falls and Montevideo.

5:00 p.m. Minnesota River Valley Field Trip returns to Redwood Falls.

8:00 p.m.-
10:00 p.m. Discussion session, Minnesota River Valley Conference, Z.E. Peterman, Chairman.

G.B. Morey

Introduction

R.L. Bauer

STRUCTURAL STUDIES OF PRE-CAMBRIAN ROCKS IN THE MINNESOTA RIVER VALLEY

C.E. Hedge &
S.S. Goldich

Rb-Sr GEOCHRONOLOGY OF THE MONTEVIDEO GNEISS, MINNESOTA RIVER VALLEY

W. Wilson &
V.R. Murthy

GEOCHRONOLOGY AND GEO-CHEMISTRY OF GRANULITE FACIES ROCKS NEAR GRANITE FALLS IN THE MINNESOTA RIVER VALLEY

B.R. Doe &
M.H. Delevaux

LEAD ISOTOPE INVESTIGATIONS IN THE MINNESOTA RIVER VALLEY

S.S. Goldich,
J.L. Wooden,
G.A. Ankenbauer, Jr.
T.M. Levy &
R.U. Suda

PRECAMBRIAN HISTORY OF THE MORTON-NEW ULM REACH OF THE MINNESOTA RIVER VALLEY

P.W. Weiblen ,
K.J. Schulz &
B.V. Nielsen

COMPOSITIONAL VARIATIONS OF MINNESOTA RIVER VALLEY AMPHIBOLITE

S.S. Goldich

Summary

WEDNESDAY, May 5, 1975

- 8:00 a.m. Minnesota River Valley Field Trip departs Redwood Falls for Morton and New Ulm.
- 8:00 a.m. Field Trip B on Engineering and Pleistocene Geology in the Twin Cities area departs Radisson St. Paul.
- 5:00 p.m. Field Trip on Engineering and Pleistocene Geology returns to Radisson St. Paul.
- 6:00 p.m.-
9:00 p.m. Early registration, Minnesota East, lower level, Radisson St. Paul.
- 8:00 p.m. Conferences Smoker (cash bar) Capitol Ballroom, lower level Radisson St. Paul.
- 8:00 p.m. Minnesota River Valley field trip returns, Radisson St. Paul.

THURSDAY, May 8, 1976

- 7:30 a.m.-
9:30 a.m. Registration, outside Minnesota East, Radisson St. Paul.
- 8:00 -
8:10 Welcome, Matt Walton, General Chairman, 1976 Institute on Lake Superior Geology.
- 8:10 SESSION I - SYMPOSIUM ON GEOLOGY AND GEOCHEMISTRY OF EARLIEST PRECAMBRIAN ROCKS, S.S. Goldich and A.M. Goodwin, Co-Chairmen.
- 8:10 G.P. Beakhouse A REAPPRAISAL OF THE WESTERN PORTION OF THE ENGLISH RIVER SUBPROVINCE, NORTHWESTERN ONTARIO AND SOUTHEASTERN MANITOBA
- 8:30 C.F. Gower THE GEOLOGY OF GNEISSIC ROCKS IN THE KENORA DISTRICT, ENGLISH RIVER GNEISS BELT
- 8:50 A.M. Goodwin LITHIC AND MAJOR ELEMENT COMPOSITION IN THE SUPERIOR GEOTRAVERSE, ONTARIO
- 9:10 C.-L. Chou,
N.B.W. Harris, &
A.M. Goodwin ABUNDANCES OF RARE EARTH AND OTHER ELEMENTS IN ARCHEAN GRANITIC AND GNEISSIC ROCKS FROM THE ENGLISH RIVER GNEISS BELT, ONTARIO
- 9:30 G.N. Hanson &
S.S. Goldich RARE EARTH ELEMENT STUDIES OF THE ARCHEAN GNEISSES OF THE MINNESOTA RIVER VALLEY

9:50	J.L. Welsh	PETROLOGY OF THE ARCHEAN GNEISSES AT THE NORTHWEST CORNER OF THE SACRED HEART PLUTON; MINNESOTA RIVER VALLEY, MINNESOTA
10:10	W.R. Van Schmus & J.L. Anderson	GNEISS AND MIGMATITE OF ARCHEAN AGE IN THE PRECAMBRIAN BASEMENT OF CENTRAL WISCONSIN, U.S.A.
10:30	Z.E. Peterman, R.E. Zartman, & P.K. Sims	OLD PRECAMBRIAN W GNEISSES IN NORTHERN MICHIGAN
10:50	M.M. Kehlenbeck	NATURE OF THE QUETICO-WABIGOON BOUNDARY IN THE de COURCEY-SMILEY LAKES AREA, NORTH-WESTERN ONTARIO
11:10	D. Birk	TRACE ELEMENTS IN THE ARCHEAN GRANITOID DIAPYRS PIERCING THE WABIGOON GREENSTONE BELT
11:30	T.E. Smith, A. Turek, & C. Riddle	THE GEOCHEMISTRY OF THE GAMITAGAMA LAKE COMPLEX, WAWA, ONTARIO
11:50	E.C. Perry, Jr. S.N. Ahmad	CARBON IN METAMORPHOSED SEDIMENTS FROM ISUA, WEST GREENLAND

THURSDAY, May 8, 1976

8:10 am	SESSION II - ENGINEERING AND ENVIRONMENTAL GEOLOGY, D.M. Yardley and C. Goldsmith, Co-chairmen.	
8:10	H.O. Pfannkuch	A SYSTEMS APPROACH TO ENVIRONMENTAL GEOLOGY
8:30	D. Pollack & H.O. Pfannkuch	ENVIRONMENTAL IMPLICATIONS OF GROUNDWATER-LAKE INTERACTION WITH LAND USE APPLICATION
8:50	W. Rohrer & H.O. Pfannkuch	GROUNDWATER SPREADING OF HYDROCARBON SPILLS WITH SPECIAL EMPHASIS ON MONITOR SYSTEM DESIGN IN GLACIAL DRIFT
9:10	D.I. Siegel	SOURCES OF DISSOLVED SOLIDS IN GROUNDWATER FROM SUPERIOR AND RAINY LOBE TILL

9:30	S.I. Jacobsen	THE TRACE ELEMENT GEOCHEMISTRY OF PEAT BOGS OVER DIFFERENT BEDROCK TYPES, SOUTHERN HOUGHTON COUNTY, MICHIGAN
9:50		Coffee
10:10	M.G. Mudrey, Jr. B.C. Parker, K. Cartwright & L.D. McGinnis	DIAMOND DRILLING IN ENVIRONMENTALLY SENSITIVE AREAS - ENVIRONMENTAL IMPACT: MONITORING AND ASSESSMENT
10:30	E. Booy & S.J. Dyl, II	STRATIGRAPHIC VARIATION IN MINERALOGY AND ENGINEERING CHARACTERISTICS OF ONTONAGON CLAY NEAR A MAJOR SLOPE FAILURE, ONTONAGON COUNTY, MICHIGAN
10:50	A.M. Johnson & H.O. Sorenson	ENGADINE DOLOSTONE OF MICHIGAN'S EASTERN UPPER PENINSULA: GEOLOGY AND RESOURCE EVALUATION
11:10	E. Booy & R.D. Harris	SECONDARY MINERAL GROWTH OF THE WHITE PINE SHALE COMPARED WITH CLASSIC "HEAVING" SHALES
11:30	C.R. Nelson & D.H. Yardley	MODIFICATION OF ENGINEERING PROPERTIES OF ST. PETER SANDSTONE
12:10 p.m.- 1:30 p.m.		Lunch
12:10 p.m.- 1:30	Informal meeting of geologists interested in Precambrian of Wisconsin. M.G. Mudrey, Jr., convenor. All interested geologists are welcome. (See bulletin board for notice of location).	
1:30 p.m.	SESSION III - GENERAL GEOLOGY, D.L. Southwick and R.W. Marsden, Co-Chairmen	
1:30	R.W. Ojakangas	ANATOMY OF A WELL-COVERED GREENSTONE BELT, NORTHWESTERN MINNESOTA
1:45	D.L. Southwick	HIGH-GRADE METAMORPHISM ASSOCIATED WITH THE VERMILION BATHOLITH, MINNESOTA-ONTARIO
2:00	R.S. Maass & L.C. Medaris, Jr.	PENOKEAN STRUCTURES AND PLUTONIC ROCKS IN PORTAGE AND WOOD COUNTIES, WISCONSIN

2:15	G.L. LaBerge & P.E. Myers	THE CENTRAL WISCONSIN BATHOLITH
2:30	P.E. Myers	THE WAUSAU SYENITE OF CENTRAL WISCONSIN
2:45	E.J. Smith	GEOLOGY AND GEOCHEMISTRY OF THE PRECAMBRIAN MARCELLON RHYOLITE, COLUMBIA COUNTY, WISCONSIN
3:00		Coffee
3:15	P.K. Sims	MIDDLE PRECAMBRIAN AGE OF VOLCANOGENIC MASSIVE SULFIDE DEPOSITS IN NORTHERN WISCONSIN
3:30	W.C. Prinz	CORRELATIVE IRON-FORMATIONS AND VOLCANIC ROCKS OF PRE- CAMBRIAN X AGE, NORTHERN MICHIGAN
3:45	M.S. Lougheed & J.J. Mancuso	ORIGIN OF LAMINAE IN PRECAMBRIAN IRON-FORMATION
4:00	T.-M. Han	GEOCHEMICAL PROCESSES FOR THE FORMATION OF MAGNETITE IN LOW-GRADE METAMORPHIC PRECAMBRIAN IRON-FORMATIONS
4:15	W.F. Cannon & L.J. Drew	RESOURCES OF RECOVERABLE IRON ON THE MARQUETTE RANGE, MICHIGAN — ESTIMATES BY A MONTE CARLO SIMULATION METHOD
4:30	D.W. Snider	A GROUND INVESTIGATION OF AN AEROMAGNETIC ANOMALY, DICKINSON COUNTY, MICHIGAN
5:30 p.m.- 6:30 p.m.	SOCIAL HOUR (cash bar) Capital Ballroom, Radisson St. Paul	
6:30 p.m.	ANNUAL BANQUET, Capital Ballroom, Radisson St. Paul, Eugene M. Shoemaker, Guest Speaker.	

FRIDAY, May 9, 1976

8:00 a.m.	SESSION IV - GENERAL GEOLOGY. P.W. Weiblen and J.C. Green, Co-Chairmen	
8:10	F.J. Sawkins	ORE DEPOSITS IN RELATION TO HOTSPOT-GENERATED INTRA- CONTINENTAL RIFTING

8:30	J.M. Robertson	GEOLOGY AND MINERALOGY OF SOME COPPER SULFIDE DEPOSITS NEAR MOUNT BOHEMIA, KEWEENAW COUNTY, MICHIGAN
8:50	W.A. Bartlett, M.S. Loughheed, J.J. Mancuso & L.J. Walters	DISTRIBUTION OF SULFUR IN THE WEST KIERNAN SILL, IRON COUNTY, MICHIGAN
9:10	B. Bonnichsen & R.I. Botto	THE BEHAVIOR OF PRECIOUS METALS AND OTHER TRACE ELEMENTS DURING THE FRACTIONAL CRYSTALLIZATION OF DULUTH COMPLEX SULFIDES
9:30	T.A. Vogel, M.B. McBride & R. Ehrlich	SYNGENETIC MODEL FOR THE ORIGIN OF THE WHITE PINE COPPER DEPOSIT
9:50	N. Scofield	CHEMISTRY OF PRIMARY AND SECONDARY MINERALS OF SOME PORTAGE LAKE LAVAS, KEWEENAW PENINSULA: DEVELOPMENT OF MODELS OF DIFFERENTIATION AND LOW-RANK METAMORPHISM
10:10		Coffee
10:30	J.G. Grimes	APPLICATION OF A FLOW DIRECTION TECHNIQUE TO THE PORTAGE LAKE VOLCANICS, MICHIGAN
10:50	C. Brumleve	PETROLOGY AND FRACTURE CHARACTERISTICS OF THE KINGSTON CONGLOMERATE, KEWEENAW COUNTY, MICHIGAN
11:10	B.E. Aaquist	AN INTERPRETATION OF THE KINGSTON CONGLOMERATE AS A RHYOLITE TUFF IN THE PORTAGE LAKE LAVA SERIES, KEWEENAW PENINSULA, MICHIGAN
11:30	J.M. DeGraff	STRUCTURAL AND AGE RELATION- SHIPS AT THE LAC LA BELLE MAGNETIC ANOMALY, KEWEENAW COUNTY, MICHIGAN
11:50	L.L. Babcock	CONTACT RELATIONSHIPS BETWEEN THE JACOBVILLE SANDSTONE AND THE PORTAGE LAKE LAVA GROUP: A PROGRESS REPORT

12:15 p.m.- 1:15 p.m.		Lunch
12:15 p.m.- 1:15 p.m.	Annual Business Meeting, Institute Board of Directors.	
1:30 p.m.	SESSION V - GENERAL GEOLOGY, F.J. Sawkins and D.M. Davidson, Jr., Co-Chairmen.	
1:30	F.M. Swain, J. Baysinger & J.M. Bratt	HYDROCARBONS OBTAINED BY PYROLYSIS OF SOME PRECAMBRIAN ROCKS OF MINNESOTA
1:50	S.W. Stuhr & E.N. Cameron	GEOLOGY OF THE ROUND LAKE INTRUSION, SAWYER COUNTY, WISCONSIN
2:10	R.M. Tyson & B. Bonnichsen	HORNFELSED BASALTS IN THE DULUTH COMPLEX
2:30	J.R. Burnell, Jr.	THE PETROLOGY AND STRUCTURAL RELATIONS OF THE LATER PRE- CAMBRIAN BRULE LAKE INTRUSIONS, COOK COUNTY, MINNESOTA
2:50	D.M. Davidson, Jr., H. Halls & J.R. Burnell, Jr.	PALEOMAGNETISM OF THE LATE PRECAMBRIAN BRULE LAKE INTRUSION, COOK COUNTY, MINNESOTA
3:10		Coffee.
3:30	N.M. Pope	PETROLOGY AND STRUCTURE OF THE LATE PRECAMBRIAN SILVER CREEK CLIFF AND LAFAYETTE BLUFF MAFIC INTRUSIONS, LAKE COUNTY, MINNESOTA
3:50	R.P. Meyer, J.R. Moore, E.L. Nebrija & C.T. Young	GEOPHYSICAL PROSPECTING OFF THE KEWEENAW PENINSULA
4:10	H.C. Halls	THE SLATE ISLANDS: THE CENTRAL UPLIFT OF A METEORITE IMPACT CRATER?

ABSTRACTS

AN INTERPRETATION OF THE KINGSTON CONGLOMERATE AS A
RHYOLITE TUFF IN THE PORTAGE LAKE LAVA SERIES,
KEWEENAW PENINSULA, MICHIGAN

B.E. Aaquist, Department of Geology, University of Western Ontario, London,
Ontario N6A 5B7

ABSTRACT

The rock type included under the formation name of Kingston Conglomerate within the Ahmeek quadrangle is interpreted as having formed by the fracturing and minor reworking of a rhyolite tuff. The average thickness of the formation is 10 meters and individual layers, which commonly are lenticular in shape and cross bedded, range in thickness from 1 mm to 65 cm. Fragments consist entirely of rhyolite having quartz and plagioclase phenocrysts in a cryptocrystalline ground-mass. The phenocrysts have vague boundaries and deep embayments characteristic of a volcanic origin. Sandy parts of the formation consist of angular quartz and feldspar crystals, feldspar laths, fine angular grains of cryptocrystalline material, and rounded grains of hematite. Some of the poorly sorted, coarse-grained layers have a texture indicative of in situ fracturing of fragments with separation the only movement of the fragments. Also, sand around fragments in these layers appears to have formed by the breakdown of adjacent fragments.

The distribution of the Kingston rhyolite plus similar rhyolitic facies in three other interflow horizons in the overlying basaltic sequence suggests the source of the rhyolite was to the southeast, and indeed, rhyolite domes outcrop within the lower part of the Portage Lake Lava Series from the area of the Ahmeek quadrangle to the east end of the Keweenaw Peninsula. Native copper has been mined from the rhyolite facies of all four interflow horizons in the Ahmeek quadrangle map area.

CONTACT RELATIONSHIPS BETWEEN THE JACOBSTOWN SANDSTONE
AND THE PORTAGE LAKE LAVA GROUP:
A PROGRESS REPORT

Larry L. Babcock, Institute of Mineral Research, Michigan Technological University, Houghton, Michigan 49931

ABSTRACT

Logs of all diamond drill holes in the Laurium quadrangle which collar between the Scales Creek Flow (PSc) and the Jacobstown Sandstone (JS) - Portage Lake Lava Group (PLLG) contact were officially obtained from Universal Oil Products. These logs comprise 105 holes and represent 25,000 m of drilling. Stratigraphic correlation between the southernmost four field sections along the contact trace and adjacent drill holes has been completed. These sections are Gooseneck, Quincy, Dover, and Dover (north) Creeks and the Oneco (ON), New Baltic (NB), and New Arcadian (NA) drill holes, respectively.

The stratigraphic succession across the JS-PLLG contact zone in the four field sections consists of the following units, from oldest to youngest: (1) "typical" flat-lying JS, (2) basal PLLG melaphyre, (3) "contact" conglomerate, and PLLG lavas. However, an additional unit is present between (1) and (2) in the Quincy Creek section: 35 to 48 m of steeply dipping JS beach sand-beach gravel quartzite conglomerate.

The JS-PLLG contact zone on Quincy Creek was mapped in detail. An asymmetrical buttress zone extends 250 to 300 m across the contact at this location. Proceeding southeast from PLLG lavas, the dip steepens in three successive stages from 15° to 29° NW to $22-55^{\circ}$ NW to 30° NW $\rightarrow 90^{\circ}$ $\rightarrow 50^{\circ}$ SE. The latter stage is an anticlinal flexure consisting, in the crushed axial portion, of large quartzite blocks (NW limb) and sandstone blocks and slabs (SE limb). Typical flat-lying JS is encountered immediately southeast of this buckle.

Results of field and diamond drill section correlations are outlined below:

- (1) Interbedding between the JS and PLLG is noted in four of six NA holes near Gooseneck Creek. Isopach maps were constructed on two successive, essentially flat-lying undisturbed stratigraphic intervals in these four holes: volcanics (3-14 m) and sediments (4-18 m) which underlie these volcanics. Two transport direction solutions were computed for each interval: volcanics, $S27^{\circ}E$ and $S45^{\circ}E$; sediments, both $N15^{\circ}E$. The latter direction is identical to those measured on "typical" JS exposed in the bed of Gooseneck Creek and represents the "normal" JS transport direction in the Laurium quadrangle. Sediments exposed in the bed of the creek directly overlie the above mentioned volcanic interval.
- (2) The contact conglomerate is exposed in all four field sections and was intersected by five adjacent drill holes. In three of these holes, 12 to 120 m of lava separate this conglomerate from the underlying Baltic No. 3 conglomerate, i.e. the contact conglomerate is No. 4.
- (3) Between the Dover Creek section and the nearest drill holes (ON9), Nos. 3 and 4 conglomerates exhibit identical dips, $6.2^{\circ}NW$, and identical

stratigraphic separation intervals, 120 ± 4 m. These values are constant over a horizontal distance of 2.3 km.

- (4) The uppermost JS conglomerate in the Dover Creek Section is correlative with the Baltic No. 3 of the PLLG: the lowermost conglomerate, No. 2.
- (5) A regionwide unconformity in the JS occurs at the top of the uppermost JS conglomerate on Dover Creek (Babcock, 1975). This unconformity represents a definitive rock-and time-stratigraphic break (timeline) at the top of the Baltic No. 3 conglomerate which is present in both the JS and PLLG.

These correlations require that virtually all of the JS exposed on the Keweenaw Peninsula is time equivalent to lowermost portions of the PLLG.

REFERENCE

Babcock, L.L., 1975 The Jacobsville Sandstone: Evidence for a Lower-Middle Keweenawan Age: Field Trip 3, Proc., 21st Ann. Inst. on Lake Superior Geol., pp. 87-123.

DISTRIBUTION OF SULFUR IN THE WEST KIERNAN SILL, IRON COUNTY, MICHIGAN

W.A. Bartlett*, M.S. Loughheed, J.J. Mancuso, and L.J. Walters, Department of Geology, Bowling Green University, Bowling Green, Ohio 43403 *Current address: Lindgren Exploration Co., Wayzata, Mn. 55391

ABSTRACT

The West Kiernan Sill, located in eastern Iron County, Michigan, is a differentiated body of mafic igneous rock ranging in composition from peridotite through gabbro to granophyre. It is Middle Precambrian in age, and has been metamorphosed to the greenschist facies. The sill was intruded into the Hemlock formation, and now occupies an outcrop area of approximately 26 square miles.

The sulfur content of the West Kiernan Sill varies with rock type, but in general is low as compared to published averages for similar rocks. The peridotitic rocks of the sill average 5 micromoles/gram sulfur, the gabbroic rocks average 40 micromoles/gram sulfur and the granophyric rocks average 11 micromoles/gram sulfur. Based on statistical analyses and graphical techniques the distribution of copper and nickel in the sill is shown to correlate with the distribution of sulfur.

Because copper and nickel ore deposits in mafic igneous rocks are made up of concentrations of sulfide minerals, the distribution of sulfur can be used as a prospecting tool to indicate the relative abundance of sulfide minerals in mafic igneous bodies.

STRUCTURAL STUDIES OF PRECAMBRIAN ROCKS IN THE MINNESOTA RIVER VALLEY

Robert L. Bauer, Department of Geology and Geophysics, University of Minnesota,
Minneapolis, Minnesota 55455

ABSTRACT

The gneisses in the Minnesota River Valley between Montevideo and Morton, Minnesota have been folded into a series of shallow, eastward-plunging antiforms and synforms, (F_2), with wavelengths on the order of several kilometers (Himmelberg, 1968; Grant, 1972). These major structures are pre-dated in the Granite Falls area by, rare isoclinal, intrafolial folds, (F_1), which are coaxial with, but deformed by the F_2 structures.

A third period of folding, (F_3), not evident from a the mapping of the major structures, is deduced from a detailed analysis of the minor folds and mineral lineations in the gneisses. In the Morton-Sacred Heart area this third period of folding yields minor folds trending about $N53^\circ E$, plunging 20° (Grant, 1972). In the Granite Falls area the orientations of the minor folds vary with their location on the Granite Falls antiform (F_2). On the north limb of the antiform the folds have an average orientation of $N60^\circ E$, plunging 30° . The axial planes of these folds generally trend NE-SW with a moderate to steep SE dip. This is very close to the orientation of the south limb of the Granite Falls antiform and the foliation orientation in the outcrops near Montevideo. This near coincidence results in a large variation in the F_3 fold axis orientations in these areas, ranging from NE to SE to SW-plunging. An S_3 axial plane foliation defined by flattened quartz lenses is locally well developed on the south limb of the Granite Falls antiform. L_3 quartz lineations defined by the intersection of S_0 (compositional banding) and S_3 are common in this area, and show the same range in orientation as the F_3 fold axes.

A fourth generation of minor folds, (F_4) is common only in the outcrops near Montevideo. F_4 axial planes generally trend NW-SE and are moderately inclined to the northeast. The F_4 fold axes in this area have an average orientation of $S80^\circ E$, 40° and generally occur as open warps of the gneissic banding with amplitudes ranging from 20-50 cm. A few NW-trending folds on the north limb of the Granite Falls antiform have orientations which are consistent with that expected of F_4 folds superimposed on this limb. Unlike the F_4 folds in the Montevideo area, these folds are concentric, parallel folds with wavelengths ranging from 1-5 meters. Both F_4 fold types occur in granitic gneiss suggesting a distinct difference in the mechanical properties of the gneiss at the time of folding.

A similar difference in mechanical properties of the gneiss is suggested by the difference in the character of narrow NW and NE-trending shear zones which occur in both the Granite Falls and Montevideo areas. The shear zones near Granite Falls are mylonitic and have a cataclastic microfabric. Similarly oriented zones in the Montevideo area are generally diktyonitic structures rather than shear zones, commonly containing remobilized granitic material without a cataclastic microfabric.

REFERENCES CITED

- Grant, J.A., 1972, Minnesota River Valley, southwestern Minnesota, in Sims, P.K. and Morey, G.B., eds., *Geology of Minnesota: A centennial volume*; Minnesota Geol. Survey, p. 177-196.
- Himmelberg, G.R., 1968, *Geology of Precambrian rocks, Granite Falls-Montevideo area, southwestern Minnesota*; Minnesota Geol. Survey Spec. Pub. Ser. 5, 33 p.

A REAPPRAISAL OF THE WESTERN PORTION OF THE
ENGLISH RIVER SUBPROVINCE, NORTHWESTERN ONTARIO
AND SOUTHEASTERN MANITOBA

G.P. Beakhouse, Centre for Precambrian Studies, Department of Earth Sciences,
University of Manitoba, Winnipeg, Manitoba, Canada.

ABSTRACT

The English River subprovince has been considered to be a high grade, Archean metasedimentary basin flanked by typical greenstone-granite terranes. Recent investigations, however, suggest that this is an oversimplification and that the English River subprovince is divisible into two units; a northern, largely sedimentary, unit (Ear Falls-Manigotagan gneiss belt) and a southern, mainly plutonic unit (Winnipeg River batholithic belt).

The Ear Falls-Manigotagan gneiss belt comprises a high grade metagray-wacke-metasilstone sequence intruded by subordinate felsic plutons. The distribution of lithologies and recognizable primary sedimentary structures imply a major sedimentary basin with sediment deposited below wave base from turbidity flows. This sedimentation is, at least in part, a distal facies of volcanism in the Red Lake subprovince to the north.

In contrast, the Winnipeg River batholithic belt is largely a felsic plutonic terrane comprising two major suites; an earlier, massive to weakly gneissic, pre- and syn-tectonic trondhjemite-granodiorite-quartz diorite suite and a later, massive, post-tectonic granodiorite-quartz monzonite-granite suite. A complex assemblage of well layered, felsic orthogneisses with subordinate interlayered remnants of recognizable metavolcanic and metasedimentary rocks occurs on the southern flank of this plutonic terrane. The origin of the Winnipeg River batholithic belt is problematic, and several possibilities are currently being evaluated, including the possibility that the belt could represent a reactivated ancient crustal remnant.

Regional geophysical anomalies support the two-fold subdivision of the English River subprovince. The Ear Falls-Manigotagan gneiss belt has a thicker granitic crust, thinner total crust, and higher Bouguer gravity values than the Winnipeg River batholithic belt. Aeromagnetic patterns also are distinctly different in the two belts.

TRACE ELEMENTS IN THE ARCHAEOAN GRANITOID DIAPIRS PIERCING THE WABIGOON GREENSTONE BELT

Dieter Birk, Department of Geology, McMaster University, Hamilton, Ontario L8S
4M1

ABSTRACT

Major and trace element analyses are reported for twelve synkinematic to late-kinematic granitoid diapirs intruding Keewatin greenstones of the Wabigoon Greenstone Belt of northwestern Ontario. Analyses are included of associated enclaves and aplitic dikes to evaluate the role of endomorphism and late diking.

Despite a common tectonic setting, these diapirs range from homogeneous granodiorites to concentrically zoned plutons or complexes of granite-monzodiorite. The range of element concentrations ($4.3 > \text{Na/K} > 0.9$) is not compatible with a "late K granite" classification as required by current Archaean models of secular granitoid chemistry. Each pluton carries a distinctive "fingerprint" of trace element abundances, but as a group these granitoids carry high Sr and Ba, and low Rb/Sr, Th, and U.

The lensoid mafic enclaves, ubiquitous in these plutons, have undergone basification and/or alkali metasomatism, resulting in trace element abundances markedly different from either their granitoid hosts or suggested metavolcanic sources. Strong enrichment in Rb, Ce and Th can be demonstrated, whereas Sr and Ba values are more erratic. Although a reciprocal reaction process is envisioned between enclave and host, there is little evidence of large scale contamination of the host plutons. Homogeneous granodiorite plutons (such as the Burditt Lake Stock, Scattergood Stock) show heterogeneous enclave distribution without noticeable modal mineral or chemical effect.

Aplitic patches and dikes show trace element contents typical of late differentiates complicated by strong core-to-rim zoning. Aplite apophyses cutting metavolcanic rocks differ little from the intraplutonic aplites.

THE BEHAVIOR OF PRECIOUS METALS AND OTHER TRACE ELEMENTS DURING THE FRACTIONAL CRYSTALLIZATION OF DULUTH COMPLEX SULFIDES

Bill Bonnichsen, Department of Geol. Sciences, Cornell Univ., Ithaca, N.Y. 14853
and Robert I. Botto, Exxon Corp., Box 4255, Baytown, Texas 77520

ABSTRACT

In the Duluth Complex, the sulfide mineral assemblages can be described in terms of the high temperature phases that crystallized from sulfide melts. The three principal phases that formed from such melts are (1) MSS (monosulfide solid solution) which cooled to pyrrhotite with exsolved chalcopyrite-cubanite and pentlandite, (2) ISS (intermediate solid solution) which cooled to chalcopyrite and cubanite (commonly in exsolution intergrowths), and (3) BSS (bornite-chalcocite solid solution), which cooled to bornite-chalcopyrite intergrowths.

For normal Fe-rich sulfide melts, the early crystallization of MSS leads to Cu enrichment in the liquid. On the Cu-Fe-S system liquidus surface the MSS-ISS field boundary is not a cotectic, but is a reaction boundary, with the ISS field on the low temperature side. Thus, the continued crystallization of MSS will enrich the residual melt in Cu until its composition migrates into the ISS field, causing the cessation of MSS and start of ISS crystallization. The ISS has a lower Cu/Fe ratio than the melt so that its removal will cause further Cu enrichment, which can lead to liquid compositions reaching the ISS-BSS field boundary.

In the Duluth Complex, the sulfide-rich basal segregations crystallized as MSS, whereas the disseminated sulfides crystallized as MSS-ISS mixtures. The Cu-rich epigenetic sulfides which percolated into the footwall and inclusions, crystallized mainly as ISS and BSS. Fractional crystallization of sulfide liquids, as outlined above, is one of several mechanisms that may account for the wide range of compositions that characterize the Duluth Complex sulfides. Such a process seems particularly applicable to the Cu-enriched epigenetic occurrences.

Six Duluth Complex samples, chosen to encompass the observed range of Cu/Fe ratios, were analyzed by neutron activation, spark-source mass spectrometry, and atomic absorption to further examine the fractional crystallization process. The results are in very good agreement with our predictions for fractional crystallization trends. During sulfide crystallization, Ni, Co, and Mo were selectively incorporated into MSS along with Fe, whereas Ag, Au, Pd, Pt, Rh, Ir, Zn, Cd, Pb, Tl, Se, Te, Sb, Bi, W, and Sn were enriched in the liquid along with Cu, to eventually become incorporated in the Cu minerals. Our investigation of element behavior indicates preferences for octahedral lattice sites in MSS, versus tetrahedral sites in ISS, which largely governs element distributions during sulfide liquid crystallization.

STRATIGRAPHIC VARIATION IN MINERALOGY AND ENGINEERING CHARACTERISTICS OF ONTONAGON CLAY NEAR A MAJOR SLOPE FAILURE, ONTONAGON COUNTY, MICHIGAN

Emmy Booy and Stanley J. Dyl, II, Department of Geology and Geological Engineering, Michigan Technological University, Houghton, Michigan 49931

ABSTRACT

U.S. 45 for approximately one mile north and south of the East Branch of the Ontonagon River on the Keweenaw Peninsula of Michigan is plagued by slope failures of varying types and sizes along the road cuts. The area of particular interest for this discussion is the largest slide which lies to the north of the East Branch almost at the crest of the hill. The area is one in which the river has incised a valley about 200 feet deep into a flat glacio-lacustrine deposit of thinly-layered red clays and silts.

The particular slide under discussion is approximately 700 feet long and 400 feet high. It is immediately adjacent to Highway 45 and causes annual disruption of the drainage on the west side of the roadway. Both mud flows and block gliding contribute at various times and in different areas to the slope recession.

Material of the slope was studied at 1 meter vertical intervals in the as-yet unfailed zones north and south of the failed area in order to ascertain variability of the clay-silts in situ. Mineralogy of the clay-size fraction, Atterberg Limits, particle-size distribution, and vane shear strengths were determined.

The material, like that previously studied on a regional scale, ranges throughout the clay and clay-silt regions of the Corps of Engineers and U.S. Bureau of Soils classifications. In general, sand content is less than 5% although in some layers this is not true.

The mineralogy of the layers, in agreement with the variability of the particle sizes, varies from layer to layer. However, it may be accurate to state that the rock flour includes considerable quartz and feldspar in the clay-size fractions as well as the clay minerals kaolinite, illite, and mixed-layer material which appears to be dominantly smectite.

Plastic limits vary in the general range of 24-30 and liquid limits vary from 35 to 70 reflecting variation in particle size and clay mineral content. The natural moisture content of the material generally approach the plastic limits although in certain cases it is higher than the plastic limit. This moisture content increases in general towards the base of the hill, but not at a uniform rate. Anomalously high values occur part way up the hill in zones of higher clay content.

Shear strengths are extremely variable, generally in the 4-25 tons/sq. ft. region. This variability occurs not only on a scale of tens of feet up the slope, but within a single hole at vertical and horizontal distances of inches. The variation within a hole may be as much as 10 tons/sq. ft.

SECONDARY MINERAL GROWTH OF THE WHITE PINE SHALE COMPARED WITH CLASSIC "HEAVING" SHALES

Emmy Booy, Department of Geology and Geological Engineering, Michigan Technological University, Houghton, MI, 49931 and Robert D. Harris, Gillette Co., South Boston, MA.

ABSTRACT

Workers in the eastern United States and Canada have observed secondary mineral growth, particularly gypsum and a variety of iron sulfates which have caused "heaving" of shales under buildings. Because of similarities of conditions (i.e. high oxygen contents and presence of moisture) between shales at the surface of the earth and along the surfaces of mine openings, the possibility that similar phenomena might be taking place in the White Pine Mine, Michigan was investigated.

In occurrences in shales near Ottawa, Ontario, Cleveland, Ohio, and Pittsburgh, Pennsylvania, substantial (up to several inches) vertical expansion has taken place in shales which contain some pyrite and calcite. It has been hypothesized that the reactions which take place in the shales are catalyzed by oxidizing bacteria. These bacteria would include Thiobacillus ferrooxidans and Ferrobacillus ferrooxidans. Repeated efforts to grow such bacteria in cultures of the White Pine Shale have proven unsuccessful. Therefore, a bacterial mechanism for gypsum growth on White Pine shales has been ruled out.

Samples ranging in time of exposure to the mine atmosphere from 1 day to 10 years were collected from the mine roof — most samples were from the Brown Massive but several were from the Dark Gray Massive. These strata contain scattered nodules of calcite which provide a logical source for Ca in the expected reactions. Microscopic examination suggests the presence of between 0.2 and 0.4 percent pyrite which coincides with data for sulfur analyses of the material. Therefore, the basic chemicals needed for the generation of gypsum are present.

Soluble sulfates in the samples were on the order of magnitude of 10 ppm or less. However, careful examination of samples exposed to the mine atmosphere showed some growth of gypsum on the surfaces of the samples. However, distribution was random throughout the samples studied. The absence of a linear relationship between time of exposure to the mine atmosphere and quantity of gypsum present is attributed to the anisotropic distribution of parent materials in the mine. Subsequently, similar gypsum growth was observed on the surfaces of polished thin sections made of the interior of the rock.

It has been concluded that possible weakening of the strata by progressive growth of secondary gypsum does not present a major hazard at the White Pine Mine. However, some such growth is possible and is concentrated at the rock surfaces. Further, halite may also be growing on the surfaces of the White Pine Shale. The relatively low rate of gypsum growth in this atmosphere may be due to the relatively high pH (about 8) in the mine which inhibits growth of the bacteria which elsewhere are reported to catalyze the chemical reactions responsible for shale deterioration.

PETROLOGY AND FRACTURE CHARACTERISTICS OF THE KINGSTON CONGLOMERATE, KEWEENAW COUNTY, MICHIGAN

Charles Brumleve, Department of Geology and Geological Engineering, Michigan Technological University, Houghton, Michigan 49931

ABSTRACT

The Kingston conglomerate is composed of subangular to subrounded clasts of quartzite feldspar porphyry. These red rhyolite gravels make up approximately 60 percent of the total rock. The matrix is predominantly sand of the same composition as the clasts, with secondary mineralization of copper, hematite, calcite, and chlorite, in order of increasing abundance. The unit as a whole is unsorted but is made up of bands or lenses of poor to well sorted clasts.

The intensity of mineralization is related to the amount of matrix present and is an indication of the original permeability of the rock. The hanging wall zone has the most matrix and received the most secondary mineralization whereas the intermediate zone has the least matrix and the least mineralization.

Permeability tests using compressed air demonstrated the tight cementation of the rock. Conductivity tests were used to determine the nature of the native copper framework in elongate lenses parallel to bedding.

The fracture characteristics of the conglomerate are controlled by the degree of cementation and type of matrix mineralization. Silica cement produces a competent, nonfriable rock which tends to fracture transgranularly across clasts. Chlorite and copper mineralization in the matrix produces weak clast bonds. This results in failure by intergranular fracturing of matrix, clasts and native copper masses.

THE PETROLOGY AND STRUCTURAL RELATIONS OF THE LATER PRECAMBRIAN BRULE LAKE INTRUSIONS, COOK COUNTY, MINNESOTA

James R. Burnell, Jr., Department of Geology, University of Minnesota, Duluth,
Duluth, Minnesota 55801

ABSTRACT

The Duluth Complex splits into two east-trending tongues at its eastern extent to form a northern and a southern prong, exposing a strip of older Keweenawan volcanic rocks between them. Brule Lake is located at the westernmost extent of the strip of volcanic rocks just east of the point where the gabbro prongs coalesce. The volcanic rocks are intruded by a series of large sill-like bodies which terminate against rocks of the nearby Duluth Complex. Thus, these intrusions, known informally as the Brule Lake sills, were formed between the time of the eruption of the local Keweenawan volcanic rocks and the subsequent gabbroic intrusions.

The intrusive rocks of the Brule Lake area, which occur as both dikes and sills, consist of porphyritic intrusions and subsidiary non-porphyritic intrusions. The porphyritic intrusions form the most striking geologic features at Brule Lake. These diabase porphyries are approximately 80 to 300 meters thick and extend for 2 to 8 kilometers along strike. Most contain 50-60% plagioclase phenocrysts. Mineralogy is simple, consisting of plagioclase, augite, opaque oxides (magnetite and ilmenite) with minor quartz and potash feldspar. A typical mode includes plagioclase 68%, augite (-uralite) 17%, opaque oxides 9%, quartz 2%, K-feldspar 1%, chlorite-groundmass-epidote 3%.

The porphyry units are tabular in form and are tilted to form steep north-facing slopes and more gradual south slopes. Several sills are concordant with the trend of the intruded flows whereas others transect this trend at angles of up to 30°.

The texture of the porphyry units is dominated by abundant plagioclase phenocrysts with subophitic textures poorly developed. Fine-grained groundmass occurs in the interstices of the plagioclase laths, commonly including vermicular intergrowths of quartz-plagioclase or quartz-potash feldspar.

Small bodies of non-porphyritic diabase intrude both the volcanic rocks and the diabase porphyries. When intruded into one of the porphyritic bodies, they are typically irregular in form and cross-cut the trends of the larger intrusions. When intruded into volcanic units, they form small tabular sills, several meters in thickness. The mineralogy of these smaller intrusions is identical to that of the porphyries although, modally, the proportions of plagioclase are less (45-52%) and of augite, more (19-25%).

Chemically the Brule Lake intrusions represent a tholeiitic magma saturated with respect to silica. They are characterized by values of $\text{SiO}_2 = 50\%$. MgO is low, ranging from 2-3% in the porphyry units, 5-6% in the non-porphyritic intrusions. Na_2O is particularly high ($>4\%$ in the porphyries) as is TiO_2 (2.25%).

Considering the abundance of plagioclase phenocrysts in the Brule Lake intrusions the bulk chemistry of the intrusive melt closely approximates the chemistry of several Keweenawan basalts of the North Shore Volcanic Group.

RESOURCES OF RECOVERABLE IRON ON THE MARQUETTE RANGE, MICHIGAN— ESTIMATES BY A MONTE CARLO SIMULATION MODEL

W.F. Cannon and L.J. Drew, U.S. Geological Survey, National Center, 12201 Sunrise Valley Drive, Reston, Virginia 22092

ABSTRACT

The Negaunee Iron-formation, the principal iron-bearing unit in the Marquette Iron Range, contains about 205 billion long tons of material averaging about 32 percent iron. About 49 billion tons are within 1,000 feet of the surface, which we consider a reasonable average depth for open-pit mining, although some present mines will probably be deeper.

Three classes of iron-formation are now being beneficiated on the range. These are:

- 1) coarse-grained hematitic and magnetic iron-formation beneficiated by froth flotation,
- 2) magnetic iron-formation beneficiated magnetically, and
- 3) fine-grained (less than 0.05 mm) nonmagnetic iron-formation beneficiated by selective flocculation and flotation.

We have divided the range into 1/4 square-mile areas and computed the tonnage and characterized the iron-formation in each according to its suitability for beneficiation by one of these processes, using a detailed computerized data bank developed by the senior author. By using available metallurgical data and by means of a Monte Carlo simulation model designed by the junior author, we have estimated the total amount of metallic iron recoverable from the Marquette range by each process, assuming surface mining to 1,000 feet. The model considers the quality of concentrate, using quality standards of $\text{Fe} > 60$ percent and $\text{SiO}_2 < 10$ percent; it estimates the amount of iron-formation that will make concentrates of this quality. From the empirical distribution of recoverable iron derived from many metallurgical tests, the total recoverable iron is then estimated. Figure 1 indicates that if recoverable grades of about 20 percent Fe are economically feasible, then about 11 billion short tons of metallic iron can be recovered from iron-formation that responds satisfactorily to beneficiation by an existing process. Most of this—about 7.2 billion tons—is in fine-grained nonmagnetic iron-formation. About 3 billion tons is in magnetic iron-formation, and about 0.7 billion tons is in coarse-grained hematitic iron-formation.

These figures indicate the geologic availability of iron and place maximum limits on iron reserves on the range in terms of current mining and beneficiating technology. The percentage of this iron that is now, or ever will be, economically available cannot be estimated without much more detailed study.

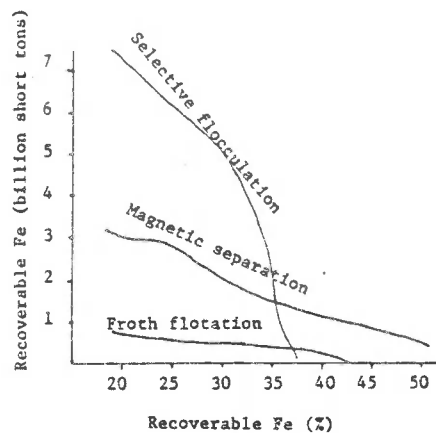


Figure 1. — Relationship between estimated tonnage of recoverable iron and percentage of recoverable iron for three beneficiating processes.

ABUNDANCES OF RARE EARTH AND OTHER ELEMENTS IN ARCHEAN GRANITIC AND GNEISSIC ROCKS FROM THE ENGLISH RIVER GNEISS BELT, ONTARIO

C.-L. Chou, N.B.W. Harris, and A.M. Goodwin, Department of Geology and Erindale College, University of Toronto, Canada M5S 1A1.

ABSTRACT

The early Precambrian rocks in the eastern Lac Seul region of the English River gneiss belt consist mainly of tonalitic and trondhjemitic gneisses overlain by tonalitic migmatized metasedimentary rocks. Both are intruded by granitic plutons and sills and pegmatite veins. Smaller bodies of amphibolitic gneiss also are found. Using neutron activation techniques we have analyzed an amphibolitic gneiss, two tonalitic gneisses, two granites, and two pegmatites for 24 elements (Na, K, Sc, Cr, Mn, Fe, Co, Ni, Zn, Rb, Zr, Sb, Ba, La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Hf, Ta and Th). Scandium, Mn, and Co are positively correlated with Fe, as they generally are concentrated in mafic minerals. The K/Rb ratios of three granitic rocks are 290-440. Slight variation of Zr/Hf ratios in granitic and tonalitic rocks (32-28) contrasts with large variation of Hf by a factor of 3. A fine-grained amphibolitic gneiss has a flat REE pattern and a total REE content of 12X chondritic abundance. It resembles Archean basalts, suggesting that its parent is basaltic, formed by partial melting of upper mantle material. A 3.04-Gyr old gray tonalitic gneiss (74-115) has a smooth and steep-sloped REE pattern with remarkable enrichment of light REE and depletion of heavy REE ($La_N = 71$, and $Yb_N = 6.4$). It has a total REE content of about 2X and a Ce_N/Yb_N ratio of 0.5X those of Saganaga tonalites analyzed by Arth and Hanson (1975). It is likely that this tonalite may have formed from a granitic melt which has been significantly contaminated by mafic material. A second tonalitic gneiss (74-222B) has a total REE content 2X higher than that of 74-115 and a significant negative Eu anomaly, suggesting that a plagioclase-rich component was removed from the magma. The REE patterns of two granites have very steep slopes, their Ce_N/Yb_N ratios are 160 and 85, respectively, significantly higher than that of granitic rocks from the Vermilion district. These granites might have formed by crustal anatexis of earlier Archean metasedimentary rocks. Two pegmatites show a strong positive Eu anomaly, but differ in total REE and other trace element contents reflecting that they are derived from different source materials.

PALEOMAGNETISM OF THE LATE PRECAMBRIAN BRULE LAKE INTRUSIONS, COOK COUNTY MINNESOTA

Donald M. Davidson, Jr., Henry Halls*, and James R. Burnell, Jr., Department of Geology, University of Minnesota, Duluth, *Department of Geophysics, University of Toronto

ABSTRACT

Paleomagnetic analysis, involving ac demagnetization up to 40 oe, has been carried out on one rhyolite flow (Keweenawan) and two porphyritic intrusions which cut flows in the Brule Lake area. These flows and intrusions are truncated by various units of the Duluth Complex.

The Brule Lake intrusive units give indications of primary reverse magnetization which has been altered by normal intrusive activity, probably associated with emplacement of the Duluth Complex. The northern intrusion (Fishbox Island) shows a hard primary component which is closer to a reversed than normal direction. The southern intrusion (Jock Mock Point) exhibits stable end points but with a two component response which in at least one sample indicates a soft, reversed state.

The rhyolite flow exhibits a mixed magnetic response with a harder normal and soft reversed components.

Mean site determinations and paleo pole positions for these sites are given below:

	Mean Site					Paleo Pole Position	
	D	I	N	K	α_{95}	Lat.	Long.
No. Intrusive-u	139°	-66°					
No. Intrusive-c	120°	-75°					
So. Intrusive-u	316°	12°	3	35	21		
So. Intrusive-c	317°	22°	3	35	31	34.04N	145.41E
Rhyolite Flow-u	307.5°	48°	3	31	23		
Rhyolite Flow-c	299°	55°	3	31	23	45.70N	173.35E

u - uncorrected

c - corrected structurally

Thus it appears that the southern most intrusion and adjacent flow unit more clearly show the effects of remagnetization than the northern sill. Although the results are consistent with available data on both normal and reversely magnetized rocks of Keweenawan age, positive correlation between the Brule Lake intrusions and the Logan sills does not appear feasible.

STRUCTURAL AND AGE RELATIONSHIPS AT THE LAC LA BELLE MAGNETIC ANOMALY, KEWEENAW COUNTY, MICHIGAN

James M. DeGraff, Department of Geology and Geophysics, Michigan Technological University, Houghton, Michigan 49931

ABSTRACT

Along the Keweenaw Peninsula of Michigan the contact between the Portage Lake Lava Series and the Jacobsville Sandstone has generally been considered to be a great thrust fault. This Keweenaw Fault describes a site along which the Middle Keweenawan PLLS on the north has been thrust southward over the Lower Cambrian(?) Jacobsville Sandstone, with a possible vertical throw of 10,000 feet (Bacon, 1966). Aeromagnetic maps for this region compiled by Balsley et al in 1963 delineate this regional contact quite well. However, an earlier map compiled from the same data by L.O. Bacon shows that a prominent magnetic anomaly exists along this contact near the site of Lac La Belle. This anomaly takes the form of a magnetic "high" which projects southward from the nearly east-west magnetic lineations of the PLLS into a region of low magnetic gradients underlain by Jacobsville Sandstone. Diamond drilling and field mapping has shown that this Lac La Belle magnetic anomaly is associated with a lobe of basaltic lava flows extending southward from the PLLS into the Jacobsville Sandstone.

The purpose of this project was to investigate the structural and age relationships of the PLLS, Jacobsville Sandstone and basalts within the area of the Lac La Belle magnetic anomaly. In order to accomplish this, the following four field methods were used:

- (1) ground magnetic work over the Lac La Belle magnetic anomaly,
- (2) palaeomagnetic studies of basalts in the anomalous zone in comparison with basalts of the PLLS immediately to the north,
- (3) geologic mapping and diamond drill hole correlations, and
- (4) two regional gravity traverses across the PLLS-Jacobsville Sandstone contact, one on either side of the Lac La Belle magnetic anomaly.

Some conclusions which can be drawn at the present time are that:

- 1) the flows within the anomalous zone have been rotated up to 45 degrees counter-clockwise with respect to the N.70° E. strike of the PLLS to the north,
- (2) faulting on both the east and west sides of the anomaly has been very important in controlling the emplacement and rotation of the anomalous lavas,
- (3) the exposed basalts associated with the anomaly are the eastern extension of a larger block of lavas which has been downdropped on the west and covered by Jacobsville Sandstone,
- (4) lavas in the lower section of the PLLS and within the anomalous zone

are not reversely magnetized, and therefore correlate with the Middle Keweenawan rocks of the Lake Superior basin, and

- (5) in this area the evidence points to the Jacobsville Sandstone being younger than the PLLS.

REFERENCES CITED

- Bacon, L.O., 1966, Geologic structure east and south of the Keweenaw fault on the basis of geophysical evidence, in The Earth Beneath the Continents-A Volume of Geophysical Studies in Honor of Merle A. Tuve: Am. Geophys. Union Geophys. Mono. 10, p. 42-55.

LEAD ISOTOPE INVESTIGATIONS IN THE MINNESOTA RIVER VALLEY

B.R. Doe, and M.H. Delevaux, U.S. Geological Survey, Denver, Colorado 80225

ABSTRACT

The U-Th-Pb isotopic systems have been investigated for whole-rock and feldspar samples of the foliated and also more massive phases of the Montevideo Gneiss of Lund (1956), the Sacred Heart Granite, and the adamellite of Section 28 near Granite Falls. We have not been able to resolve events which affected the Montevideo Gneiss prior to 3.0 b.y. ago. At approximately that time a thermal event reset the U-Th-Pb system in the older, dark-colored foliated phase. This event may have been accompanied by or resulted from the introduction of granitic magma which formed the massive phase of the gneiss.

The Sacred Heart Granite has a microcline-whole-rock isochron age of 2590 m.y. The feldspar isochron model-lead age is in excellent agreement at 2560 m.y., whereas the Pb-208/Pb-204 model age is somewhat younger at 2300 m.y. The cause for this variation is not understood at present.

The epizonal adamellite of Section 28 has a feldspar-whole-rock isochron of approximately 1850 m.y., determined by an acid-leach method. The model-lead age is 2200 m.y., but the Pb-208/Pb-204 model age is in excellent agreement with the acid-leach, feldspar-whole-rock isochron at 1850 m.y. The anomaly of about 350 m.y. in the model ages is similar to that found in rejuvenated cratons where Mesozoic and Cenozoic igneous rocks have penetrated an 1800 m.y.-old basement. The 1850 m.y.-old adamellite of Section 28 has penetrated an Archean basement of rocks ranging from 2600 to ~3800 m.y. in age. It is one of the few Precambrian examples displaying derivation of lead from a cratonized continent and the only example as old as 1850 m.y.

All the rocks appear to have lost about half of their uranium fairly recently, but thorium has been affected to a lesser degree. These relationships appear to be common in near-surface crystalline rocks and may reflect dilatancy.

PRECAMBRIAN HISTORY OF THE MORTON-NEW ULM REACH OF THE MINNESOTA RIVER VALLEY

S.S. Goldich, J.L. Wooden, G.A. Ankenbauer, Jr., T.M. Levy, and R.U. Suda,
Northern Illinois University, DeKalb, Illinois 60115

ABSTRACT

On the basis of current research on the Precambrian rocks in the Minnesota River Valley a tentative chronology of events in the Morton-New Ulm area is proposed.

Time - M.Y.	Event
(?)	Folding
1800 - 1200 (?)	Deposition of the Sioux Formation. Uplift and erosion.
1900 - 1800	Emplacement of diabasic dikes and small granitic plutons. Thermal metamorphism strong enough to reset mineral ages.
~2600	Late tectonic emplacement of aplitic and pegmatitic dikes. Late tectonic or syntectonic emplacement of Sacred Heart and related adamellites.
(?) 2700 - 2550	Deformation and low-grade metamorphism.
2800	Emplacement of granodiorite and adamellite.
3000 $\pm$ 150	Deformation and metamorphism of high-potash granite, basaltic rocks, and gray tonalitic gneiss. Possible formation of speckled gneiss in shear zones.
3050	Emplacement of high-potash granite and pegmatite. Emplacement (?) of high- and low-alumina basaltic dikes or sills. Deformation and metamorphism.
3550 $\pm$ 125	Extrusion and intrusion of trondhjemitic, tonalitic, and granodioritic magma. Possibly basaltic magma also at this time.

LITHIC AND MAJOR ELEMENT COMPOSITION IN THE SUPERIOR GEOTRAVERSE, ONTARIO

A.M. Goodwin, Department of Geology, University of Toronto, Toronto, Canada.

ABSTRACT

The Superior Geotraverse constitutes a rectangular area of 24,610 mi² bounded by 90° and 92°W longitude and 49° and 52°N latitude in the western Superior Province of the Canadian Shield. The area crosses or includes parts of six major east-trending subprovinces or belts which in alternating succession from south to north are: Wawa Volcanic, Quetico Gneiss, Wabigoon Volcanic, English River Gneiss, Uchi Volcanic, and Berens Plutonic Belt.

Lithic proportions (percent) in the Geotraverse are as follows: Granitic rocks - 69.2; Migmatite - 10.5; Metasedimentary rocks - 5.3; Volcanic rocks - 14.0; Mafic to ultramafic intrusions - 0.5; and Syenite - 0.4. Granitic rocks are equally divided between gneissic (34.8) and massive (34.6) phases. Volcanic rocks comprise mafic (12.8) and felsic (1.2) phases. The ratio of mafic to felsic volcanic rocks is 91.5 to 8.5.

Lithic proportions in the two gneiss belts differ significantly with the English River Belt containing equally high proportions of migmatite (49.7) and granitic gneiss (46.1) and negligible metasedimentary material, whereas the Quetico Belt has predominant migmatite (64.8) and metasedimentary material (29.0). This contrast reflects a higher degree of metamorphism together with greater exposure of older basement gneiss dated to be at least 3040 m.y. old in the English River Belt to the north.

The three volcanic belts are essentially similar in lithic composition. A salient feature is the high proportions of granitic rocks especially in the two northern belts (Uchi - 65.0; Wabigoon - 77.1) equally divided between numerous massive plutons and adjoining gneissic rocks. The latter appears to represent foliated plutonic rocks intrusive into nearby volcanic rocks which would imply a post-volcanic age dated at 2750-2850 m.y.

The weighted mean major element composition of the Geotraverse is as follows in weight percent: SiO₂ - 65.64, Al₂O₃ - 15.96, FeO (total) - 4.98, MgO - 2.32, CaO - 4.20, Na₂O - 3.85, K₂O - 2.32, TiO₂ - .45, MnO - .09, H₂O - .88, CO₂ - .09, P₂O₅ - .07. This compares closely with that of the Red Lake-Lansdown region of northwestern Ontario (Shaw, et. al.) as well as both of the Canadian Shield (Fahrig and Eade) and the Ukrainian shield (Ronov, et. al.), the only significant difference being low K₂O and higher CaO contents in the Geotraverse.

Although the tectonic development of the Geotraverse crust remains uncertain, available data indicate some blend of (1) spreading of older gneissic crust (older than 3.0 b.y.) with (2) accretionary growth of ensimatic volcanic belts (2750 -2900 m.y.) in resulting troughs and basins relative to a metastable craton to the north.

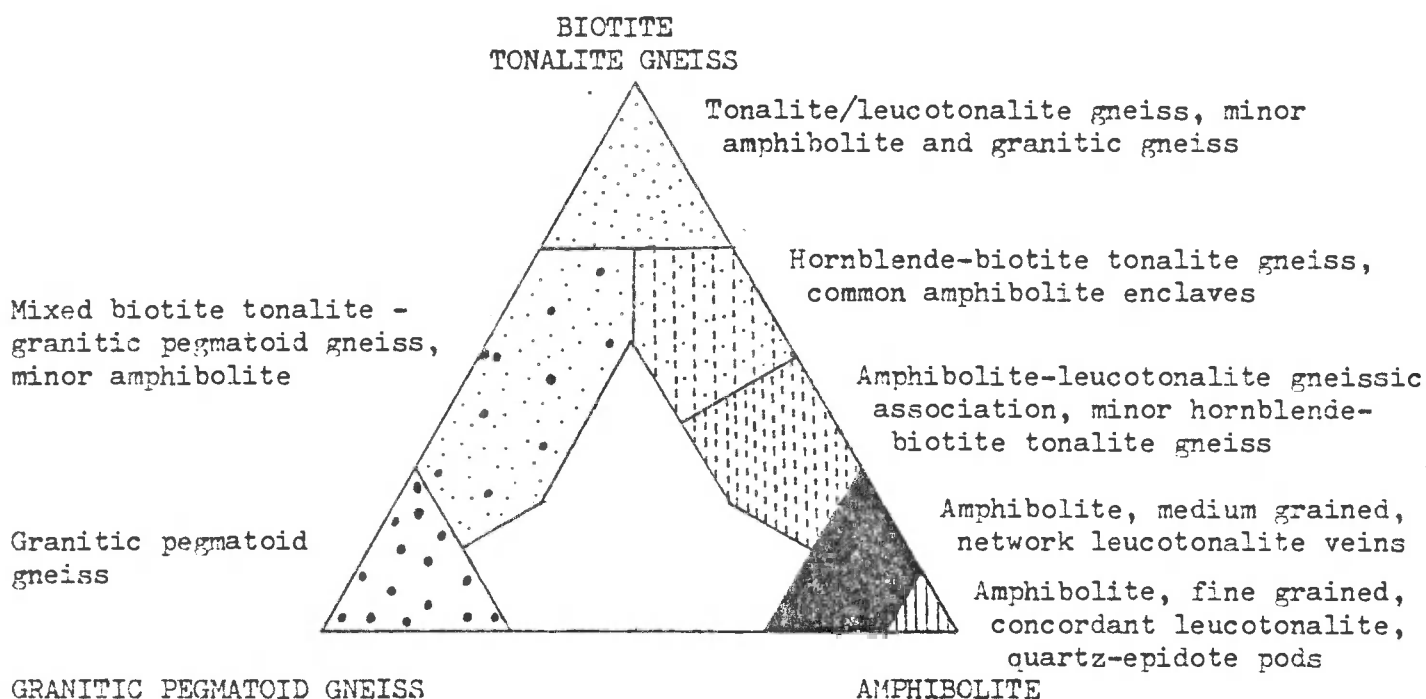
THE GEOLOGY OF GNEISSIC ROCKS IN THE KENORA DISTRICT, ENGLISH RIVER GNEISS BELT.

C.F. Gower, Department of Geology, McMaster University, Hamilton, Ontario

ABSTRACT

After an initial reconnaissance geological investigation of 2400 sq. km. in the southwest part of the English River Gneiss Belt, an area of 100 sq. km. near Kenora was selected for detailed study.

Most of the area is underlain by gneissic rocks which range from granitic to untramafic composition. They are best described with the aid of a "triangular diagram" having granitic pegmatoid gneiss, biotite tonalite gneiss, and amphibolite as end members.



Field studies suggest that, (i) much of the granitic material represents intensely deformed intrusive pegmatite, (ii), the amphibolite represents both mafic lavas and mafic dikes, but (iii) do not assist in determining a protolith for the biotite tonalite gneiss.

The tectonic history is complex. F_1 isoclinal folds have been refolded by tight to open F_2 folds. The minor F_2 folds have been used to define major F_2 folds. These major structures have been refolded by an F_3 fold which appears to be a rim synform associated with the margin of a large tonalite/granodiorite batholith. Two later periods of open folding (F_4 , F_5) also are recognized. Mafic dikes which have been intruded throughout the history of the area which, together with superimposed fold relationships assist in distinguishing individual deformational phases.

APPLICATION OF A FLOW DIRECTION TECHNIQUE TO THE PORTAGE LAKE VOLCANICS, MICHIGAN

James G. Grimes, Department of Geology and Geological Engineering, Michigan Technological University, Houghton, Michigan 49931

ABSTRACT

A study was made to test if the flow direction technique developed by Elston and Smith (1970) could be applied to the Portage Lake Volcanics in Michigan. The technique, as modified by Smith and Rhodes (1972) for basalts, presumes that elongated fragments (i.e. crystals) will statistically align themselves in the direction of flow.

Samples were collected from various locations within the series. The majority of samples were collected within the City of Houghton and represent a rough stratigraphic section through the series. The remaining samples were collected between South Range and Keweenaw Point.

The orientation of plagioclase crystals having a length/breadth ratio greater than three was measured in oriented thin sections. The results were then submitted to a computer program for statistical analysis.

Lineation values all had a chi-square value above the 90 percentile for two degrees of freedom. Aximuth was determined by imbrication and blocking effect criteria.

Two samples were collected within four feet of each other within the same flow to check the repeatability of the method. In addition to these two samples, another thin section was measured twice. The difference between the two flow directions were 10.3 and 11.2 in each case, respectively. This difference could be mostly accounted for by the ten degree intervals that the data is divided into for analyses.

The upper, middle, and lower portions of the Scales Creek Flow also was sampled to test the application of the method to some of the thicker flows in the sequence. Flow aximuths were S16.6W, S35.0E, and S0.6E respectively. The upper and lower samples generally conform to the aximuth directions of samples above (S2.8W) and below (S9.0E) the Scales Creek Flow.

Taken together, the results indicate a general flow direction from the north. Within the City of Houghton, the flow azimuth was S9.0E for the lower part, S2.0W for the middle part, and S28.0W for the upper part of the series. Individual sample directions are S17.0E and S1.0E for the lower part, S7.2W, S4.0E, and S4.5W for the middle part, and S23.4W and S33.7W for the upper part.

Further application of the technique could demonstrate regional patterns for directions of lava flow movements, and multiple sampling of long strike lengths of certain flows might allow triangulation of the source area.

REFERENCES

- Elston, W.E., and Smith, E.I., 1970, Determination of flow direction of rhyolitic ash-flow tuffs from fluidal textures: Geol. Soc. America Bull., v. 81, pp. 3393-3406.
- Smith, E.I., and Rhodes, R.C., 1972, Flow direction determination of lava flows: Geol. Soc. America Bull., v. 83, pp. 1869-1874.

THE SLATE ISLANDS: THE CENTRAL UPLIFT OF A METEORITE IMPACT CRATER?

H.C. Halls, Department of Geology, Erindale College, University of Toronto, Mississauga, Ontario L5L 1C6 and R.A.F. Grieve, Earth Physics Branch, Department of Energy Mines and Resources, Ottawa, Ontario

ABSTRACT

Shock metamorphic effects in samples from the Slate Islands, Lake Superior ($48^{\circ}40'N$, $87^{\circ}00'W$) suggest that the islands are part of a meteorite impact structure. The islands form the central uplift of a complex crater and are ringed by a submerged trough and annular ridge with a diameter of 30 km. Precambrian bedrock units are locally brecciated and cut by allochthonous breccia dikes. These dikes contain clasts of identifiable country rock and also fragments of a sedimentary unit, possibly Upper Keweenawan in age, which is no longer present in outcrop. The orientations of shatter cones present in the breccia host rocks indicate the interior of the islands as the approximate shock centre. Microscopic planar features, equivalent to those described from other impact sites, occur in quartz and plagioclase and the level of shock deformation increases towards the interior of the islands. The shock event postdates Keweenawan igneous activity (about 1.1 b.y. old) and on the basis of the erosion level, may be early Paleozoic in age.

GEOCHEMICAL PROCESSES FOR THE FORMATION OF MAGNETITE IN LOW-GRADE METAMORPHIC PRECAMBRIAN IRON FORMATIONS

Tsu-Ming Han, The Cleveland-Cliffs Iron Company, Ishpeming, Michigan 49849

ABSTRACT

A substantial number of magnetite ores, magnetite-containing specimens and their oxidized equivalents collected from the low-grade metamorphic iron formations in the Mesabi, Gogebic, and Marquette districts of the Lake Superior region, and the Lake Alabel District of the Quebec Province, Canada have been microscopically investigated. The study reveals that the magnetite in these iron formations not only varies in grain size, crystallinity, external morphology, inclusion composition, distribution, and genetic relationships to its coexisting minerals but also significantly differs in internal microstructures. The last variable was found to be the most useful key to the interpretation of the geochemical processes of the magnetite formation. These internal microstructures are normally not microscopically visible unless a laboratory-induced oxidation procedure is employed. The well-polished sections were heated at about 300°C for three to four days under weakly to moderately oxidizing conditions and then cooled to room temperature for reexamination. The most important internal microstructures in this study, as outlined by the artificially produced hematite are listed as follows:

1. Lath-like, bladed, wedge-shaped, rhombhedral, and hexagonal crystals arranged randomly, or subparallel, or in such forms resembling druses and inner linings of geodes within individual crystals, clusters, granules, and laminae of magnetite.
2. Irregular bodies resembling spheroids uniformly scattered throughout granules, clusters, and laminae of magnetite.
3. Botryoidal structures in clusters, laminae, and granules of magnetite.
4. Zonal and core-and-shell concentric structures in individual magnetite crystals with or without inclusions of the preexisting lath-like crystals.

All of the afore mentioned internal microstructures have been found in the magnetite coexisting with: (a) chert, (b) hematite and chert, (c) carbonates and chert, (d) silicates and chert, and (e) carbonates, silicates, and chert.

The outlines of crystals, irregular bodies, and botryoidal masses are apparently of restored preexisting hematite which was probably deposited as $\text{Fe}(\text{OH})_3$ gel. The later magnetite was developed by: (a) nucleation followed by one or several stages of enlargement, and (b) pseudomorphic replacement of hematite supplemented by extensive overgrowth.

Based on the ratio of: (a) the size of the existing magnetite crystals to that of their initial magnetite nuclei, and (b) the amount of magnetite to that of the restored preexisting hematite, the following conclusion is drawn: The migration of iron in conjunction with the redepositoin of iron as magnetite on nuclei of magnetite or preexisting hematite is a much more important magnetite forming process than the simple reduction of hematite or the metamorphic oxidation of the primary ferrous minerals like siderite and greenalite.

The presence of preexisting hematite in the magnetite laminae, clusters, and

granules of the silicate and carbonate iron formations indicates that some iron formations normally referred to as "silicate", "carbonate", and "mixed" facies might have been oxide facies prior to post-depositional alterations - silication, magnetitization, carbonatization, etc. Carbonaceous matter is believed to be responsible for the facies change.

On the basis of the results of these iron formation studies, one could conclude that the magnetite in the low-grade metamorphic Precambrian iron formations of the Lake Superior type found elsewhere may well have the same ancestry.

RARE EARTH ELEMENT STUDIES OF THE ARCHEAN GNEISSES OF THE MINNESOTA RIVER VALLEY

G.N. Hanson, Department of Earth and Space Sciences, State University of New York, Stony Brook, New York and S.S. Goldich, Department of Geology, Northern Illinois University, DeKalb, Illinois.

ABSTRACT

Rare earth elements (REE) have been analyzed on tonalitic to granodioritic units of the up to 3800 m.y. old Morton and Montevideo gneisses, mafic and ultramafic units within the gneisses, and later granitic intrusions. The subparallel REE patterns along with similarities in other geochemical data suggest that the upper amphibolite to granulite grade gneisses and later granitic intrusions have a similar origin resulting from partial melting of mafic quartz diorite or diorite sources, perhaps in the crust.

Significantly different REE patterns for K-rich pegmatoidal veins and zones containing porphyroblastic hornblende within the nebulitic Morton Gneiss suggest that under conditions of recrystallization and major element mobilization, the REE may have been mobilized on dimensions of many centimeters.

A relatively flat REE pattern for a tholeiitic amphibolite is similar, although slightly more enriched in REE, to the 2700 m.y. old Archean basalts in a greenstone belt in northeastern Minnesota (Arth and Hanson, 1975). Hornblende rich, komatiitic amphibolites have patterns with about 30 times chondrites for Ce and about 8 times chondrites for Yb. This would suggest that if the REE have not been affected by recrystallization, the source (the mantle?) for this rock type also is light REE enriched.

Rb-Sr GEOCHRONOLOGY OF THE MONTEVIDEO GNEISS, MINNESOTA RIVER VALLEY

C.E. Hedge, U.S. Geological Survey, Denver, Colorado 80225 and S.S. Goldich,
Northern Illinois University, DeKalb, Illinois 60115

ABSTRACT

The Montevideo Gneiss of Lund (1956) is a hybrid rock consisting of biotite-quartz-feldspar gneissic, amphibolitic, and granitic phases of different ages. The biotite gneiss, the oldest major phase, was probably derived from volcanic material of andesitic to rhyodacitic composition and is 3700 ± 100 m.y. old. Amphibolite clasts in the gneiss may represent basaltic lavas or dikes that were broken up.

At approximately 3000 m.y. ago, granitic magma was intruded in the form of small irregular masses, sheets, and lit-par-lit injections. The Rb-Sr systematics in the older gneiss were disturbed at this time. Failure to recognize the age difference between the older foliated gneiss and the younger more massive leucogranitic phase invalidates the earlier geochronologic investigations of the Montevideo Gneiss.

High-grade metamorphism (upper amphibolite to lower granulite facies) affected the massive phase as well as the older gneiss, but we are not certain whether this occurred shortly after emplacement of the leucogranite (~ 3000 m.y. ago) or during the interval from 3000 to 2600 m.y. ago.

A 2600-m.y. event is represented in the emplacement of large granitic masses exposed in the Minnesota River Valley southeast and northwest of the Montevideo-Granite Falls area. Locally intensive cataclasis affected the rocks approximately 2400 m.y. ago. These events also affected the Rb-Sr systematics in the older rocks.

Small masses of adamellite and numerous diabasic dikes were intruded in the Montevideo Gneiss 1850 m.y. ago, and locally these intrusions affected the Rb-Sr system in the older rocks.

THE TRACE ELEMENT GEOCHEMISTRY OF PEAT BOGS OVER DIFFERENT BEDROCK TYPES, SOUTHERN HOUGHTON COUNTY, MICHIGAN

Sue I. Jacobsen, Department of Geology and Geological Engineering, Michigan Technological University, Houghton, Michigan 49931

ABSTRACT

A preliminary investigation of the feasibility of using peat in geochemical prospecting in the Upper Peninsula of Michigan was carried out using twelve peat bogs in southern Houghton County. The bogs were sampled to determine if difference in bedrock type is reflected in the trace element geochemistry of the peat layers above them. The bogs were selected to provide as many bedrock varieties as possible: Portage Lake Lava Series, Copper Harbor Conglomerate, Nonesuch Shale, Freda Sandstone, and Jacobsville Sandstone.

Samples were taken at sites 100 ft. apart along at least one line run through each bog. As both the Davis and the Hiller peat samplers proved inadequate, a simple aluminum piston-type sampler was used. Peat samples 15 inches long at depth intervals of 3 feet were taken, as well as samples of the living Sphagnum moss mat and the underlying mineral material where possible. Peat was identified in the field as to type and degree of humification. Maximum peat depth differed from bog to bog and ranged from 3 feet to 30 feet.

The pH was determined in the laboratory and ranged from 3.1 to 6.0. After oven drying at 85° C for 24 hours, the peat was ashed at 500° C for 2 hours. Trace element concentrations are being determined using the Atomic Absorption Spectrometer.

As element distributions in peat profiles are not uniform, a study of the vertical distribution of trace elements is being made. Spatial distributions of elemental concentrations and pH are also being investigated.

ENGADINE DOLOSTONE OF MICHIGAN'S EASTERN UPPER PENINSULA: GEOLOGY AND RESOURCE EVALUATION

Allan M. Johnson, Institute of Mineral Research, Michigan Technological University, Houghton, Michigan 49931 and Harry O. Sorenson, Michigan Geological Survey Division, Department of Natural Resources, Stevens T. Mason Building, Lansing, Michigan 48926

ABSTRACT

Results of geologic mapping and core-drilling of the Middle Silurian Engadine dolostone are reported. The work is part of a continuing cooperative project between the Michigan Geological Survey and the Institute of Mineral Research to evaluate high-purity limestone resources of the State. Preliminary results of similar work on the Fiborn limestone were reported last year at this Institute (Johnson and Sorensen, 1975).

The massive Engadine dolostone is exposed as a resistant cuesta for more than 100 miles along the northern margin of the Michigan Basin from Manistique to Drummond Island. Despite a thickness of only 200 feet the shallow regional dip of 50 feet/mile south allows the unit to form a belt from 5 to 10 miles wide along the northern shores of Lakes Michigan and Huron. Three steel companies quarry metallurgical grade stone from the Engadine.

Previously unpublished field work by G.M. Ehlers, University of Michigan, and H.O. Sorenson, M.G.S., establishes the following stratigraphic subdivisions for the Engadine dolostone:

<u>Name</u>	<u>Description</u>	<u>Thickness</u>
Bush Bay dolostone	-massive, lt. gray with cream mottling, med. to coarsely crystalline, porous	50'
Swede Road dolostone	-massive (weathers thin), buff-brown, finely crystalline	33'
Prentiss Creek dolostone	-thinly bedded, gray to brown, chert layers, med. crystalline	26'
Rapson Creek dolostone	-massive, lt. gray-buff with lighter mottling, med-coarsely crystalline, porous	60'
Rockview dolostone	-massive, gray, med-coarsely crystalline, stromatolitic at base	44'
	TOTAL	213'

These divisions were established from field mapping in the eastern portion of the Engadine. Examination of 16 cores drilled during 1975 spanning 100 miles of the Engadine, support these stratigraphic subdivisions in the eastern portion. Cores from the western portion show some inconsistencies. However, if the Engadine is interpreted to have formed as a reef or carbonate bank along a shelf margin where minor onlap-offlap fluctuations occurred, these inconsistencies can be resolved. Features of the Engadine dolostone supporting this origin include its massive, porous structure, complete dolomitization, fossil assemblage, and its position in relation to other shelf formations and to the Michigan Basin.

Core logs and chemical analyses will be employed to evaluate the potential of the Engadine as a high purity dolostone. Results are scheduled for publication by the Michigan Geological Survey in 1977. This year similar work will begin on Traverse group limestones (Devonian) in the northern part of the Lower Peninsula of Michigan.

REFERENCES

- Ehlers, G.M., and Kesling, R.V. 1957, Silurian rocks of the Northern Peninsula of Michigan, Guidebook Mich. Basin Geol. Soc., 63 p.
- Ehlers, G.M., 1973, Stratigraphy of the Niagaran Series of the Northern Peninsula of Michigan, Univ. of Mich. Papers on Paleontology, no. 3, 200 p.
- Johnson, A.M., and Sorensen, H.O., 1975, Michigan Upper Peninsula Middle Silurian Limestones: Geology and Resource Potential, (abs.), 21st Annual Inst. on Lake Superior Geology, p. 16-17.

NATURE OF THE QUETICO-WABIGOON BOUNDARY IN THE DE COURCEY-SMILEY LAKES AREA, NORTHWESTERN ONTARIO

Manfred M. Kehlenbeck, Department of Geology, Lakehead University, Thunder Bay, Ontario

ABSTRACT

In the de Courcy-Smiley Lakes area, the boundary between the Quetico and Wabigoon Belts is expressed by a sequence of pelitic to semi-pelitic schists and gneisses. At the present level of erosion, these metasedimentary rocks are in contact with granodioritic gneisses, granites, and pegmatites, which are exposed to the south.

To the north of this area, regional metamorphism of volcanic and sedimentary rocks has resulted in greenschist facies assemblages which characterized the Wabigoon Belt in general. In the boundary zone the metamorphic grade increases southward toward de Courcy and Smiley Lakes.

Formation of three distinct foliation surfaces was accompanied by syn-tectonic as well as post-tectonic recrystallization producing polymetamorphic schists.

In the boundary zone, mineral assemblages comprising andalusite, sillimanite, cordierite, garnet, biotite, and muscovite form a facies series of the Abukuma-type.

The boundary between Quetico and Wabigoon Belts in this area is a complex zone in which rocks of both belts have been reconstituted by multiple-phase metamorphism and partial melting.

THE CENTRAL WISCONSIN BATHOLITH

Gene L. LaBerge, Geology Department, University of Wisconsin-Oshkosh, Oshkosh, Wisconsin 54901 and Paul E. Myers, Geology Department, Washington State University, Pullman, Washington

ABSTRACT

Geological mapping of over 1500 square miles in Marathon County, Wisconsin, has revealed an extensive complex of volcanic and possible co-genetic intrusive rocks. The volcanic rocks, as pendants and xenoliths, are surrounded by granitic intrusions showing an inward decrease in the volume of contaminant material. The volcanic "pendants" generally decrease in size and relative abundance westward across Marathon County, thus suggesting exposure of the eastern portion of a convex batholith roof with its apex extending approximately along the west edge of the county. The batholith comprises at least twenty separate stock-like plutons, each of which has its own contaminated margin. Mafic quartz diorites and quartz monzonites grade inward to a more granitic core. The younger plutons are more felsic.

Gravity and aeromagnetic maps and geological reconnaissance suggests that Marathon County and most of central Wisconsin are underlain by granitic rocks containing scattered volcanic roof pendants. We suggest that this plutonic complex be called the "Central Wisconsin batholith."

Aeromagnetic and geologic mapping show that several major structural trends intersect within Marathon County. These structural trends coincide with zones of intense cataclasis which occurred before, during and after batholith emplacement. Most of the six northeast-trending cataclastic zones mapped to date terminate against or merge with a major northwest-trending zone which crosses the southwestern part of the county. Although the cataclastic zones locally acted as conduits for magmas, most of the plutons show features of pervasive shearing, suggesting a long period of intrusion alternating with cataclasis. Available isotopic ages indicate the batholith was formed during Middle Precambrian (Penokean?) time.

ORIGIN OF LAMINAE IN PRECAMBRIAN IRON-FORMATION

M.S. Loughheed and J.J. Mancuso, Department of Geology, Bowling Green University, Bowling Green, Ohio 43403

ABSTRACT

The original particulate constituents of Precambrian iron-formation are biogenic-carbonate minerals, opaline silica tests and organic material. These constituents control Eh and pH of contiguous water which is replenished from an open sea source. Important secondary minerals, which include ferroan carbonates, iron oxides, iron silicates, chalcedony-quartz, and pyrite, are produced in response to environmental factors affecting the original constituents, and we have discussed their genesis over the past several years at these meetings. Typically, in banded iron-formation, the thickness and lateral extent of the bands or laminations are determined by the presence of opaline slurry or gel. An exception occurs when grains of secondary carbonate constitute the bedload during current transport and are then deposited as thin laminae of nearly pure carbonate, (ex. Empire mine, Negaunee-siderite facies.). Most commonly, however, laminae are deposited from a bedload composed primarily of biogenic opaline gel or slurry which functions as a medium of support for any combination of the other constituents of iron-formation. Siliceous laminae, which may be more than one centimeter thick, often contain components such as flakes and shreds of algal hash, which commonly show evidence of having been transported by laminar or turbulent current flow. Commonly undulating bedded algal mats are inundated by an opaline slurry mix to produce an anoxic environment conducive to the production of pre-greenalite (greenaloid) which is the precursor of greenalite. Beds of this nature, as well as beds principally composed of greenalite granules, upon dewatering and concomitant compression, produce thin undulating laminae, notably in "slaty" facies, but when oxidized they produce iron-oxide chert laminae. Graded bedding commonly occurs in chert laminae containing particulate material such as granules. The suspended load was apparently transported in a tenuous silica slurry or gel, which upon coming to rest, allowed the load to gravitationally settle into a graded profile. There is at least one case in which chalcedonic laminae were formed by gravity accumulation of siliceous tests of planktonic organisms. Normally the tests would be comminuted to a slurry during bedload transport by water currents. These few genetic examples of laminae in iron-formation, emphasize the complexities involved when we use the term "banded iron-formation."

PENOKEAN STRUCTURES AND PLUTONIC ROCKS IN PORTAGE AND WOOD COUNTIES, WISCONSIN

R.S. Maass and L.G. Medaris, Jr., Department of Geology and Geophysics,
University of Wisconsin, Madison, 53706 and W.R. Van Schmus, Department of
Geology, University of Kansas, Lawrence, 66044

ABSTRACT

Three exposures of Precambrian rocks along the Wisconsin River (Stevens Point, Conants Rapids, and Biron Dam) have been investigated in order to establish the relative and absolute ages of lithologic units and to characterize the geometry and age of folding.

Relative ages of the lithologic units from oldest to youngest are: banded quartzo-feldspathic gneiss and amphibolite (the Basal Group of Weidman, 1907); medium-grained tonalite; a series of fine-grained tonalite dikes, less mafic with decreasing age of intrusion; mafic dikes; and diabase. All these rock types except for diabase have been recrystallized under middle grades of metamorphism. Quartzo-feldspathic gneiss and tonalites contain quartz, microcline, plagioclase (oligoclase to andesine), biotite, hornblende, epidote, sphene, and opaques; amphibolite and mafic dikes contain hornblende, plagioclase (andesine to labradorite), and sphene + biotite and epidote.

An early deformation produced isoclinal folds, F_1 , and a penetrative foliation, S_1 , in the banded gneiss. S_1 is parallel to compositional banding, S_0 , except in fold hinges, where S_0 is transected by S_1 . A later deformation produced broad open folds, F_2 , in the gneiss, with axial surfaces at a high angle to S_1 . The gneiss contains a pronounced mineral lineation, L_1 , parallel to F_1 and F_2 fold axes. The tonalites and mafic dikes, although intrusive into the gneiss and discordant, at least in part, to structures in the gneiss, contain mineral lineations which are parallel to the linear elements in the gneiss, plunging steeply to the southeast. In addition, S_1 is present in the medium-grained tonalite.

A U-Pb age of 1900 m.y. from zircons in the medium-grained tonalite (Van Schmus, et al., 1975) indicates that intrusion and deformation occurred during the Penokean Orogeny. Although the banded gneiss may be Archean in age, it was re-worked during the Penokean Orogeny, and the predominant structures in it were produced during that event.

REFERENCES

- Weidman, S., 1907, The geology of north central Wisconsin, Bull. No. 16, Wis. Geol. Natural History Survey.
- Van Schmus, W.R., et al., 1975, Geology and Rb-Sr chronology of Middle Precambrian rocks in eastern and central Wisconsin: Geol. Soc. Am. Bull. 86, 1255-1265.

GEOPHYSICAL PROSPECTING OFF KEWEENAW PENINSULA

Robert P. Meyer, J. Robert Moore, Edgardo L. Nebrija and Charles T. Young,
Department of Geology & Geophysics, Geophysical and Polar Research Center,
University of Wisconsin, Madison 53706

ABSTRACT

With NOAA-Wisconsin Sea Grant sponsorship, we have been conducting experiments using towed resistivity and active-source audiomagnetotelluric (AMT) measurements and magnetic and high-resolution seismic profiling to explore for copper deposits offshore of Keweenaw Peninsula. Among the areas studied were Copper Harbor and Silver Island where there are known underwater copper veins, Great Sand Bay where offshore extensions of onshore copper-bearing fissures may exist, Five-Mile and Seven-Mile Points where we searched for a chalcocite deposit within the Nonesuch Shale, and Bete Grise Bay where a potential placer deposit may exist.

Surface- and bottom-towed arrays were both used in resistivity profiling. In 1975, AMT tests were started using a 150 m diameter circular loop of wire laid on the lake bottom and excited by a 400 Hz AC generator as source. With the ship's position regulated by electronic navigation, concentric arcs were traversed about the loop to measure the vertical magnetic field, radial magnetic field, and tangential electric field. Both methods yielded distinct and reproducible anomalies in apparent resistivity and E/H ratios over known copper veins at Copper Harbor and correlatable anomalies over expected lithologic contacts. A zone of heavy-mineral concentrations inside Great Sand Bay was discovered with towed resistivity and verified with AMT. The apparent resistivity correlates inversely with the heavy-mineral content of the sands. A probably underwater vein was also discovered in this area. At Five-Mile and Seven-Mile Points, the offshore extensions of the Nonesuch Shale were mapped and structures favorable to copper deposition were delineated. Both methods are strongly affected by topography. For resistivity profiling, a first-order correction for topography has been developed and applied.

High-resolution seismic and magnetic profiling at Bete Grise Bay delineated a basin off the Montreal River characterized from grab samples by anomalous concentrations of trace metals that decrease outward from the center of the filled basin. Within this area we also delineated a logical offshore manifestation of the Keweenaw Fault. Whether the anomalies represent the lake bottom expression of a deeper hydrothermal deposit, a placer deposit formed during lower lake levels from materials delivered by the Montreal River, or results from more current enrichment of surficial sediments is not presently known, and this question awaits the opportunity for physical sampling at depth.

DIAMOND DRILLING IN ENVIRONMENTALLY SENSITIVE AREAS — ENVIRONMENTAL IMPACT: MONITORING AND ASSESSMENT

M.G. Mudrey, Jr., Wisconsin Geological and Natural History Survey, 1815 University Avenue, Madison, Wisconsin 53706, Bruce C. Parker, Department of Biology, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24601, Keros Cartwright, Illinois State Geological Survey, Natural Resources Building, Urbana, Illinois 61801, and Lyle D. McGinnis, Department of Geology, Northern Illinois University, DeKalb, Illinois 60115

ABSTRACT

A sophisticated exploratory diamond drilling program can be mounted to moderate depths, and environmental disturbance minimized in a conscientious program involving impact assessment, training, and real-time feedback among all parties. Although not normally the case with exploratory drilling, environmental disturbance can occur in sensitive areas such as wilderness areas, public park lands, and delicate, unique regions, such as the polar regions. One factor, of course, is the public fear that the proposed exploratory drilling program might irreversibly disturb environmental conditions in areas noted for their recreational and scientific value. A secondary fear is that exploitable natural resources will be found, and that they will be developed causing major impact to the local environment.

It is important to recognize that the concept of no impact is an unrealizable human goal. The objective of all impact statements is to minimize or reduce potential adverse impacts to the environment, whenever and as far as possible and practical.

We propose to address only the design and implementation of an environmentally responsible exploratory drilling program in a sensitive area, the dry valley region of Antarctica. From January 1973 until December 1975, a comprehensive diamond drilling program in antarctic permafrost and under severe environmental restraints — the Dry Valley Drilling Project — was carried on. A total of 13 months of drilling resulted in the recovery of over 2100 meters of core at 15 sites. Although scientific in objectives, the international, multidisciplinary program, and its techniques of environmental analysis are applicable to resource-oriented drilling programs in other areas of environmental and public concern, such as the scenic vistas of the Lake Superior region.

The first stage of environmental evaluation, after identification of the target sites, was the preparation of an environmental assessment, in which the proposed engineering operations plans, and possible environmental impacts were identified. These were addressed by an impact matrix which identified all projected actions and all characteristics of the environment. Probability, areal extent, and significance were assessed at this time by an impact committee consisting of environmentalists, project engineers, and other knowledgeable scientists. Potential environmental impacts were identified, and revision of proposed operations were made without undue hardship to the environment or to the drilling contractor, in as much as no operations had yet started.

Subsequently, appropriate documents were submitted for review to governmental bodies. Questions raised were addressed by the environmental committee. Pertinent documents directly addressed the proposed program, and the language was directed to the general public. Technical details were appended. An effort was made to make the main text of the document readable and concise.

In the case of DVDP, the antarctic soil and lake ecosystems are particularly delicate, and consequently vulnerable to any human activity. An environmental scientist on the drill site, and prior environmental discussion of each site by scientists and drill team personnel comprised the basis for the DVDP environmental protection program. An operations procedure and monitoring scheme was implemented to detect and control environmental impact. Monitoring before, during, and after the drilling operations identified environmental changes caused by the activities at all sites, and those results were reported to enhance the accuracy of the predictive model, the Environmental Impact Appraisal. One objective was to prevent or reduce impacts by DVDP, and thus assist planning for any future projects in Antarctica.

For DVDP, critical environmental limitations included no surface transport, minimal crew size, few drilling options with respect to equipment and circulating fluids, an absolute requirement that all waste and equipment be removed from the site areas, and that an interactive environmental monitoring program be in constant operation.

THE WAUSAU SYENITE OF CENTRAL WISCONSIN

Myers, Paul E., Department of Geology, Washington State University, Pullman, Washington 99163

ABSTRACT

The Wausau syenite-quartz syenite pluton in two segments and the more alkalic Stettin syenite pluton are exposed west of the Wisconsin River near Wausau in central Wisconsin. These Middle Precambrian (1650 ± 50 m.y.) plutons are concentrically zoned and show a distinct north-northeasterly elongation. Each pluton has a contact metamorphic zone of fenitized wall rocks, an alkalic, laminated, xenolith-rich wall zone, an intermediate zone, and a core. Silica content increases inward in each pluton.

The southern segment of the Wausau pluton is circular in plan with a diameter of eight miles. Although the core and south half of this caldera-like structure were intruded by granite of the Ninemile pluton, its structure is preserved as a discontinuous ring of large xenoliths five miles in diameter. The largest of these xenoliths -- the Rib Mountain quartzite -- is over two miles long. Bedding in the xenolith dips very steeply southward toward the granite core. The top of the xenolith has been eroded leaving a keel-shaped mass, slightly convex northward, and surrounded at depth by quartz syenite of the crescentic intermediate zone. Quartzite xenoliths near intrusive contacts are typically veined and impregnated by K-feldspar. Pyroxene and amphibole syenite commonly containing volcanic xenoliths, form a discontinuous outer rim (wall zone) of the southern segment.

The northern segment of the Wausau pluton is semicircular in plan with its truncated southern edge along the Rib River. The Stettin pluton is contiguous with it on the northwest. Although its size and internal structure are similar to that of the southern segment, its intermediate zone consists of coarse gray syenite, and volcanic xenoliths predominate. The older northern segment probably represents a caldera structure, which was partially destroyed by intrusion of the southern segment.

The Stettin pluton is oval in plan with dimensions of 5.0 x 3.5 miles. Three major zones distinguished in mapping were: (1) a wall zone comprising aplitic biotite syenite, nepheline syenite gneiss, and "tabular syenite", (2) an intermediate zone, aplitic to pegmatitic amphibole and pyroxene syenite with swirled flow lineation, and (3) a circular core zone one mile in diameter comprising a rim of magnetite-rich nepheline-hedenbergite-fayalite syenite, and an inner core of pyroxene syenite.

Both the Wausau and Stettin plutons possess strongly metasomatized, but unassimilated xenolith-rich wall zones. Concentric cataclastic lamination was developed by high-angle displacements accompanying the forceful emplacement of these plutons. Subsequently, more passive intrusion of the Ninemile granite caused a partial foundering of the southern part of the Wausau pluton.

MODIFICATION OF ENGINEERING PROPERTIES OF ST. PETER SANDSTONE

C.R. Nelson and D.H. Yardley, Department of Civil and Mineral Engineering,
University of Minnesota, Minneapolis, Minnesota 55455

ABSTRACT

The St. Peter sandstone is a formation of major geotechnical importance in the Twin City Metropolitan area as well as elsewhere in Minnesota and some nearby states. Nearly 200 miles of tunnels and other openings have already been constructed in it in the Metro area.

The St. Peter is a rather massive, weakly cemented, very pure sandstone of 98.5% - 99% SiO_2 . The compressive strength varies between 670 and 2800 psi in harder zones, but in softer zones it commonly varies from less than 100 to 300 psi, hence while some openings in it will support themselves most need some type of support. Because most of its strength is a result of compaction and grain interlocking, it is water-sensitive to the degree that if water agitates the grains much of the sandstone will deteriorate rapidly. The St. Peter has a porosity of about 28% and a permeability of 3.5×10^{-3} cm per second. The grains are quite rounded, have a frosted surface and a diameter of 0.1 mm to 0.5 mm.

A spray-grouting technique has been developed by the senior author, using a silicate-based liquid that can permeate into exposed sandstone for a few inches. This forms a hardened shell of sandstone with a compressive strength on the order of 1500 psi in the soft zones. Test patches in place for 3 years show no evidence of deterioration.

This system of artificially strengthening sandstone is being used for rehabilitation of utility tunnels. It is also being used as the main excavation support on a 10 foot tunnel where it has replaced the use of steel rings and oak lagging at a substantial cost reduction. Elimination of steel and wood support makes it possible to pour a final concrete lining directly against the sandstone so that when the tunnel is pressurized the resistance of the coupled sandstone wall will so greatly decrease lining deformation that steel reinforcing is not required. Spray-hardening also makes it possible for the first time to apply shotcrete to the St. Peter sandstone in this area.

It has been estimated that the cost savings on one large tunnel, and for one utility tunnel repair project, both in progress, will be about 1.3 million dollars. Support funds of less than \$100,000 from the NSF, RANN program have led to the development.

ANATOMY OF A WELL-COVERED GREENSTONE BELT, NORTHWESTERN MINNESOTA

Richard W. Ojakangas, University of Minnesota, Duluth, Duluth, Minnesota 55812

ABSTRACT

The rocks of the Birchdale-Indus area are part of a poorly-exposed volcanic-sedimentary sequence within the Wabigoon Volcanic Belt. The bedrock is Early Precambrian in age, and includes mafic to intermediate flows and intrusives; felsic dikes, agglomerates, tuffs and volcaniclastic rocks; iron-formation and associated metasediments; and granitic rocks of Algoman age. All of these lithologies are cut by northwest-trending Middle Precambrian mafic dikes. The area is well-covered by Pleistocene deposits.

The volcanic-sedimentary sequence has been isoclinally folded; northeast-trending bedding and foliations are generally steep to vertical. One doubly-plunging anticline and one syncline have been mapped within the area. A second folding with more northerly-trending fold axes is indicated by some general and detailed relationships. Three sets of faults and fractures are documented; the first set trends east-west, the second northwest, and the third northeast. All of the Lower Precambrian rocks have been metamorphosed to amphibolite grade.

Synthesis of the geology of the Birchdale-Indus area with that of the Emo area in adjacent Ontario (Fletcher and Irvine, 1954) allows an interpretation of the development of the volcanic accumulation. Mafic and intermediate volcanic and intrusive rocks apparently constitute the lowest stratigraphic unit. An explosive felsic volcanic center, marked by abundant agglomerates, developed upon the mafic platform in the vicinity of Birchdale, Indus and Emo. Felsic tuffs, volcaniclastics, and iron-formation were deposited outward from this center.

The Birchdale-Indus area, and areas to the west and south, have been actively explored for base metal sulfide deposits for the past decade. Thick zones of massive, sub-massive, and disseminated pyrite and/or pyrrhotite have been penetrated at several localities, but copper and zinc minerals have not been found in economic quantities. Several of the drilled iron-sulfide bodies are associated with oxide iron-formation.

REFERENCES CITED

- Fletcher, G.L., and Irvine, T.N., 1954, Geology of the Emo area: Ontario Division of Mines 63rd annual report, V. LXIII, part 5, 36 p. plus map No. 1954-2, scale 1 inch to 1 mile.

CARBON IN METAMORPHOSED SEDIMENTS FROM ISUA, WEST GREENLAND

Eugene C. Perry, Jr. and Syed Neaz Ahmad, Department of Geology, Northern Illinois University, DeKalb, Illinois 60115

ABSTRACT

About 2.5% graphitic carbon ($\delta^{13}\text{C} = -16.1 \text{ ‰}$ vs. PDB) occurs in a specimen from the 3.7×10^9 year old supracrustal sequence at Isua, West Greenland. The specimen, which contains quartz, amphibole, and minor magnetite and pyrite, is associated with a thick succession of metamorphosed chert and magnetite-bearing iron-formation and within 2.4 km across strike of a thick quartz-magnetite unit containing sufficient iron to be of possible commercial significance. Rocks in the area have been metamorphosed to amphibolite facies and are sufficiently sheared so that primary textures are obliterated.

Carbonaceous organic matter is a common constituent of iron-formation, and it has been suggested that the iron oxide of iron-formation is a biogenic precipitate. Thus, the association of carbonaceous material with oxide facies iron-formation at Isua is consistent with an organic origin for this ancient carbon. However, the Isua carbon is enriched in ^{13}C by about 15 ‰ compared to later Precambrian material of known biogenic origin. Since metamorphism accompanied by isotope-fractionating reactions could produce a 15 ‰ carbon isotope fractionation, the stratigraphic association of this carbon with iron-formation may be a more reliable guide to its origin than is its present isotopic composition.

OLD PRECAMBRIAN W GNEISSES IN NORTHERN MICHIGAN

Zell E. Peterman, Robert E. Zartman, and P.K. Sims, U.S. Geological Survey, Denver, Colorado 80225

ABSTRACT

Radiometric dating of gneisses in the western part of northern Michigan has confirmed the presence of an ancient sialic terrane that formed more than 3400 m.y. ago. An antiformal structure in the Watersmeet area contains a core of tonalitic to granitic gneiss that is surrounded by folded and metamorphosed Precambrian X graywackes. The gneiss is cataclastically deformed and recrystallized, and geochronologic data reflect the effects of severe tectonic and thermal events. Whole-rock Rb-Sr systems are highly disturbed, but data for samples from two localities define secondary isochrons of about 1800 m.y. A substantially older age of the gneiss is indicated by high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.773 to 0.717 for the two isochrons. These high initial ratios resulted from local redistribution of previously generated radiogenic ^{87}Sr during the major period of cataclasis and recrystallization. Metamorphism of adjacent Precambrian X rocks occurred synchronously with the reactivation and mobilization of the gneiss as suggested by an 1810 m.y. isochron obtained on four whole-rock samples of graywacke immediately adjacent to the gneiss along the northern contact.

U-Pb data obtained on zircon separated from the gneisses also reflect the complex geology history but clearly place the time of primary crystallization at 3400 m.y. ago or more. Three size fractions of zircon from a tonalitic gneiss have $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 3310 to 3370 m.y. and a primary age of about 3500 m.y. is suggested. Zircon from a compositionally similar but much more thoroughly deformed and recrystallized phase of the gneiss yields $^{206}\text{Pb}/^{238}\text{U}$, $^{207}\text{Pb}/^{235}\text{U}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ ages that are concordant at 1760 m.y. This lower age agrees with the whole-rock Rb-Sr ages and apparently indicates total resetting or perhaps even crystallization of the zircon during this metamorphic episode. Data for two zircon fractions from a leucocratic phase of the gneiss plot on a chord that intersects concordia at about 2600 m.y. These data may indicate the presence of granitic intrusions that were emplaced in the older gneisses during the Algoman orogeny. About 20 km northwest of the gneiss at Watersmeet, the 2710 m.y.-old Puritan Quartz Monzonite and Precambrian W metavolcanic and metasedimentary rocks form a greenstone-granite terrane that evolved in an ensimatic environment. The presence of Algoman granitic rocks in the older gneiss terrane may indicate that both blocks were in juxtaposition at 2600 to 2700 m.y. ago and subsequently formed a continuous and coherent sialic basement to the Precambrian X sedimentary basins.

A SYSTEMS APPROACH TO ENVIRONMENTAL GEOLOGY

H.O. Pfannkuch, Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota 55455

ABSTRACT

The term "environmental geology" has been loosely applied to situations ranging from pure engineering problems to those of traditional general geology. The concept needs clarification and definition in order to provide the reference space in which solutions for the most pressing problems can be attempted. This is attempted by a systems approach where the three interacting principal components are human ecology, geology on a global scale, and cultural anthropology from a socio-economic point of view.

The approach is based on an analogy argument, that is that human ecosystems behave in a similar way as other ecosystems. This means that ecosystem concepts such as structure, process dynamics and evolutionary trends from young and unstable but highly productive to mature, complex and stable systems can be used as parallels. The interface with geology is provided by global material cycles and energy flow processes. The impact of interaction is measured in a first order approximation by simple mass change to total mass, and rate change to geologic rate relationships. It has to be refined to include effects of additivity and accumulation, and those of stability of feedback relations. In the latter category fall the triggering effects of possibly small temperature changes on world climatic changes. Limitations of geological nature can be expressed by consumption or use rates, such as in resources where rate of formation is compared to rate of consumption or with the carrying capacity of the earth where loading rates are compared to dissipation or regeneration rates.

In the socio-economic context, environmental geology has two contributions to make. On a short term basis it has to help make environmentally sound compromises that can be achieved within the present structure of time and space references in the decision making process. This, however, is only a temporary and transitional solution, in the end environmental geology will have to provide the basis on which new and consistent time and space scales will have to be developed for environmentally acceptable decision making processes.

ENVIRONMENTAL IMPLICATIONS OF GROUNDWATER-LAKE INTERACTION WITH LAND USE APPLICATION

Dave Pollack and H.O. Pfannkuch, Department of Geology and Geophysics,
University of Minnesota, Minneapolis, Minnesota 55455

ABSTRACT

Many lakes, if not the majority, have to be viewed as part of and an expression of local and regional groundwater flow systems. Lake level variations are therefore strongly related to watertable fluctuations, especially in lakes without surface water inlets or outlets. Current methods of establishing groundwater contribution to the general lake water balance only give net contributions which are insufficient to calculate residence times of chemical or biological inputs. An areal flow net method is discussed to calculate absolute amounts of groundwater inflow and outflow and its spatial relationships with the lake.

Analysis of a cross section through a lake and its aquifer shows that even with a fully permeable and uniform lake bed there will be crowding of streamlines near the shore, which means relatively higher flow velocities of groundwater and enhanced transport activity in this region. Analog and dimensional analysis of some very simple cases are carried out to demonstrate the dependence on lake-aquifer geometry and to define the critical parameters. These are thickness of the lake-aquifer, degree of depth penetration of the lake, and ratio of the aquifer flow section to the lake-aquifer interface which is given by the lake diameter. Further increase of flux near shore occurs when large portions of the lake bottom are sealed by impermeable sediments.

The direct environmental implications are two fold: First it is necessary to have a clear picture of true groundwater inflow and outflow in order to relate it to the total lake budget, this provides insight into the relative importance of groundwater carried pollution. Localization and identification of areas with high groundwater flow activity in the near-shore region have obvious application to land use planning and regulation such as the implacement of domestic sewage disposal or treatment facilities. The severity of impact depends on length of flowpaths, residence time of pollutants, and adsorption or regeneration capacity of the hydrogeologic unit. Guidelines are given to classify lakes on a semi-quantitative basis according to the expected volume contribution of the active flow region near shore.

PETROLOGY AND STRUCTURE OF THE LATE PRECAMBRIAN
SILVER CREEK CLIFF AND LAFAYETTE BLUFF MAFIC
INTRUSIONS, LAKE COUNTY, MINNESOTA

Neil M. Pope, Department of Geology, University of Minnesota, Duluth, Duluth, Minnesota, 55801

ABSTRACT

Approximately 4-1/2 Miles northeast of Two Harbors, Minnesota, the North Shore Volcanic Group is intruded by the Silver Creek Cliff sill which trends north-northeast from Silver Cliff for 6 miles. The Lafayette Bluff sill, approximately 6-1/2 miles northeast of Two Harbors, intrudes the North Shore Volcanic Group and trends north toward the Silver Creek Cliff sill.

The Silver Creek Cliff sill is dominantly olivine diabase with thin layers and lenses of olivine-free diabase. Commonly a plagioclase - augite pegmatitic facies borders the lenses or an entire lens may be pegmatitic. The Silver Creek Cliff sill is approximately 200 feet thick and is conformable with the lava flows throughout most of its extent. In the Encampment River area the contact of the sill is steep and crosscuts the flows. This area may represent the feeder zone for the sill.

The Lafayette Bluff sill is an amygdaloidal porphyritic olivine diabase with plagioclase phenocrysts which average 2 cm in length. The sill is approximately 600 feet thick and is deformed into a south-plunging syncline and anticline. Subsidence of the underlying flows into the magma chamber is proposed for the origin of this deformation.

The mineral compositions of the sills are similar. The olivine diabase of each sill normally consists of an average of 66% plagioclase, 12% olivine, 16% augite, 2% Ca-poor pyroxenes, 2% altered interstitial material, 2% opaques (ilmenite and magnetite), and trace amounts of apatite and a interstitial granophyric intergrowth of quartz and alkali feldspar.

Field evidence does not support any definite structural relation between the sills. The Lafayette Bluff sill is poorly exposed where it approaches the Silver Creek Cliff sill, and there are no outcrops which show any contact between them. A whole rock analysis (by S.S. Goldich, 1939) of the diabase from the Lafayette Bluff sill shows 46.9% SiO₂, 21.0% Al₂O₃, 8.8% total Fe, and 4.7% MgO. An average of three new whole rock analyses of the Silver Creek Cliff olivine diabase shows 47.8% SiO₂, 17.5% Al₂O₃, 11.2% total Fe, and 6.5% MgO. The Fe/Mg is 1.73 for the Silver Creek Cliff sill olivine diabase and 1.86 for the Lafayette Bluff sill olivine diabase. Both sills contain normative hypersthene. The olivine diabase from the Silver Creek Cliff sill has 7.1% normative olivine indicating the diabase is an olivine tholeiite. The diabase of the Lafayette Bluff sill has 0.2% normative quartz suggesting the diabase is on the border of oversaturation or of being a quartz tholeiite, despite the modal olivine.

CORRELATIVE IRON-FORMATIONS AND VOLCANIC ROCKS OF PRECAMBRIAN X AGE, NORTHERN MICHIGAN /

William C. Prinz, U.S. Geological Survey, National Center -- Stop 954, Reston, Virginia 22092

ABSTRACT

The Ironwood, Vulcan, and Negaunee Iron-formations have long been accepted as correlative. They, along with immediately underlying slate and quartzite (Palms, Felch, Siamo, and Ajibik), are sandwiched between shallow-water quartzite and dolomite below, except where locally absent because of erosion or nondeposition, and eugeosynclinal graywacke and slate above (Michigamme, Copps, and Tyler). Volcanic rocks of the Hemlock Formation in Iron County, the Emperor Volcanic Complex of the eastern Gogebic range, and possibly the volcanic rocks at Blair Lake near Watersmeet also occupy this stratigraphic interval. Except for the eastern end of the Gogebic range, the distribution of the iron-formations and the volcanic units is mutually exclusive. Volcanic units are centrally situated in Iron and eastern Gogebic Counties, whereas the iron-formations are to the east in the Marquette and Menominee districts and to the northwest in the Gogebic range. The ironformations are relatively thin compared with the highly variable and locally great thicknesses of the volcanic units.

Volcanic rocks of the Emperor Volcanic Complex are interbedded with and overlies the upper part of the Ironwood Iron-formation in the eastern Gogebic range, and tuff beds are present in the lower part of the Ironwood in the main part of the range. Thus, the Emperor Volcanic Complex and the Ironwood Iron-formation are, at least in part, equivalent in time. Hemlock volcanics, on the other hand, have been thought to be younger than the iron-formations. This is based on correlation of ferruginous conglomerate beneath the Hemlock with the Goodrich Quartzite, which overlies the Negaunee Iron-formation. I suggest here that this conglomerate is not Goodrich, and that Hemlock volcanic rocks correlate with the Emperor, and thus, at least in part, with the Ironwood, Vulcan, and Negaunee Iron-formations.

I postulate that the iron-formations were deposited in relatively stable and slowly subsiding areas bordering a tectonically unstable and rapidly subsiding basin or series of basins or troughs in which large volumes of volcanic material accumulated. The northwestern margin of the volcanic basin was near the eastern end of the Gogebic range, probably striking west-southwest into Wisconsin south of the main iron range. The eastern margin of the basin lay approximately along the boundary between Dickinson and Iron Counties. The basin may have extended south and southwest to include the volcanic units in north-central Wisconsin and the volcanogenic base-metal deposits that they contain. The extension of the basin to the north is uncertain.

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

GEOLOGY AND MINERALOGY OF SOME COPPER
SULFIDE DEPOSITS NEAR MOUNT BOHEMIA,
KEWEENAW COUNTY, MICHIGAN

James M. Robertson, New Mexico Bureau of Mines & Mineral Resources, Socorro,
New Mexico 87801.

ABSTRACT

Copper sulfides, in interesting amounts, have been recently discovered in the Keweenaw Peninsula of northern Michigan, a district long famous for its deposits of native copper. The sulfides occur extensively in the vicinity of Mount Bohemia, chiefly as open-space fillings and replacements in amygdaloidal flow tops, a traditional mode of occurrence of native copper in the region. An andesite dike (or dikes), almost invariably associated with the mineralized flow tops, typically carries at least trace amounts of sulfides.

The present study indicates that both copper and sulfur have been added to dikes and flow tops in the Mount Bohemia area, probably by hydrothermal solutions moving upward along zones of structural weakness, and outward along relatively permeable flow tops and broken dike margins. The sulfur and most of the copper are most likely of direct magmatic origin, although some copper may have been derived at depth from pre-existing flows.

Microscopic studies, supplemented by X-ray fluorescence analyses, have defined a zonal pattern of total copper, sulfur, and sulfide minerals developed about the Bohemia Fault, a northwest-trending break on the northeast flank of Mount Bohemia. Chalcocite predominates nearest the fault, with bornite, chalcopyrite, and finally pyrite becoming increasingly abundant with increasing distance from the break.

The chronologic sequence developed in the Mount Bohemia area is: dike emplacement and alteration, faulting and fissuring, and sulfide mineralization. At least some of the faulting is related to regional deformation thought to have occurred in later Upper Keweenawan time. Regionally, native copper deposition is also believed to have followed this period of deformation and preceded copper sulfide mineralization.

Mineralization in the Mount Bohemia area followed several chemical trends during the period of sulfide deposition, with each point in a mineralized dike or flow top undergoing at least part of a generalized sequence which included: (1) introduction of solutions whose initial Cu/S ratios were relatively low; (2) progressive increase in the Cu/S ratios of the ore-forming solutions; and (3) progressive increase in the fO_2 of the solutions.

GROUNDWATER SPREADING OF HYDROCARBON SPILLS WITH SPECIAL EMPHASIS ON MONITOR SYSTEM DESIGN IN GLACIAL DRIFT

W. Rohrer and H.O. Pfannkuch, Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota 55455

ABSTRACT

The introduction of immiscible hydrocarbons into the hydrogeologic environment by accidental spills or subsurface pipeline breaks presents a class of problems that is different from miscible leachate or soluble contamination propagation.

The mechanisms of subsurface spreading comprise three distinct stages; downward movement of the free hydrocarbon phase through the unsaturated zone, spreading on the groundwater table and through the capillary fringe, and finally transport of the dissolved hydrocarbon phase vertically with infiltrating recharge water and horizontally in the groundwater flow field. Each one of these processes is characterized by different material constants. For the downward movement it is the retention capacity of the unsaturated zone that determines the total amount of hydrocarbon phase reaching groundwater, the capillary characteristics of the capillary fringe system defines the extent of spreading on the watertable, and hydrodynamic dispersion coefficients delimit the shape and extent of the dissolved phase spreading. Very little is known about these material constants in drift material, since most reported research has dealt with alluvial deposits. This work presents experimental results for retention capacity of glacial drift and hydrocarbon depth in the capillary zone of spreading. The retention capacity depends on grain size distribution, initial water saturation, and surface characteristics of the liquids involved. The values for outwash sands are on the order of 20 l/m^3 and for tills 80 l/m^3 . Furthermore some preliminary values of hydrocarbon thickness in the capillary fringe of equilibrium is given for the same material.

The design of a monitoring system deals with the recognition of the spatial distribution of the free and dissolved hydrocarbon phase in the subsurface after the spill, the reconstruction of infiltration site and infiltration mechanism (intergranular or preferred path), the determination of general flow pattern and emplacement of interceptor wells, and the establishment of background noise, well sampling techniques and analytical methods.

ORE DEPOSITS IN RELATION TO HOTSPOT-GENERATED INTRACONTINENTAL RIFTING

Frederick J. Sawkins, Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota 55455

ABSTRACT

It can be demonstrated that the tectonic, igneous, and sedimentary processes associated with subcontinental hotspot activity provide favorable environments within which ore-generating systems can operate.

In particular certain tin deposits are associated with the products of crustal melting during the early stages of hotspot activity. Copper mineralization is in some cases closely associated with hotspot controlled geologic regimes, and both hydrothermal and stratiform copper deposits can result. Copper-nickel mineralization in some layered mafic igneous rocks is also considered to be a product of hotspot-associated basaltic magmatism. Other metal deposit types that, at least in some instances, appear to bear a relationship to hotspot activity include stratiform lead-zinc deposits in shales and lead-zinc replacement deposits in carbonate rocks.

Two major continental fragmentation events related to subcontinental hotspot activity, have occurred in the geologic past and a number of important metal deposits can be correlated with each. This approach, that relates the age and geologic environment of intracontinental ore deposition to hotspot activity, holds significant promise for exploration geologists.

KOMATIITES AND THEIR CHEMICAL VARIATIONS

K.J. Schulz, University of Minnesota, Minneapolis, Minnesota 55455

ABSTRACT

Examination of komatiites from South Africa, Canada, Australia and Minnesota (Vermilion district) shows that distinct chemical suites can be defined which, while showing a general similarity also have notable differences (Fig. 1). A striking difference is the $\text{CaO}/\text{Al}_2\text{O}_3$ ratio of the South African (> 1 , Fig. 1a) versus the Australian and Canadian (generally ≤ 1 , Fig. 1b, c) komatiites. Vermilion samples are relatively high Fe, Ti and P (Fig. 1d). (This is also true of the Minnesota River Valley low Al_2O_3 amphibolites, see Weiblen and others, this meeting). Work in progress suggests that on a global scale at least two distinct Archean komatiite suites may exist, distinguished not only by $\text{CaO}/\text{Al}_2\text{O}_3$ ratio but also by Al_2O_3 vs FeO/MgO and $\text{Al}_2\text{O}_3/\text{TiO}_2$. In Minnesota, it appears that the unique occurrence of komatiites with normal tholeiites is repeated in time in the Lower and Upper Archean and the Keweenawan.

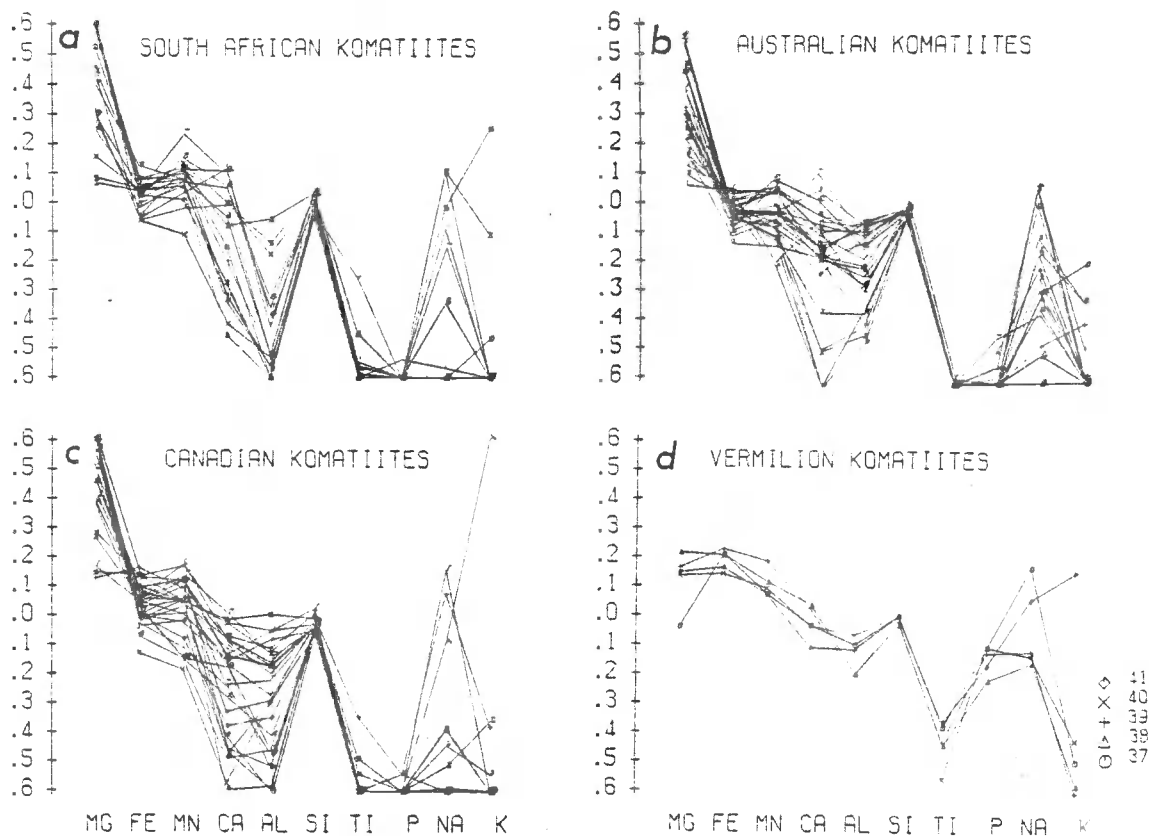


Fig. 1. Log plots of komatiite compositional normalized to Hawaiian tholeiite (as oxides, right to left: 8.1, 10.04, .17, 10.9, 13.4, 50.4, 2.7, .28, 2.3, .53). Numbers below 0 have negative values. Data from various sources.

CHEMISTRY OF PRIMARY AND SECONDARY MINERALS OF SOME PORTAGE LAKE LAVAS, KEWEENAW PENINSULA: DEVELOPMENT OF MODELS OF DIFFERENTIATION AND LOW-RANK METAMORPHISM

Nancy Scofield, Department of Geology and Geological Engineering, Michigan
Technological University, Houghton, Michigan 49931

ABSTRACT

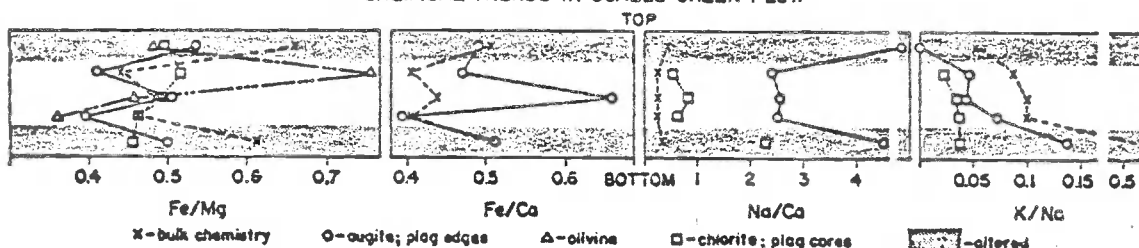
Minerals from the Scales Creek flow (SCF) and two thinner (40', 55') basalt flows above SCF were analyzed by electron microprobe. The interior of the SCF shows some igneous differentiation as evidenced by increases of Fe/Fe+Mg (9%) and Fe/Fe+Ca (14%) in augite and an increase of Na/Na+Ca (6%) in plagioclase.

Drill-hole depth	plag (%An) (40-70% modal)	cpx (20-40% modal)			Fe ₂ O ₃ *	MgO	CaO	Na ₂ O	K ₂ O	Cu (ppm)
		Wo	En	Fs						
pump D81-1832					10.5	2.06	18.8	0.07	0.02	85
ab D81-1839	2-3 (6)	42-39	42-39	16-22 (5)	11.1	7.83	6.9	4.30	0.07	180
D55-1185	2-3 (5)	42	38	20 (3)	12.0	5.64	8.2	3.90	0.30	455
SCF 1233	48-80 (11)	38	44	18 (3)	11.7	7.75	9.9	2.26	0.27	130
200' 1285	50-82 (8)	34	44	22 (2)	12.2	7.45	9.7	2.15	0.30	110
1320	65-80 (5)	40	44	16 (2)	12.3	7.80	10.4	2.32	0.31	150
1370	43-50 (5)	42-38	43-39	15-23 (8)	12.3	5.90	8.4	2.90	2.10	420

Number of analyses in parentheses.
Pump = pumpellyite metadomain

*Total iron as Fe₂O₃.
ab = albitized basalt

CHEMICAL TRENDS IN SCALES CREEK FLOW



The basalts are altered by low-rank metamorphism of the prehnite-pumpellyite facies. The proportion of secondary minerals, as alteration products and in veins and amygdulites, increases toward flow tops. Augite is replaced by chlorite and plagioclase is albitized. The Ca thus released is available for pumpellyitization of plagioclase, which occurs concurrently and subsequently to albitization, releasing Na. However, a closed-system model demands overall participation of the relatively unaltered flow interiors by a depletion of a few percent of the Na present, but this is not observable petrographically. Pyroxene in pumpellyite metadomains is altered to pumpellyite and/or epidote. The Mg thus mobilized augments the Mg content of chlorite and results in higher Mg values in chlorite than in augite from which chlorite is derived. Both pumpellyitized and albitized zones are depleted in K relative to less altered parts of flows, and K is concentrated in the base of the SCF, where sericitization of plagioclase is extensive.

SOURCES OF DISSOLVED SOLIDS IN GROUNDWATER FROM SUPERIOR AND RAINY LOBE TILL

Donald I. Siegel, Department of Geology and Geophysics, University of Minnesota,
Minneapolis, Minnesota 55455

ABSTRACT

Preliminary study of recent analyses of water quality shows that groundwater within surficial aquifers related to Superior and Rainy lobe deposits contains significantly less sodium than is found in bedrock aquifers within igneous rocks of central and northeastern Minnesota. Inasmuch as Superior and Rainy lobe deposits consist mainly of materials derived from these and similar igneous rocks, the observed difference in sodium content between groundwaters within the surficial and bedrock aquifers may be considered anomalous assuming that groundwater chemistry is most influenced by aquifer mineralogy. Possible mechanisms explaining the differing sodium values and gross water chemistry are suggested, in particular, by using theoretical reconstructions of surficial and bedrock waters. Initial results highlight the importance of compositional differences within aquifers in local and small, intermediate flow systems as the dominant control of both gross groundwater chemistry and ultimately the gradual evolution of water types as deduced by Chebotarev and others.

MIDDLE PRECAMBRIAN AGE OF VOLCANOGENIC MASSIVE SULFIDE DEPOSITS IN NORTHERN WISCONSIN

P.K. Sims, U.S. Geological Survey, Denver, Colorado 80225

ABSTRACT

The copper-zinc massive sulfide deposits at the Flambeau mine, near Ladysmith and at Pelican River, east of Rhinelander, Wisconsin, have model lead ages of $1,830 \pm 150$ m.y. (J.S. Stacey, B.R. Doe, and L.T. Silver, written commun., 1976). Inasmuch as the deposits are considered as being of submarine volcanic exhalative origin, the associated volcanic rocks also are interpreted as being middle Precambrian (Precambrian X) in age.

The analytical data on the leads from the two ores, provided by Stacey, Doe, and Silver, are tabulated below.

Deposit	$\frac{206 \text{ Pb}}{204 \text{ Pb}}$	$\frac{207 \text{ Pb}}{204 \text{ Pb}}$	$\frac{208 \text{ Pb}}{204 \text{ Pb}}$	Model age in m.y.
Flambeau	15.323	15.167	35.016	1,820
Pelican River	15.688	15.359	35.202	1,835

The isotopic composition of the leads is similar to the least radiogenic leads from the massive sulfide deposits at Flin Flon, Manitoba. The model lead ages are consistent with zircon U-Pb ages of 1,800-1,900 m.y. on volcanic and granitic rocks in northeastern Wisconsin and adjacent Michigan, determined by W.R. Van Schmus and his associates in 1975.

The volcanic rocks in the Ladysmith-Rhinelander belt are interpreted as being approximately correlative with the dominantly submarine volcanic rocks that are interbedded with turbidite-like sedimentary rocks in the upper part of the Marquette Range Supergroup in northern Michigan. Apparently these rocks accumulated in a eugeosynclinal environment in the southern part of the middle Precambrian basin in the Lake Superior region.

GEOLOGY AND GEOCHEMISTRY
OF THE PRECAMBRIAN MARCELLON RHYOLITE,
COLUMBIA COUNTY, WISCONSIN

Eugene I. Smith, Division of Science, University of Wisconsin-Parkside, Kenosha, Wisconsin 53140

ABSTRACT

The Marcellon inlier is formed by four mineralogically and chemically distinct rhyolite flows and ash-flow tuffs which are folded into a northeast-striking, asymmetric antiform. Rhyolite on the western limb of the antiform strikes N. 50 E. and dips 50° - 85° to the northwest. The units on the eastern limb also strike N. 50 E., but dip steeply (80° to vertical) to the southeast. Two chemically dissimilar greenstone dikes intrude the rhyolite flows.

The core of the antiform is formed by a quartz (2%), plagioclase (15%), and alkali feldspar (2%) rhyolite with well preserved shard outlines in the matrix (unit 4). This unit probably is an ash-flow tuff. Structurally above unit 4 is: (a) well banded, plagioclase-bearing (14-18%) rhyolite with local spherulitic lenses (unit 3); (b) flow banded, quartz (6%), alkali feldspar (4%), plagioclase (1%) rhyolite (unit 2); and (c) quartz (2%), alkali feldspar (2%), plagioclase (1%) rhyolite characterized by spherulites up to 15 cm in diameter (unit 1).

The Marcellon rhyolite is one of ten major rhyolite and granite inliers in south-central Wisconsin. Chemically most of the rocks which form the inliers can be divided into three groups: (1) high CaO (1.48-1.68%), high TiO_2 (0.30-0.42%), and low Rb/Sr (0.37-0.79) rhyolites and granites (Observatory Hill Rhyolite dikes and the Baxter Hollow Granite); (2) intermediate CaO (1.28±0.32%) and Rb/Sr (1.09±0.29) rhyolite (unit 3 at Marcellon and the Marquette Rhyolite); and (3) low CaO (0.37±0.14%), high Rb/Sr (159) rhyolites and granites (Observatory Hill, Berlin, Utley, and Endeavor rhyolites, and granophyric granites at Montello and Red Granite). Although unit 3 at Marcellon falls into chemical group 2, the other Marcellon units, along with rhyolites in the Baraboo area, are transitional in chemistry between groups 2 and 3. For example, units 1 and 2 are more closely related to group 3 in terms of low CaO (0.29-0.36%), but differ by having lower Rb/Sr (2.27±0.57). Unit 4 is similar to group 2 because of intermediate CaO (0.94%) and Rb/Sr (1.32), but it is higher in $\text{K}_2\text{O}/\text{Na}_2\text{O}$ and lower in Ba than typical group 2 rocks.

Rocks of the three chemical groups, along with the transitional types, fall along a trend typical of a rock series showing strong calc-alkaline affinities. Rhyolites are comagmatic, and the granophyric granites are apparently the subvolcanic equivalents. These chemical data along with available U/Pb dates (1.8 b.y.) confirm that these rhyolites and granites formed during the last stages of the Penokean Orogeny.

THE GEOCHEMISTRY OF THE GAMITAGAMA LAKE COMPLEX, WAWA, NORTHERN ONTARIO

T.E. Smith, A. Turek, and C. Riddle, Department of Geology, University of Windsor, Windsor, Ontario, Canada

ABSTRACT

The Gamitagama Lake Complex is a calc-alkaline stock (Ayres, 1969), exposed within the Abitibi volcano-plutonic belt in the Superior Province of Canada, south of Wawa in Ontario. It penetrates a series of regionally metamorphosed felsic and mafic volcanic rocks interbedded with metasedimentary rocks and iron-formation, and is associated with a variety of other plutons. The metamorphic grade varies from greenschist to amphibolite facies within the area and is overprinted by contact metamorphic aureoles adjacent to the plutons. The plutonic rocks include cataclastic and gneissose trondjemites, gabbros, norites, diorites, syenites, and granites.

Major and trace elemental contents of the volcanic and plutonic rocks are used to identify the various igneous rock suites of the area, to follow their evolution and to determine which are co-magmatic. Comparisons with recent igneous rock suites are used to reconstruct the development of the Archean crust in this area and to identify the tectonic environments in which the magmas were generated.

A GROUND INVESTIGATION OF AN AEROMAGNETIC ANOMALY, DICKINSON COUNTY, MICHIGAN

David W. Snider, Geology and Minerals Research Unit, Geological Survey Division,
Michigan Department of Natural Resources, Lansing, Michigan 48926

ABSTRACT

During the latter part of September, 1975, the Geology and Minerals Research Unit of the Michigan Geological Survey conducted a ground reconnaissance investigation of a small, closed aeromagnetic anomaly in north-central Dickinson County. The purposes of the study were two-fold: (a) to determine what geologic feature caused the aeromagnetic anomaly and, (b) to investigate any mineral resource potential associated with the area in and around the anomaly. Nearly all of the closed anomaly lies within an east-west trending swamp covering an area of nearly three square miles.

The methods of investigation consisted of sampling outcrops for petrographic and chemical analyses, ground magnetic surveys, and a VLF-EM survey.

The combined results of the study indicate that the closed, airborne anomaly was caused by the near-surface occurrence of serpentized peridotite that contains appreciable amounts of magnetite. This ultramafic body underlies most of the northern portion of the swamp area, strikes N75°-80°W and dips to the south. The relative position of the body with respect to metasedimentary rocks to the south and southwest suggest that this ultramafic unit was emplaced as a sill.

The results of the chemical analyses show no anomalous Ni-Cu-Co values.

The results of the VLF-EM survey show the presence of two separate anomalous zones within the project area. The first is caused by the relatively magnetic, serpentized peridotite that crops out within the swamp. This area produced a high ground magnetic response as well as a VLF-EM response. However, the combined geophysical, geological, and chemical evidence indicate that the surface exposures of the magnetic, serpentized peridotite has limited economic potential.

The feature responsible for the second VLF-EM anomalous zone does not express itself at the surface, nor does it correspond with any ground magnetic anomalies.

All of the major VLF-EM anomalies generated in the project area were correlated with the serpentized peridotite and showed a reverse cross-over anomaly form. It was determined that the VLF-EM instrument was responding to the magnetic permeability of the rock rather than its conductivity. It was therefore concluded that the VLF-EM survey yielded no reliable data concerning the conductivity of the serpentized ultramafic.

The VLF-EM instrument used in this study is a rather restrictive, reconnaissance tool, and as such cannot be used for detailed interpretation of buried conductive bodies, especially when those bodies possess high magnetic permeability. It is therefore suggested that this occurrence of ultramafic rock be investigated in more detail by those using a more discriminating EM method which would better determine its economic potential.

HIGH-GRADE METAMORPHISM ASSOCIATED WITH THE VERMILION BATHOLITH, MINNESOTA-ONTARIO

David L. Southwick, Department of Geology, Macalaster College, St. Paul, Minnesota.

ABSTRACT

Aluminous, magnesian schists along the north contact of the Vermilion batholith contain various combinations of sillimanite, cordierite, staurolite, garnet, and sapphirine along with biotite, oligoclase, and quartz. Muscovite is rarely present; tourmaline is a common and sometimes abundant accessory. So far as known, this is the first reported occurrence of sapphirine in Minnesota or western Ontario.

Staurolite-bearing assemblages appear to represent the highest metamorphic grade. There is excellent textural evidence that the reaction garnet + staurolite + quartz $\rightarrow$ cordierite has taken place. Experimental work indicates that this reaction is pressure-controlled, with lower pressure favoring the formation of cordierite. Sapphirine occurs together with staurolite in some rocks, indicating formation at the highest metamorphic grade. There is no clear-cut evidence as to the reactions governing sapphirine formation.

Field relations indicate that the high-grade schists are the product of thermal metamorphism by the adjacent batholith. Observed assemblages in the schists suggest maximum temperature and pressure in the neighborhood of 600-700°C and 3-5 kb. This environment is compatible with the inferred temperature and pressure at crystallization of the major part of the Vermilion batholith.

Detailed investigations of the phase chemistry currently are underway.

GEOLOGY OF THE ROUND LAKE INTRUSION, SAWYER COUNTY, WISCONSIN

S.W. Stuhr and E.N. Cameron, Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706

ABSTRACT

The Round Lake intrusion is enclosed in Archean rocks a short distance southeast of the edge of the Lake Superior Syncline in Sawyer County, Wisconsin. Geophysical data indicates that the intrusion is at least five miles long but less than one mile wide. The intrusion may be a derivative of a gabbroic magma. Diabasic gabbro occurs as inclusions in the outer portions of the oxide-rich core. Magnetite-troctolite, magnetite, anorthositic olivine gabbro and mafic pegmatite form the troughshaped core of the intrusion.

The dominant minerals are olivine, plagioclase and titanomagnetite in various proportions. In the core of the intrusion, olivine and plagioclase crystallized early and the iron-titanium oxides crystallized late. At the base of the narrow intrusion a thick zone of magnetite troctolite was formed. The iron-titanium oxides became enriched in the residual liquid and a large zone of magnetite formed in the central part of the intrusion. As differentiation proceeded, additional magnetite-troctolite formed toward the top of the intrusion. Plagioclase clusters accumulated into lenses of anorthositic olivine gabbro in the lower and middle portions of the intrusion. Finally, mafic pegmatites, consisting of plagioclase, perthite, augite, iron-titanium oxides and apatite as major minerals, developed in the upper portions of the intrusion.

Chemical variation of specific minerals is a function of both the oxide/silicate ratio and cryptic changes related to position in the intrusion. Olivine, plagioclase and iron-titanium oxides show slight but consistent chemical changes. Cryptic variations are most pronounced in the portion of the intrusion that crystallized last.

The iron-titanium oxides were concentrated in the residual liquid under conditions of low oxygen fugacity. If the intrusion is the product of iron enrichment of basaltic magma, it must have migrated from the site of differentiation. After the iron-rich magma was intruded, it followed a "normal" path of differentiation in place.

HYDROCARBONS OBTAINED BY PYROLYSIS OF SOME PRECAMBRIAN ROCKS OF MINNESOTA*

F.M. Swain, J. Baysinger, and J.M. Bratt, Department of Geology and Geophysics,
University of Minnesota, Minneapolis, Minnesota 55455

ABSTRACT

Drill core samples of 42 Precambrian sedimentary, igneous, and metamorphic rocks were analyzed by heating under partial vacuum at 100°C and at 400°C to release hydrocarbons and other volatile products.

The core samples yielded methane in amounts ranging from traces to 3 microliters per gram, but averaged much less. By way of comparison, samples of Middle Devonian Marcellus black shale, from Pennsylvania, yielded methane in amounts up to 7 ul/g.

Other straight chain hydrocarbons up to C₁₁ were found in the volatile products, especially those obtained at 400°C; benzene also was a common product, mainly in the 400°C experiments. Carbon dioxide and nitrogen appear to form a large part of the non-hydrocarbon volatiles in at least some of the samples.

Spectral data indicate that the straight chain pyrolysis products of the Precambrian rocks are mainly alkenes, whereas those of the Devonian rocks, referred to above, are a mixture of alkanes and alkenes. Alkanes were however, obtained from several algae-bearing Middle Precambrian argillites. Available evidence indicates, although not conclusively, that the alkenes were contained in the rock rather than being produced from alkanes during pyrolysis.

The writers believe that surface contamination in most of the drill cores was minimal owing to the low permeability of the rocks studied, and that contamination by drilling was also minimal.

There is a reasonable possibility that the volatiles, if not formed from kerogen residues by the pyrolysis experiments, are in part juvenile igneous gases or are substances that were distilled out of the deeper-lying rocks during intervals of folding and metamorphism, and subsequently accumulated at higher levels.

*The paper is scheduled for publication in July 1976 "Origins of Life."

HORNFELSED BASALTS IN THE DULUTH COMPLEX

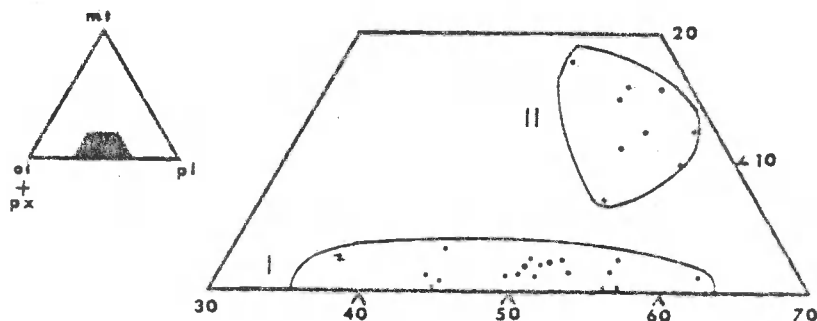
R.M. Tyson and B. Bonnichsen, Department of Geological Sciences, Cornell University, Ithaca, New York 14853

ABSTRACT

Two compositional types of hornfelse basalt (see figure) occur in the Babbitt-Hoyt Lakes region of the Duluth Complex. The Erie Hornfels (Sec. 18, T.59N., R.13W.), Dunka Railroad Hornfels (Sec. 33, T.60N., R. 12W.) and Reserve Hornfels (Sec. 32, T.60N., R.12W.), (Type I) are olivine tholeiites consisting of plagioclase (40-62%), augite (16-45%), olivine (0-21%), and inverted pigeonite (0-18%). The Reserve body has less than 1% opaque oxides and more than 10% olivine, whereas the others have 1-3% opaque oxides and generally less than 10% olivine. The textures range from granoblastic in the Dunka Railroad and Reserve bodies, which are surrounded by intrusive rocks, to a better-preserved basaltic fabric in the Erie Hornfels at the base of the complex. This type contains plagioclase-two pyroxene metamorphosed amygdulites and plagioclase phenocrysts. The Colvin Creek Hornfels (T.58N. and T.59N. R.13W.) is an example of Type II, and contains equant plagioclase (52-56%), irregular to locally poikilitic augite (28-34%), hypersthene (1-6%) mantling augite, and magnetite (10-20%). It represents an oxidized basalt which has been metamorphosed. This type has a granoblastic texture and contains zoned plagioclase phenocrysts and metamorphosed amygdulites composed of augite enclosing plagioclase.

We believe these hornfels bodies were originally flows that were part of the North Shore Volcanic Group. Their metamorphism to the pyroxene hornfels or sanidinite facies was predominantly thermal in nature. Devolatilization was one major effect as shown by the anhydrous minerals now constituting the amygdulites and the scarcity of hydrous minerals common in unmetamorphosed North Shore Volcanic rocks. Partial melting locally occurred with the formation of syenite and granite dikes. Such dikes, composed of Na-plagioclase, quartz, chlorite and local biotite and tremolite, conspicuously occur in the Dunka Railroad Hornfels and have been observed at many other localities.

The volcanic hornfels at the base of the complex lie above only a few hundred feet of Virginia Formation. This is much thinner than farther to the west. It suggests the Virginia was eroded prior to extrusion of the volcanic rocks. Perhaps this accompanied regional doming preceeding the Keweenawan episode of continental rifting.



SYNGENETIC MODEL FOR THE ORIGIN OF THE WHITE PINE COPPER DEPOSIT

Thomas A. Vogel, Geology Department, Michigan State University, East Lansing, Michigan 48824; M.B. McBride, Department of Agronomy, Cornell University, Ithaca, New York 14853; and Robert Ehrlich, Geology Department, University of South Carolina, Columbia, South Carolina 29208.

ABSTRACT

The syngenetic model for the mineralization of the lower Nonesuch Shale at White Pine, Michigan depends upon copper entering the basin complexed to clay minerals. In order for this model to be viable for the White Pine deposit, it is necessary to demonstrate that significant copper can be complexed to clay minerals and that these minerals can be produced in the source terrane for the lower Nonesuch Shale. Furthermore, if copper entered the basin complexed to clay minerals, the clay mineral fraction present in the lower Nonesuch Shale may record its occurrence.

Basalts and andesites are extensively exposed in the rocks of the Middle Keweenawan and all workers agree that the sediments of the Nonesuch Shale are derived predominantly from weathering of these rocks. In most environments, the first clay mineral to form from weathering of basalt is montmorillonite. The dominant clay mineral assemblages that exist in the lower Nonesuch Shale are a complex intergrowth of chlorite and illite. A probable origin for these intergrowths is due to a diagenetic alteration of montmorillonite. Many workers have traced the change from montmorillonite to chlorite-illite intergrowths in the geologic column and experimentally, the alteration of montmorillonite to chlorite-illite is well known. It is reasonable that the chlorite-illite intergrowths in the lower Nonesuch Shale represents montmorillonite that has been diagenetically altered.

One of the characteristic features of montmorillonite is their ability to adsorb cations, and considerable research has been devoted to the study of the adsorption and exchange properties of copper and clays. Heydemann (1959) 1959, was one of the first workers to show experimentally that copper could be selectively adsorbed on montmorillonite from copper ions in solution. In addition, it is well-known that organic-clay complexes will adsorb copper from dilute aqueous solutions (Kaufherr, et. al., 1971; Steger, 1973). Steger has suggested that organic-clay complexes could be used to remove trace amounts of copper, zinc and lead from water. Many workers have shown that copper is bound preferentially over other divalent cations on organic-clay complexes.

A study of the clay fraction of samples from a copper-rich, black shale was undertaken in order to determine if some of the copper was structurally bonded in the clay mineral lattice and also to determine the oxidation state of the iron in order to better understand the environment of formation of these minerals. The original samples contained 4.75% copper and the < 2 micron (clay) fraction contained 0.96% copper. After leaching the < 2 micron fraction with sodium tetraphenyl boron - sodium chloride (NaTPB - NaCl), no Cu II was removed, thus indicating that the copper is not present as interlayer Cu II or soluble Cu II. A detailed electron scanning microscope and microprobe study of the < 2 micron fraction failed to show the presence of any free native copper or chalcocite grains.

Electron Spin Resonance studies of these samples show Fe III (G about 4.0) in octahedral sites in the clay minerals. Abundance of Fe III in the clay minerals is

probably about 2-3% (determined by comparing the spectrum with known clays). The presence of Fe III in the octahedral sites must result from the montmorillonite having formed in an oxidizing environment.

These data are consistent with a model in which montmorillonite formed in the weathering environment and copper was complexed, probably as a copper-organic complex. The insoluble copper in the <2 micron fraction indicates that when the copper-organic-montmorillonite complex broke down, some of the copper was forced into the octahedral sites of the resulting chlorite-illite intergrowth. However, most of the copper was released and provided the source of copper for the mineralized zone.

REFERENCES CITED

- Heydemann, A., 1959, Adsorption ans sehr verdünnten Kupferlösungen an reinen Tonmineralen; *Geochim. Cosmochim. Acta.* v. 15, p. 305-329.
- Kaufherr, N., Yariv, S., and Heller, L., 1971, The effect of exchangeable cations on the sorption of chlorophyllin by montmorillonite; *Clays and clay minerals*, v. 19, p. 193-200.
- Steger, H.F., 1973, On the mechanism of adsorption of trace copper by bentonite; *Clays and clay minerals*, v. 21, p. 429-436.

GNEISS AND MIGMATITE OF ARCHEAN AGE IN THE PRECAMBRIAN BASEMENT OF CENTRAL WISCONSIN, U.S.A.

W.R. Van Schmus, Department of Geology, University of Kansas, Lawrence, Kansas, 66045, and J.L. Anderson, Department of Geological Sciences, University of Southern California, Los Angeles, California 90007

ABSTRACT

Many of the southernmost exposures of the Precambrian shield in central Wisconsin consist of gneiss, migmatite, and/or amphibolite with associated younger intrusive rocks ranging in composition from tonalite to granite. Rb-Sr whole-rock analyses and U-Pb zircon analyses show that the migmatite- and gneiss-forming events occurred about 2.8 b.y. ago. Ages on minerals and younger plutonic rocks indicate that older gneiss and migmatite were intruded and locally metamorphosed during major events 1.5 to 1.9 b.y. ago.

Rb-Sr isochrons for the migmatite have elevated initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios (ca. 0.710), suggesting that the migmatites formed from crustal rocks of intermediate to granitic composition and which were themselves formed more than 3.0 b.y. ago. If this is true, then the gneissic and migmatitic rocks in central Wisconsin may represent an eastward extension of the ancient (>3.3 b.y. old) Minneosta River Valley Terrane.

COMPOSITIONAL VARIATIONS OF MINNESOTA RIVER VALLEY AMPHIBOLITES

P.W. Weiblen, K.J. Schulz, and B.V. Nielsen, Minnesota Geological Survey, St. Paul, Minnesota 55108

ABSTRACT

Studies of Archean amphibolites at Morton, Minnesota reveal that hornblende-plagioclase enclaves (two meters in size) contain only rare clinopyroxene, whereas larger enclaves (20 meters long) contain up to 30%. Both types are rimmed by biotite. Except for K, compositional variations within and between the two types reflect igneous processes and resemble northern Minnesota greenstones (Figs. 1a & b). Some amphibolites from near Delhi and Montevideo contain < 10 wt. % Al_2O_3 . Their compositions mimic komatiite-like greenstones (Figs. 1c & d). The data suggest that magmas of igneous precursors of certain southwest Minnesota amphibolites and northern Minnesota greenstones were generated from similar source rocks in comparable tectonic regimes.

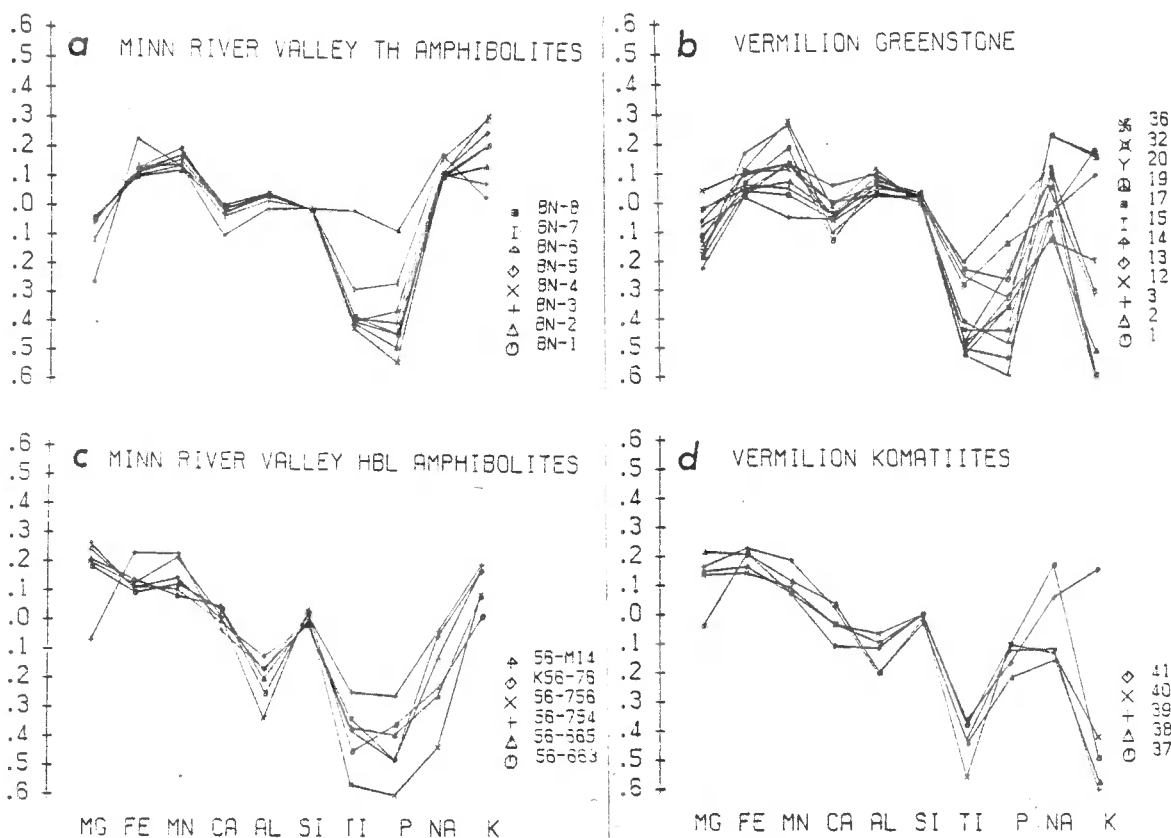


Fig. 1. Log plots of compositions normalized to Hawaiian tholeiite (as oxides, right to left: 8.1, 10.04, .17, 10.9, 13.4, 50.4, 2.7, .28, 2.3, .53). Numbers below 0 have negative values. (Data from Nielsen, in prep., Sims, P.K., 1972, and Green and Schulz, in prep).

REFERENCES

- Sims, P.K., 1972, Metavolcanic and associated synvolcanic rocks in Vermilion district, in Sims, P.K. and Morey, G.B., eds., *Geology of Minnesota: A Centennial Volume*, Minnesota Geological Survey, p. 632.

Rb-Sr GEOCHRONOLOGY AND TRACE ELEMENT GEOCHEMISTRY OF GRANULITE FACIES ROCKS NEAR GRANITE FALLS, IN THE MINNESOTA RIVER VALLEY

Wendell E. Wilson and V. Rama Murthy, Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota 55455

ABSTRACT

The Sr- isotopic composition and the trace-element abundances of K, Rb, Sr, and Ba have been determined in several whole rocks and mineral separates from four lithologic units in the Minnesota River Valley, near Granite Falls, Minnesota. The sampled units are the inner and outer units of hornblende-pyroxene gneiss, the biotite-garnet gneiss, and the metagabbro originally included in the "hornblende-pyroxene gneiss" of Himmelberg (1968).

The whole rock isochron ages (T) obtained from the Rb-Sr data are given below; ages obtained for metamorphic events, as determined by mineral isochrons are given in brackets. All ages are in units of aeons (10^9 yrs); all errors are 2σ . The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (I) refer to the whole rock isochrons.

Garnet-Biotite gneiss

$$T = 3.54 \pm 0.14 (1.81); I = 0.7008 \pm 0.0009.$$

Hornblende-Pyroxene Gneiss (outer unit)

$$T = 3.31 \pm 0.26 (1.78); I = 0.7011 \pm 0.0012.$$

Hornblende-Pyroxene Gneiss (inner Unit)

Data scatter precludes attempts at dating.

Meta-gabbro of Himmelberg (1968)

$$T = 2.68 \pm 0.20 (1.80); I = 0.7037 \pm 0.0001.$$

Interpretations of the above data are subject to the usual ambiguities in discussions of geochronological problems of early Archean terranes. The simplest explanation seems to be that the combined section of hornblende-garnet-pyroxene granulite facies rocks at Granite Falls has a minumum age of 3.55 AE with a pronounced metamorphism at 1.8 AE.

The trace element patterns of the hornblende-pyroxene gneisses and garnet-biotite gneisses resemble graywackes of island-arc-alkali basalt affinities and the metagabbros resembles a low-K tholeiite. The granitic rocks at Granite Falls therefore probably represents a very old layered sequence of basaltic rocks and graywackes intruded by the Montevideo Gneiss.

PETROLOGY OF THE ARCHAEOAN GNEISSES OF THE NORTHWEST CORNER OF THE SACRED HEART PLUTON; MINNESOTA RIVER VALLEY, MINNEOSTA

James L. Welsh, Department of Geology and Geophysics, University of Wisconsin-Madison, Wisconsin

ABSTRACT

Approximately 6 miles south of Sacred Heart, Minnesota, along the Minnesota River Valley, the Sacred Heart quartz monzonite is intrusive into an older gneissic complex. Detailed mapping in the gneisses along the northwestern portion of the outcrop belt reveals four structurally concordant lithologies, which are described below from south to north.

The southern part of the area consists of the Sacred Heart pluton. To the north, the pluton is in gradational, but apparently intrusive contact with a salmon-pink clinopyroxene syenite, which contains abundant, commonly nebulitic, mafic inclusions. Many of the larger inclusions are zoned, consisting of pyroxene-rich rinds and hornblende-rich cores. Separated from the syenite by a sill-like body of quartz monzonite is a sequence of interlayered tonalitic gneisses and amphibolites, which are in turn separated by another sill of quartz monzonite, from a layered leucogranitic gneiss consisting of alternating pink microcline-rich bands and yellow plagioclase-rich bands. Numerous inclusions of tonalitic gneiss are contained in the quartz monzonite sills. More quartz monzonite lies to the north, with tonalitic gneisses again cropping out across the river.

The interlayered tonalitic gneisses and amphibolites represent the oldest rocks exposed in the area. Isoclinal folding and shearing within the unit indicate deformation and probable metamorphism prior to the intrusion of the quartz monzonite. Field relations and modal data suggest that the plagioclase-rich bands of the layered leucogranitic gneiss are part of the tonalitic gneiss complex. Mineral textures and modal data also suggest a possible relationship between the microcline-rich bands of the layered leucogranitic gneiss and the pyroxene syenite. Although the microcline-rich bands of the layered leucocratic gneiss are somewhat more quartz-rich it is thought that desilication of the syenite occurred by conversion of a former amphibolite to a pyroxene-rich rock, during the intrusion of a potassium-rich magma. This reaction is evidenced by the zoning of the inclusions within the syenite.

The following sequence of events is thought to have occurred: (1) deformation and metamorphism of a volcanic pile forming the tonalitic gneisses and amphibolites; (2) dilatation of the gneiss sequence followed by infiltration of a potassium-rich magma into the rupture zones, forming the pyroxene syenite and the layered leucogranitic gneiss; (3) intrusion of the quartz monzonite.

FIELD TRIPS

FIELD TRIP A
MINNESOTA RIVER VALLEY
FIELD TRIP AND CONFERENCE

No formal guidebook for the Minnesota River Valley Field Trip has been prepared at the specific request of S.S. Goldich, convenor.

Abstracts of talks given at the Tuesday evening discussion at Redwood Falls are included as a part of these Proceedings. A collection of reprints pertaining to the geology of the Minnesota River Valley and an informal set of stop descriptions will be provided to the participants. However, inasmuch as the latter are not quotable for publication they are not included here.

FIELD TRIP B
ENGINEERING GEOLOGY, PLEISTOCENE GEOLOGY AND
GEOMORPHOLOGY IN THE TWIN CITIES AREA

INTRODUCTION

Assemble: 8:00 a.m. Wednesday, May 5th St. Paul Radisson Hotel, St. Paul. Low cost parking is available just across the river from the hotel, immediately west of the first exit from the Wabasha Avenue bridge. Field clothes are recommended for underground construction inspection. Bring a hard hat if you have one. Transportation by bus to the University of Minnesota campus.

Optional Assembly Point: 8:30 a.m., back of Pillsbury Hall, University of Minnesota campus. Near-by parking opportunities are limited. Those who find it convenient to do so may join the field trip at this point rather than going to St. Paul.

MORNING ITINERARY

The excursion will divide into two equal groups at the University of Minnesota campus. One group will be transported to site A by bus for the first half of the morning. The second group will proceed on foot to site B. In mid-morning the two groups will exchange sites via bus transportation.

Site A; Como Avenue Storm Sewer Tunnel, City of Minneapolis: Ralph Rabus and Ray Sterling; guides) The portal of the tunnel is located at the foot of the bluffs along the Mississippi River on the northeast bank about half a mile below St. Anthony Falls. The site affords a good view of the incised gorge of the Mississippi, carved since the end of the Pleistocene glaciation as St. Anthony Falls retreated from its original site at the confluence of the Minnesota and Mississippi Rivers to its present site, about 8 miles upstream. The falls is now stabilized by a lock and dam as well as water control and diversion facilities for the experimental operations of the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota.

Above the falls the river flows on a pavement of hard, slabby Platteville Limestone. The Platteville Limestone is underlain by two to

three feet of soft shale, known as the Glenwood Formation, beneath which is the St. Peter Sandstone, a light yellow to almost white, medium-grained to fine-grained, friable sandstone composed almost entirely of well rounded but frosted grains of quartz sand with one or two percent of clay binder. The sandstone is very massive, and in many exposures appears to have almost no bedding. It is about 150 feet thick in the Twin Cities basin. These formations are well exposed in the river bluffs visible from the portal site.

A storm sewer tunnel, 10 feet in diameter, is being excavated in the St. Peter Sandstone by hydraulic mining methods. A jet of water directed at the St. Peter Sandstone loosens the clay binder and the rock decomposes into a slurry of incoherent sand. The properties of the sandstone which allow it to be mined by this method also allow the rock to ravel upon exposure, especially where skin stresses are developed in underground openings. The Department of Civil and Mineral Engineering at the University of Minnesota has developed a sodium silicate based chemical grout which penetrates porous rocks and hardens to consolidate the rock into a strong, durable material. The liquid is sprayed on the surface of the tunnel to form a strong skin, which supplies all of the support needed where the St. Peter Sandstone has not been adversely affected by fracturing and decomposition. In weaker zones shotcrete and epoxy-cemented rock bolts are used for additional support.

Research by Walter Parham of the Minnesota Geological Survey has shown that the primary clay minerals in the St. Peter Sandstone are illite and montmorillite, which form an effective binder, even where present in very small quantities. In zones where these clays have been converted by diagenesis to kaolinite, the kaolinite tends to occupy interstices between sand grains, rather than coating the grains, and much of the intergranular cohesion is lost. This slight change in mineralogy greatly weakens the St. Peter Sandstone and has strongly affected underground construction locally in the Twin Cities area. This phenomenon does not appear to have been encountered in the present tunnel.

Site B; Experimental Tunnel and Test Chamber: (Donald Yardley and Charles Nelson, guides). The Department of Civil and Mineral Engineering at the University of Minnesota, aided by a grant from NSF-Rann, is constructing an experimental tunnel and large underground chamber beneath

the University of Minnesota campus to develop construction methods and structural parameters for the design of large underground spaces. One of the primary purposes is to take advantage of the very large energy savings that may be achieved through the better use of underground space. Underground space also provides opportunities for relieving urban congestion and mitigating the environmental impacts of many transportation, industrial and utility facilities.

The experimental excavation will be entered through an existing steam tunnel of the University heating system (The temperature is high. Be prepared to shed your jacket). At one point in the passage through the concrete-lined steam tunnel there is an intersection with an unlined tunnel. This tunnel, excavated in the St. Peter Sandstone, exhibits a persistent, vertical crack or fissure in its crown which makes it appear that the tunnel follows a vertical joint zone. In fact, the fissure has developed as the result of the tensional stress which characteristically develops in the crown of a circular arch in an underground structure when the overlying load is shifted from the rock that was removed to the rock on either side of the tunnel in the abutments to the arch.

The stratigraphic succession at the site consists of: Glacial drift, 45 ft.; Platteville limestone, 30 ft.; Glenwood shale, 4 ft. to 5 ft.; St. Peter sandstone, penetrated 9 ft. to 10 ft. at invert elevations.

The experimental tunnel and chamber is partly excavated in weak shale of the Glenwood Formation and partly in St. Peter Sandstone. The roof of the chamber is formed by hard, slabby limestone of the Platteville Formation. About 100 feet of unlined access tunnel is traversed in the Glenwood Formation, a shale unit, two to three feet thick, characterized by a persistent soft mud seam about one inch thick containing pyrite crystals. The shale shows severe deterioration and air slaking due to exposure.

About 70 feet of the access tunnel have been excavated in St. Peter Sandstone which has been grouted by spraying with the sodium silicate compound described under Site A. Another 70 feet of the tunnel in St. Peter Sandstone has been left untreated as a control.

The test chamber is in the process of excavation. A drift has been driven the full length of 100 feet, and a cross drift has been driven the full width of 50 feet. The long drift has been widened in one section to 20 feet. The completed chamber will be 100 by 50 feet, 8 feet high. The Platteville

Limestone will form the roof of the chamber. The invert will be in the St. Peter Sandstone. The walls from the roof down will cut about 4 feet of Glenwood shale and about 4 feet of St. Peter Sandstone.

Excavation of the access tunnels and chamber has been entirely by hand operations, using pneumatic drills and spades and hydraulic rock splitters. This has been necessitated by the small size of the access tunnels (4 feet wide by 6.5 feet high). However both the St. Peter Sandstone and the Glenwood shale are readily excavated in this way. The hydraulic rock splitters have proved very useful in spalling off the shale to the bedding surface in the overlying Platteville Limestone which has been chosen to form the roof. As construction proceeds, the underground chamber is being thoroughly instrumented to determine rock deflections, stresses, and the influence of an overlying perched water table on the underground structure. Instrumentation includes six-point extensometers, two-point extensometers, and inverted piezometers installed from below through the roof into the perched water table above the Platteville Limestone. A bore-scope is being used to examine drill holes. Principal support for the roof is provided by epoxy-grouted rock bolts which consolidate the overlying Platteville Limestone into a rigid plate.

Noon: Box lunch picnic.

AFTERNOON ITINERARY

Stanley Chernicoff, Field Leader

The surficial geology of the Twin Cities Metropolitan Area is dominated by the effects of the late Pleistocene glaciation of Minnesota. The glacial events that modified the regional landscape are reconstructed by interpreting the deposits of glacial materials and their associated landforms.

In the Metro area, glacial deposits from two points of origin have been identified. Approximately 20,000 years ago, an ice lobe accumulating in the Lake Superior basin advanced along a bedrock conduit (the Minneapolis Lowland) to a terminal position topographically expressed locally as the St. Croix moraine. This land form, characterized by hills and depressions dotted with ice-block lakes, is composed of poorly sorted mineral constituents entrained by the glacier as it traversed eastern

Minnesota. The bedrock supplied quantities of red sandstone, basalt, and red granophyre that impart the characteristic red hue to Superior lobe drift.

Approximately 16,000 years ago, ice originating in southeastern Manitoba and northwestern Minnesota advanced along the Red River valley toward a terminal position near Des Moines, Iowa. A short-lived extension of the Des Moines lobe (the Grantsburg sublobe) entered the Minnesota lowland from the southwest and proceeded across the northwest corner of the metropolitan area overriding the recently deposited red glacial drift. The deposits of the Grantsburg sublobe are markedly different from the Superior lobe materials. Along its route of advance, the ice traversed a sedimentary terrane incorporating fragments of Paleozoic limestone, dolomite, and siliceous shale. The carbonate composition and the diagnostic grey color (yellow or tan in oxidized exposures) easily distinguish Grantsburg sublobe drift from the reddish-colored Superior lobe sediments.

A field review of the geology of an urban center should describe the geologic character of the area and, wherever possible, relate the observed physical conditions to their land-use potential. The object of this part of the excursion is to introduce the salient features of the local geology and promote discussion regarding responsible urban development within the geologic framework.

Stop C; Grey Till - Red Till Interface: New Brighton Quadrangle - N. Danube Road and Matterhorn Drive. The stratigraphic relationship between the red Superior lobe till and the overlying grey Grantsburg sublobe till is demonstrated at this locality. Masses of red till have been incorporated into the grey till creating the thin interlaminations.

Stop D; Anoka Sandplain: New Brighton Quadrangle-County Road I and Lexington Ave. Sand-charged meltwaters associated with the wastage of the Grantsburg sublobe constructed this extensive sandplain. The plain is characterized by ice-block depressions and sand dunes. The high water table is a consequence of the relatively low transmissivity of the underlying glacial till.

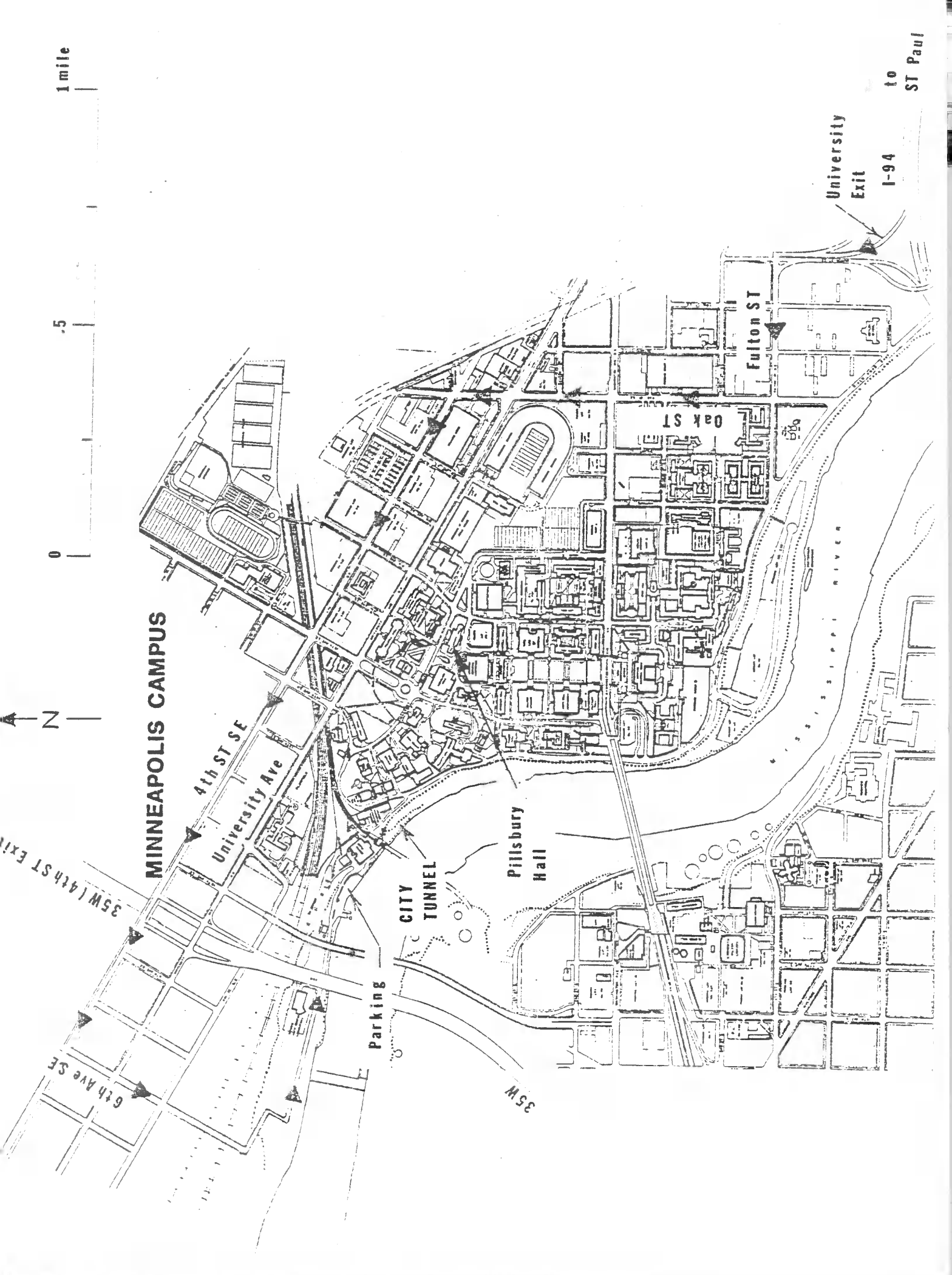
Stop E; Abandoned Valley of the Mississippi River; St. Paul East Quadrangle-Wheelock Parkway and Nebraska Ave. Along the route of

travel from the Anoka Sandplain to this locality, the alignment of ice-block lakes (Round, Valentine, Johanna, Josephine, McCarron) represents a former course of the Mississippi River. The bedrock valley is buried by deep deposits of glacial drift.

Stop F; Indian Mounds Park: St. Paul East Quadrangle - Warner Road. This site affords a view of the Mississippi River floodplain. The geological and environmental elements of the floodplain management issue (ie. the construction of dikes at the Holman Field airport and the Pig's Eye coal terminal) are visible.

Stop G; Perched Lake Plains within the St. Croix Moraine: White Bear Lake East Quadrangle - County Highway 9 and 115 St. This level plain represents a characteristic topographic reversal of a glaciated terrain. At one time, the plain was surrounded by ice that fed meltwater into an enclosed basin. The subsequent wastage of the surrounding ice resulted in the perching of basin sediments above the surface previously covered by ice.

Stop H; Land-Use Planning in a Glaciated Terrain: Marine on the St. Croix Quadrangle - County Road 81 (May Ave.) and 155 St. This site was one of several proposed for the Washington County Sanitary Landfill. The glacial drift of the locality includes a mantle of loess (windblown silt) and dense red till. The suitability of this site for a landfill will be discussed.



MINNEAPOLIS CAMPUS

1 mile

.5

0

N

35W (4th St Exit)

6th Ave SE

4th St SE
University Ave

Parking

CITY
TUNNEL

Pillsbury
Hall

35W

Oak St

Fulton St

University
Exit

I-94

to
ST Paul