

17TH ANNUAL
INSTITUTE
ON
LAKE SUPERIOR GEOLOGY



DULUTH, MINNESOTA
MAY 5-8, 1971



TECHNICAL SESSIONS

ABSTRACTS

and

FIELD GUIDES

for the

17th ANNUAL

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Sponsored by

UNIVERSITY OF MINNESOTA, DULUTH

held at

DULUTH, MINNESOTA

May 5 - 8, 1971

Edited by D.M. Davidson
D.G. Darby
J.C. Green
J.A. Grant

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17th Annual

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Sponsored by

University of Minnesota, Duluth

at

Duluth, Minnesota

May 5 - 8, 1971

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P R O G R A M

Tuesday, May 4, 1971

5:00 p.m. Field Trip A (North Shore Volcanics) leaves
Hotel Radisson Duluth.

Wednesday, May 5, 1971

6:00 p.m.
to Field Trip A returns to Duluth
7:00 p.m.

7:00 p.m.
to Institute Registration - Poolside, Hotel
9:30 p.m. Radisson Duluth

Thursday, May 6, 1971

7:30 a.m.
to Registration, Superior Street Foyer, Hotel Duluth
12:00 a.m.

S E S S I O N 1

Morning

Thursday, May 6, 1971

Symposium on Keweenawan Geology - Lake Superior Region

Co-chairmen: Jack Phillips and Walter White

Page No.

8:45	J. C. Green	Introductory Remarks	
9:00	W. White & Others	Keweenawan Stratigraphy of Westernmost Michigan	71
9:20	N. K. Huber	The Keweenawan Geology of Isle Royale, Michigan	31
9:40	H. A. Hubbard	Keweenawan Geology of the Porcupine Mountains, Western Upper Peninsula Michigan	30
10:00	J. C. Green	Stratigraphy of the North Shore Volcanic Group Northeast of Silver Bay, Minnesota	20
10:20	R. N. Annells	Middle Keweenawan Volcanism of Eastern Lake Superior	7
10:40	A. P. Ruotsala	Characteristics of Some Alteration Minerals Portage Lake Lava Series, Michigan	59
11:00	W. T. Jolly	Zeolite and Prehnite - Pumpellyite Facies in the Keweenawan Basalts of Northern Michigan II: The Role of Volatiles	34
11:20	T. A. Vogel & R.J. Rohrbacher	Chemically Zoned Native Copper and Chalcocite from White Pine Michigan	70
11:40	H. C. Halls & G. F. West.	The Isle Royale Fault	25
12:00	NOON	Adjourn for Lunch	

There will be a lunch meeting of the Board of Directors in the Hotel Radisson Duluth - location to be announced.

S E S S I O N 2

Afternoon

Thursday, May 6, 1971

Symposium on Keweenawan Geology - Lake Superior Region

Co-Chairmen: Raymond J. Leone and Paul K. Sims			<u>Page No.</u>
1:40	J. T. Mengel, Jr. & R. A. Hendrickson	Exploration Geology of Douglas County, Wisconsin	47
2:00	D. M. Davidson, Jr.	A New View of the Duluth Complex, Minnesota	13
2:20	B. Bonnichsen	Hornfelses in the Southern Part of the Duluth Complex, Minnesota	11
2:40	M. G. Mudrey & P. W. Weiblen	Reinvestigation of "Red Rocks" in the Pigeon Point Area, Minnesota	53
3:00 to 3:20	Coffee Break		
3:20	W. A. Robertson & W. F. Fahrig	The Great Logan Paleomagnetic Loop	58
3:40	A. Mattis	Lower Keweenawan Sediments of the Lake Superior Region	45
4:00	D. Myers	The Sedimentology and Tectonic Significance of the Bayfield Group, Wisconsin	54
4:20	G. B. Morey	Revised Keweenawan Subsurface Stratigraphy, Southeastern Minnesota	50
4:40	H. C. Halls & C. F. West	Shallow Structure and Stratigraphy of the Lake Superior Basin from Seismic Refraction Measurements	23

* * * * *

Evening

7:30 p.m. Banquet - Great Hall - Hotel Radisson Duluth

ADDRESS - Dr. Carl R. Annhauser
Economic Geology Research Unit
University of Witwatersrand
Johannesburg, South Africa

S E S S I O N 3

Morning

Friday, May 7, 1971

General Session

Co-Chairmen: Cedric L. Iverson and J. Kalliokoski

			<u>Page No.</u>
8:40	F. C. Tan & E. C. Perry, Jr.	Implications of Carbon Isotope Ratio Variations in Carbonates from the Biwabik Iron Formation, Minnesota	64
9:00	S. Viswanathan, E. C. Perry, Jr. & P. Sims	Oxygen Isotopic Studies of Early Precambrian Granitic and Metamorphic Rocks from the Western Part of the Giants Range Batholith, Northeastern Minnesota	66
9:20	G. L. LaBerge	Some Geology of the Marathon County Volcanic Belt	39
9:40	P. O. Banks & W. R. Van Schmus	Chronology of Precambrian Rocks of Iron and Dickinson Counties, Michigan	9
10:00	L. A. Prince & G. N. Hanson	Geochronology of the Giants Range Granite	57
10:20	G. Klein	Precambrian Clastic Paleotidal Sedimentation	36
10:40	W. Hinze, D. M. Davidson, Jr. & R. Roy	Continental Rifts	29
11:00	R. C. Malan & D. A. Sterling	Distribution of Uranium and Thorium in Pre- cambrian Rocks of the Western Great Lakes Region	42
11:20	N. W. O'Hara & W. J. Hinze	Lake Michigan Aeromagnetic Survey	56
11:40	R. L. Kellogg & W. J. Hinze	An Aeromagnetic Survey of the Southern Peninsula of Michigan	35
12:00	NOON	Lunch	

S E S S I O N 4

Afternoon

Friday, May 7, 1971

General Session

Co-Chairmen: Meredith E. Ostrom and Paul C. Tychsen			<u>Page No.</u>
1:20	Business Meeting of the Institute		
1:40	M. S. Loughheed & J. J. Mancuso	Hematite Pseudomorphic After Biogenic Pyrite in the Negaunee Iron Formation	41
2:00	E. Dimroth & J. Chauvel	Textural Facies Analysis of Precambrian Cherty Ironstones	15
2:20	W. Duhling	Precambrian Iron Formation at Copper Mountain, Fremont County Wyoming	18
2:40	E. Frodeston	Some Sedimentary Structures in the Lower Cherty Member of the Biwabik Iron Formation, The Virginia Horn Area	32
3:00	G. Spencer	Chert in Sediments	62
3:20	J. Mothersill	Limnogeological Studies of Thunder Bay, Lake Superior, Ontario	51
3:40	R. Shogelski	The General Stratigraphy of Thunder Bay, Lake Superior	61
4:00	<u>End of Technical Sessions</u>		

* * * * *

(Dinner and lodging are included in the field trip fee.)

5:00 Departure for Field Trips:

Field Trip A - North Shore Volcanic Group
Field Trip B - Cross-section, Precambrian Rocks
Field Trip C - Mesabi Range - Biwabik Taconite
Field Trip D - Vermilion District

Buses will depart from Hotel Radisson Duluth.

* * * * *

Saturday, May 8th, 1971

6:00
to (approx.) RETURN OF ALL FIELD TRIP BUSES.
7:00

MIDDLE KEWEENAWAN VOLCANISM OF EASTERN LAKE SUPERIOR.

R. N. ANNELLS

Geological Survey of Canada, Ottawa.

ABSTRACT

Following the study of the Michipicoten Island Keweenawan flows reported elsewhere (Annells, 1970), the same type of detailed stratigraphic/petrographic study has been carried out on the Keweenawan volcanic rocks of the Mamainse Point, Alona Bay and Cape Gargantua sections on the east shore of Lake Superior.

These three east shore sections are mostly made up of mafic olivine-tholeiite types of medium-coarse ophitic or diabasic texture, accompanied by a smaller number of fine-grained olivine-poor tholeiite flows. Flows of intermediate composition were not found in these sections and the flows show little variation in mineralogy. Small volumes of both basic and acid pyroclastic rocks occur interbedded with the flows in the lower part of the 14,300 foot Mamainse Point section, and conglomerates with sandstone partings showing good cross-bedding outcrop in the upper half of this section and in that at Cape Gargantua.

Evidence of the simultaneous availability of basaltic and rhyolitic material is seen in the Mamainse Point section; plugs, dykes and sheets of fine-grained, often flow-laminated and autobrecciated leucorhyolite occur at all levels of this section and one such intrusive sheet was found to be composite, having a 2-foot basal selvage of fine-grained basalt and a 50-foot acid upper part.

Petrographic similarities found in flows of the Mamainse Point and Cape Gargantua sequences provide a good basis for lateral correlation of these two sequences. Near the basal unconformity of the Mamainse section there occurs a highly distinctive glomerophytic olivine-tholeiite flow crowded with large plagioclase laths concentrated in spherulitic clusters up to two inches in diameter (Giblin, 1969); a flow of exactly similar type outcrops 40 miles NNW along strike near the base of the Cape Gargantua section (Ayres, 1969). Both these occurrences are associated with a group of olivine-tholeiite flows rich in large pseudomorphs after olivine phenocrysts which may make up to 35 per cent by volume of the rock in parts of such flows at Mamainse Point. This striking similarity of the flows in the lower levels of the Mamainse Point and Cape Gargantua piles suggests simultaneous effusion of the same mafic magma supply over a wide area to produce lava flows of similar extent to that of the Greenstone Flow of the Michigan Keweenawan.

The Mamainse Point, Alona Bay and Cape Gargantua flows are also petrographically similar to the olivine-tholeiite flows forming the basal part of the Michipicoten Island section and it is possible that these latter flows, also cut by acid intrusions, may represent the upper part of an extensive and largely uniform flood basalt pile whose earliest members rest directly on the Archaean on the east shore of Lake Superior. The more highly differentiated andesite and rhyolite flows of Michipicoten Island are thus interpreted as being of much later extrusion than the Mamainse Point, Alona Bay and Cape Gargantua flows. A general increase in the degree of alteration of lava flows is apparent as the Keweenawan lava pile is followed downwards from the top of the Michipicoten Island section to the base of the Mamainse Point section.

Some differences in general chemistry exist between flows newly analysed from the Michipicoten Island and Mamainse Point sections; 36 analyses of the Island flows follow a tholeiitic trend of moderate iron-enrichment on an MFA plot; a similar plot of 46 analyses of Mamainse Point flows gives a tholeiitic trend of high iron-enrichment.

References:

- Anne1ls, R. N., 1970, Keweenawan volcanic geology of Michipicoten Island, Lake Superior; Program, 16th Ann. Inst. on Lake Superior Geol., Thunder Bay, Ont., May 1970, 7.
- Ayres, L. D., 1969, Geology of Townships 31 and 30, Ranges 20 and 19; Ontario Dept. Mines Geol. Rept. 69,38.
- Giblin, P. E., 1969, Ontario Dept. Mines, Prelim. Geol. Maps 553 and 555.

CHRONOLOGY OF PRECAMBRIAN ROCKS OF
IRON AND DICKINSON COUNTIES, MICHIGAN

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Department of Geology
University of Kansas, Lawrence, Kansas, 66044

U-Pb analyses of cogenetic zircon suites and Rb-Sr whole rock analyses from selected Precambrian units in Iron and Dickinson Counties, Michigan, suffice to establish an internally consistent chronology for this classic area. Stratigraphic nomenclature used herein is adopted from James et al. (1961).

Zircons from the Norway Lake Gneiss, which underlies the Dickinson Group, yield a concordia intercept age of approximately 2375 m.y., but Rb-Sr whole rock analyses from the Norway Lake Gneiss do not define an isochron, and the isotopic composition of Pb from separated feldspars is abnormal. Thus, we conclude that the 2375 m.y. "age" obtained from the zircons is probably the result of complex metamorphism and deformation of the Norway Lake Gneiss and does not indicate its true absolute age. The 2375 m.y. event that affected the Norway Lake Gneiss may be pre-Dickinson, thus establishing a possible older limit for the age of the Dickinson Group. Earlier published zircon analyses suggesting a much greater antiquity for the Dickinson Group (2700 m.y. or more: Aldrich et al., 1965) are interpreted to reflect detrital zircon components in the metasedimentary gneisses.

The pre-Animikie Porphyritic Red Granite, whose field relation to the Dickinson Group is uncertain, gives a zircon concordia intercept age of approximately 2100 m.y., and whole rock Rb-Sr analyses are also consistent with this age. We interpret this age to be post-Dickinson, thus bracketing the age of the Dickinson Group between 2100 m.y. and, perhaps, 2400 m.y.

A single zircon analysis from the Hemlock Volcanics of the Animikie Series yields a Pb-Pb age of 1985 m.y., but the zircon is somewhat discordant, so that the concordia intercept age is expected to be slightly older at approximately 2000 m.y.

Rb-Sr whole rock analyses on the post-Animikie Peavy Complex yield an age of approximately 1700 m.y. However, previously published mineral age determinations on other post-Animikie units indicate that the Animikie Series is definitely older than 1900 m.y. (Aldrich et al., 1965). Thus, deposition of the Animikie Series appears to be bracketed in the interval between 2100 m.y. and 1900 m.y.

A maximum age of 2100 m.y. for the Animikie Series, in conjunction with published Rb-Sr data on the post-Huronian Nipissing Diabase (2160 m.y.) and on Huronian sediments themselves (2285 m.y.) (Van Schmus, 1965; Fairbairn et al., 1969), severely restricts possible correlations between the Animikie Series and the Huronian formations of the North Shore of Lake Huron.

References

- Aldrich, L.T., Davis, G.L., and James, H.L., 1965, Ages of minerals from metamorphic and igneous rocks near Iron Mountain, Michigan: Jour. Petrology, v. 6, pp. 447-472.
- Fairbairn, H.W., Hurley, P.M., Card, K.D., and Knight, C.J., 1969, Correlation of radiometric ages of Nipissing diabase and Huronian metasediments with Proterozoic orogenic events in Ontario: Can. Jour. Earth Sci., v. 6, pp. 489-497.
- James, H.L., Clark, L.D., Lamey, C.L., and Pettijohn, F.J., 1961, Geology of central Dickinson County, Michigan: U.S. Geol. Surv. Prof. Paper 310, 176 p.
- Van Schmus, R., 1965, The geochronology of the Blind River-Bruce Mines area, Ontario, Canada: Jour. Geol., v. 73, pp. 755-780.

HORNFELSES IN THE SOUTHERN PART OF THE DULUTH COMPLEX, MINNESOTA

Bill Bonnichsen

Cornell University

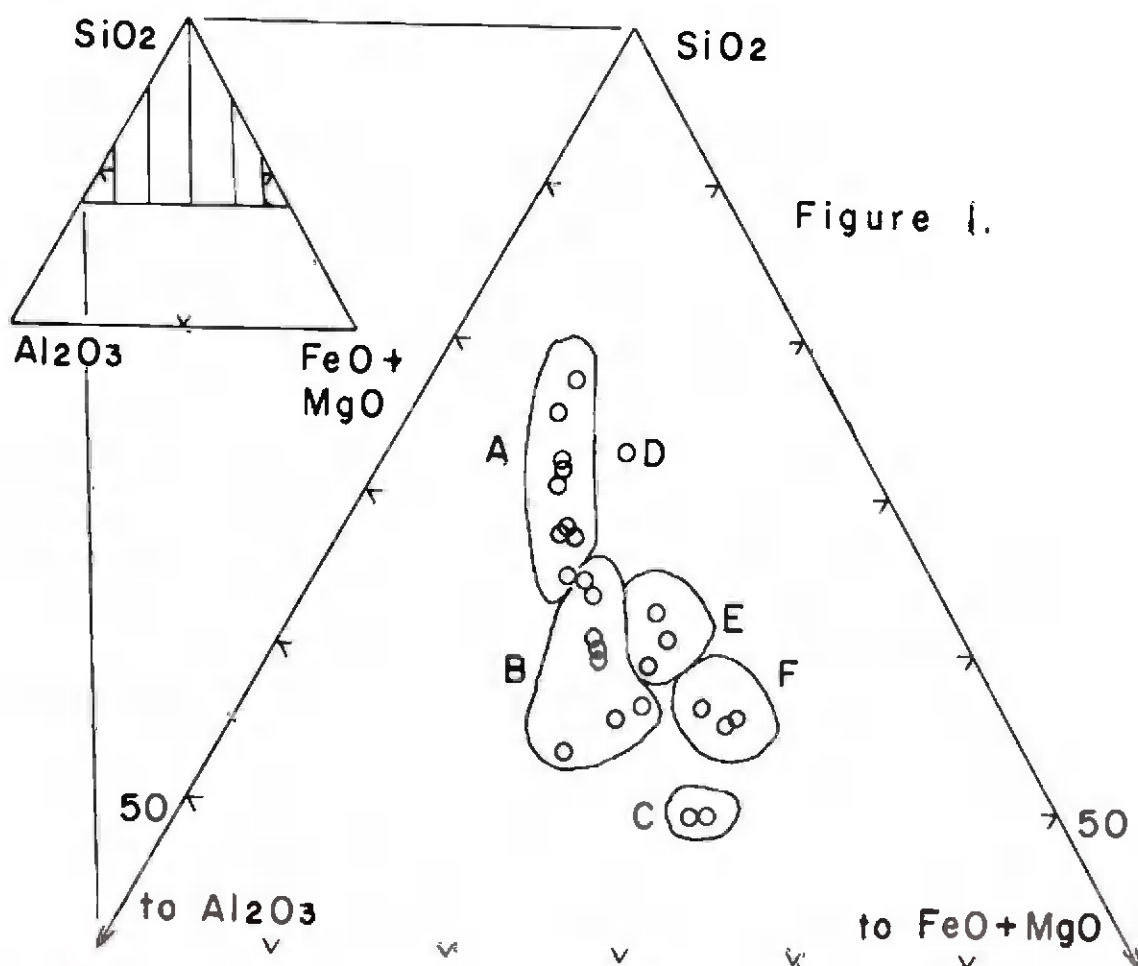
Hornfels bodies ranging from less than an inch to thousands of feet in dimensions are abundant in the southern part of the Duluth Complex. They were derived from a wide variety of initial rock types, many of which occur in the complex footwall. The most abundant types were derived from argillaceous sediments of the Virginia Formation, mafic to intermediate volcanic rocks of Keweenawan age and various intrusive rocks indigenous to the complex. Others include iron formation, quartzite and dioritic rocks from the pre-Keweenawan basement and clastic sediments of probable Keweenawan age.

Virginia inclusions are very similar to metamorphosed footwall Virginia; however, the grain size is larger and the relative mineral proportions are slightly different. The silicate mineralogy of argillaceous inclusions includes coexisting cordierite, orthopyroxene, biotite, plagioclase and potassium feldspar. Minor amounts of pyrrhotite, graphite, ilmenite and traces of chalcopyrite and pentlandite are common, but olivine and Ca pyroxene are invariably absent. Various types of relict sedimentary structures are distinguishable in all but the smallest of hornfelsed Virginia inclusions.

Volcanic hornfels inclusions are characterized by their lack of relict sedimentary structures, local round to elliptical plagioclase and Ca pyroxene segregations that probably were amygdules and their mineralogy. They consist largely of plagioclase and Ca pyroxene, and normally contain abundant magnetite and orthopyroxene (commonly inverted pigeonite). Olivine, brown hornblende, apatite, ilmenite, and traces of biotite occur in some bodies but none are known to contain cordierite, graphite, or more than traces of potassium feldspar.

The proportions of weight percent SiO_2 , Al_2O_3 and $\text{FeO}+\text{MgO}$ of various types of hornfelses and equivalent rocks are plotted in figure 1 (Bonnichsen, in prep.). The A, B and C groups are materials from the Virginia Formation, whereas the D, E and F groups are volcanic hornfelses and their equivalents. Note that, although both groups show considerable range in their proportion of SiO_2 , the Virginia materials have a higher proportion of Al_2O_3 .

The group A samples are unmetamorphosed Virginia and equivalent hornfelses from the footwall of the complex. The group B samples are from inclusions within the complex. Note their depletion in SiO_2 relative to the A group. This suggests that SiO_2 was lost from the inclusions; this loss is accompanied by a similar depletion of K_2O in several samples and suggests loss of a granitic partial melt during the hornfelsing process. The group C samples are from the margins of hornfels bodies and thus were in direct contact with the intrusive rocks. Their compositions deviate further from the initial values than do those of group B; they are considered to be refractory residuals which had become nearly equilibrated with the adjoining magmas. Part of the group B rocks contain texturally interstitial feldspars and cordierite which are interpreted as recrystallized partial melts. During the hornfelsing process a melt with the composition of cordierite and alkali feldspar evidently developed after a granitic fraction had been lost. Hornfelses with the group C composition are considered to have formed where this later type of melt had been lost. The formation of granitic dikes and the production of abundant biotite and orthopyroxene at the expense of olivine and Ca pyroxene are the principal effects on the enclosing intrusive rocks wrought by the assimilation of such partial melts.



Group E consists of hornfelsed basalts; they have bulk compositions that show little deviation from the compositions of ordinary basalts. Group F rocks, however, have lower K₂O and SiO₂ and higher TiO₂ and FeO contents than ordinary basalts and have high Fe/Mg ratios. Two of these hornfelses may have been intrusive residual liquids which separated from troctolite but the other one evidently is a hornfelsed volcanic rock that contains probable relict amygdules. Sample D is an unmetamorphosed magnetite-rich basaltic rock from along the eastern margin of the complex; its Fe/Mg ratio is like that of group F. The volcanic rock in group F may initially have had a composition similar to that of sample D. If so, it lost a substantial amount of granitic material during the hornfelsing process.

The abundance and distribution of hornfelsed volcanic rocks in the southern part of the complex supports the concept that an extensive system of Keweenawan flows was present throughout the region and had been laid down on an erosion surface cut in the Middle Precambrian rocks. The intrusion of the Troctolitic Series and accompanying crustal extension evidently broke up the volcanic rocks. As a result the hornfelses are widely distributed throughout the southern half of the complex. Many of the large bodies occur as septum between adjacent intrusive bodies. The great number of inclusions of various types along the footwall of the complex indicated that the intruding troctolitic magmas had considerable mechanical strength. Evidently, these magmas were in the form crystal-rich mushes during emplacement.

Ref: Bonnicksen, B. (in prep.); The southern part of the Duluth Complex, St. Louis and Lake Counties, Minnesota; to be publ. in Geology of Minnesota, G.M. Schwartz commemorative volume; P.K. Sims, ed.

A NEW VIEW OF THE DULUTH COMPLEX, MINNESOTA

by

Donald M. Davidson, Jr.
University of Minnesota, Duluth
and
Minnesota Geological Survey

A B S T R A C T

The late Precambrian (Keweenawan) Duluth Complex is a sequence of generally discordant intrusive rocks extending northeastward from Duluth to Hovland, Minnesota in a roughly crescentic configuration. The outcrop pattern of the Complex is bifurcated on the east and south by rocks of the North Shore Volcanic Group.

As may be noted in Table 1, three rock series (anorthosite, troctolite-olivine gabbro and felsic) constitute the major petrologic units of the Complex. Anorthosite series rocks were apparently emplaced as large, crystal-liquid masses in which cumulus plagioclase is the predominant mineral. The anorthositic rocks, which form the central portion of the Complex, have been subsequently intruded by the troctolite series along the northern and western footwall and by the olivine gabbro series to the southeast. The troctolites and gabbros are a sequence of generally layered rocks containing cumulus plagioclase and olivine and poikilitic pyroxenes. The basal troctolite series dips gently (15°) towards Lake Superior, whereas the attitudes of the upper olivine gabbro series vary from northward dips of 40° (e.g. Sawbill Lake area) to southward at low (15°) angles (e.g. along the Brule River Prong). Felsic series rocks are predominantly granophyric granite which occur as subhorizontal sheet-like masses above both margins of the olivine gabbro series. Separate minor intrusives such as the Endion Sill, the Beaver Bay Complex and the Hovland Complex appear to be younger than the Duluth Complex, whereas only the Gunflint Prong Layered Complex appears older. Petrologic relationships suggest multiple magma sources derived from the mantle, to account for the petrogenetic sequence of the Duluth Complex.

The Duluth Complex is coincident with the axis of the Mid-Continent Gravity High. Footwall shearing and the asymmetric position of the Complex with respect to the Lake Superior Syncline suggest Complex emplacement consanguinous with rifting. Gravity studies to date suggest the Complex thins or is absent beneath Lake Superior. Dominant Complex fracture trends (N.-N.90E. or W., N.20E.-N.80E.) are common throughout the Lake Superior area suggesting regional post-intrusive extension.

Significant base-metal mineralization occurs within selected troctolite series horizons with local ore controls afforded by host rock lithology and structural settling shelves. Should the proposed funnel configuration of the central complex be verified, subsurface exploration of the Southern Complex appears warranted,

Table 1. Summary of Principal Petrologic Series and Units, Duluth Complex, Minnesota

		<u>Series</u>	<u>Unit</u>	<u>Principal References</u>
			Endion Sill	Ernst, W. G., 1960, Jour. Pet., Vol. 1, p. 286-303
		Late Minor Intrusive Complexes	Beaver Bay Complex	Gehman, H. M., Jr., 1957, Unpub. Ph.D. Thesis, Univ. of Minn. Konda, T., 1970, Contr. Min. Pet., Vol 29, p. 338-344
			Hovland Complex	Jones, N., 1963 Unpub. M.S. Thesis, Univ. of Minnesota
		Felsic	Granophyric Granite and Minor Felsic Intrusives	Davidson, D. M., Jr., 1969, Minn. Geol. Surv. Misc. Map Ser., M-7, M-8 Grout, F. F., and others, 1959, Minn. Geol. Surv. Bull. 39.
e Duluth Complex Cambrian (1.1±0.2b.y.)	Troctolite-Olivine Gabbro		Upper Olivine Gabbro	Grout, F. F., and others, 1959, Minn. Geol. Surv. Bull. 39. Bonnichsen, Bill, 1969, 30th Annual Min. Sympos., Univ. Minn. pp. 89-93
			Basal Troctolite	Phinney, W. C., 1969, Minn. Geol. Surv. Rept. Inv. 9 Taylor, R. B., 1964, Minn. Geol. Surv. Bull. 44
	Anorthosite		Central Anorthosite and Anorthosite Inclusions	Bonnichsen, Bill, 1969, 30th Annual Min. Sympos., Univ. Minn. pp. 89-93 Davidson, D. M., Jr., 1969, Minn. Geol. Survey Misc. Map Ser. M-7, M-8 Phinney, W., 1966, N.Y. State, Mus. Sci. Mem. Vol. 18, p. 135-147 Taylor, R. B., 1964, Minn. Geol. Survey Bull. 44
			Gunflint Prong Sill	Babcock, R.C., 1959, Unpub. M.S. Thesis, Univ. Wisc.
	Early Minor Intrusive Complexes		Brule Lake Sills	Grout and others, 1959, Minn. Geol. Survey Bull. 39.
		North Shore Volcanic Group	Granofels	Davidson, D.M., Jr., 1969, Minn. Geol. Survey Map Ser. M-7, M-8
			Volcanics-Undifferentiated	
Middle				
Lower	Duluth Complex	Early Minor Intrusive Complexes	Gunflint Prong Layered Complex	Nathan, H., 1969, Unpub. Ph.D. Thesis, Univ. Minn.

TEXTURAL FACIES ANALYSIS OF PRECAMBRIAN CHERTY IRONSTONES*

by

Erich Dimroth, Service de l'Exploration géologique
Ministère des Richesses Naturelles, Québec, P.Q.

and

Jean-Jacques Chauvel, Département de Géologie,
Université Rennes, Rennes, France

A B S T R A C T

Textures of Precambrian cherty ironstones are very similar to those of limestones (Dimroth 1958). Accordingly the methods of limestone petrology can be applied in the study of ironstones.

Ironstones can be conceived to be composed of textural elements. Textural ironstone types are defined by the kind and proportion of textural elements present. Textural facies types compose thin (3 feet-100 feet) stratigraphic units; they are either texturally homogeneous, or are composed of several textural rock types that form beds alternating in a characteristic sequence. It is generally possible to determine the paleo-environment in which the various textural facies types formed, and by correlation of stratigraphic sections, to gain a view of the paleogeography of the depositional basin.

We distinguish the following textural elements in the ironstones:

I - Orthochems

1. Femicrite: A past of fine-grained iron silicate (minnesotaite, stilpnomelane) or of siderite derived from iron silicate and iron carbonate muds.

2. Matrix chert: Chert deposited as a silicagel matrix.

3. Cement chert: Chert that formed between allochem grains after deposition.

Matrix chert and cement chert can be distinguished only in some hematite ironstones.

II - Allochems

1. Pellets: Ellipsoidal particles 0.2 mm. across unsharply bounded, always embedded in matrix chert. Pellets are interpreted as aggregated particles.

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2. Intraclasts: Fragments of the unconsolidated sediment that have been redeposited. Previously (James, 1954) described from intraformational conglomerates (large intraclasts) and as "granules" (= sand-size intraclasts).

3. Oolites and Pisolites.

4. Shards: Shards are complex textures. Two sub-types predominate (a) welded and extremely deformed oolites and intraclasts (accommodation shards). (b) shards composed mainly of peeled off fragments of oolites and intraclasts (exfoliation shards).

Textural rock types are defined by the combination of textural elements present. Main types are:

I. Femicrites: Laminated or ribboned silicate-carbonate ironstones.

II. Matrix chert: Laminated or ribboned cherts, generally with pellets.

III. Cemented intraclastic or oolitic ironstones.

IV. Intraclastic or oolitic rocks with chert matrix.

V. Intrafemicrites: Intraclasts embedded in a femicrite matrix.

Some other types, particularly containing shard textures, are quantitatively less important.

The paleogeographic application of the method will be demonstrated at the example of the lower jaspilite member of the Sokoman Ironstone in the western half of the Labrador trough between latitudes 54°45'N and 55°15'N.

Close to the western margin of the trough this stratigraphic unit is locally represented by a massive or thickly bedded finely intraclastic and oolitic chert cemented hematite ironstone (facies type 1). Toward the east this type grades into interbedded oolitic-intraclastic hematite ironstone with chert cement or matrix, alternating with laminated matrix chert containing hematite (facies type 2). This type is thin to medium bedded (2-30 cm.) and characteristically shows lenticular bedding. It grades basinwards into a type that contains intercalated beds, 2-100 cm. thick, of laminated femicrite (facies type 3). Farther east the oolitic intraclastic beds are lacking in type 4 and finally type 5 is composed only of laminated femicrite with interbeds of laminated femicrite bearing matrix chert. Facies types 3 and 4 are characterized by slump structures and structures indicating strong syndepositional deformation. Toward the centre of the trough types 4 and 3 reappear, and grade into a facies containing interbeds with very coarse (2 cm.) intraclasts and pisolites embedded in matrix chert (facies type 6); the intraclasts and pisolites were very soft at time of deposition. Facies type 1 is tentatively interpreted as a sand bar facies that separates a lagoonal environment (not discussed here) farther west from the open basin. Facies type 2 has been deposited in the intratidal and shallow sub-tidal zone in the foreshore of the sand bars. Types 3 and 4 represent a relatively deep subtidal facies and

facies zone 5 was deposited in a relatively deep basinal environment (maybe 50-100 m. water depth). Facies type 6 was likely deposited on shallow sub-tidal shoals that extended in the centre of the Labrador trough. The coarse intraclastic and pisolitic beds may represent storm layers.

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PRECAMBRIAN IRON FORMATION AT COPPER
MOUNTAIN, FREMONT COUNTY, WYOMING

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A B S T R A C T

Precambrian banded iron formation is exposed along the south-facing flanks of Copper Mountain, approximately 15 miles north of Shoshoni, in northeastern Fremont County, Wyoming. The Precambrian metamorphic complex consists of interlayered quartzofeldspathic gneisses, amphibolites, amphibole schists, pelitic rocks, and iron formation into which granite, pegmatite, and mafic dikes and sills have been intruded. The complex has been metamorphosed to the kyanite-muscovite subfacies of the almandine-amphibolite facies. Sedimentary rocks of Paleozoic or Cenozoic age abut the Precambrian complex on all sides.

The mineralogical composition of the iron formation is very simple, consisting of magnetite, quartz, and any combination of blue-green hornblend, grunerite, and cummingtonite. Magnetite, in all degrees of alteration to hematite, occurs in thin laminae and fine clusters with angular, sharply embayed boundaries and as very fine inclusions in quartz and amphibole grains. Banding is developed by apparent increase in grain size of the magnetite at the expense of quartz and amphibole grains.

The iron formation, interlayered with amphibolite and quartz-mica schist, is exposed for a distance of about 6 miles over an approximate width of 1000 feet. The strike of the formation is N 80°E and the dip is 70° to the south.

Liberation and concentration tests indicate the presence of roughly 13½ million tons of concentrates containing 56% iron and 22% silica. The amount of very fine magnetite in quartz and amphibole grains and the amount of interstitial quartz in the magnetite-rich bands account for the high silica content of the concentrates.

Rail transportation comes within ten miles of the outcrop area, but the nearest markets for a blast furnace feed are over 240 miles away.

The distance to market, high silica content, low tonnage, and steep dip combine to indicate that this iron formation has a questionable economic potential.

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Table 1

Stratigraphy of Northeast Limb (Tofte to Grand Portage) of
North Shore Volcanic Group (Exclusive of Interflow Sediments)

<u>Approx. Thickness (ft.)</u>	<u>Lithostratigraphic unit</u>	<u>Lithic Character</u>
Top (near Tofte - Lutsen)		
1020	Lutsen basalts	olivine basalts, olivine tholeiites
160	Terrace Point basalt flow	Thomsonite-bearing ophitic basalt
310	Good Harbor Bay andesites	brown, porphyritic andesite, trachyandesite
360	Breakwater trachybasalt flow	brown, columnar, granular trachybasalt
500	Grand Marais rhyolite flow	pink, red, gray porphyritic rhyolite
600	Croftville basalts	various fine-grained basalts
1020	Devil Track felsites	aphyric and porphyritic rhyolite flows
400-900	Red Cliff basalts	amygdaloidal, ophitic olivine basalts
1300	Kimball Creek felsite	pink to tan, porphyritic felsite
1800	Marr Island lavas	mixed tholeiitic basalt, intermediate, felsic lavas
1000	Brule River basalts	granular-diabasic amygdaloidal basalts
3500	Brule River rhyolite flow	pink to gray porphyritic rhyolite
4000 (est.)	Hovland lavas	mixed porphyritic basalt, trachybasalt, rhyolite
200	Red Rock rhyolite flow	red, porphyritic rhyolite
260	Deronda Bay andesite flow	gray-brown, aphyric andesite
4500	Grand Portage basalts	mixed tholeiitic to diabasic basalts
<u>Base</u>	(at Grand Portage)	
21,430		

Table 2

Stratigraphy of Upper Part of Southwest Limb (Tofte
to Palisade Head) of North Shore Volcanic Group

<u>Approx. Thickness (ft.)</u>	<u>Lithostratigraphic unit</u>	<u>Lithic character</u>
Top (at Tofte)		
4000	Schroeder basalts	amygdaloidal, ophitic olivine tholeiites
>300	Manitou trachybasalt flow	red-brown, granular trachybasalt to basalt
	(more of the Schroeder basalts)	
>280	Bell Harbor lavas	quartz tholeiites, aphyric trachybasalts
>300	Palisade rhyolite flow	gray to pink, porphyritic rhyolite
Few 100's	Baptism River lavas	mixed lavas, mostly basalts

SHALLOW STRUCTURE AND STRATIGRAPHY OF THE LAKE SUPERIOR
BASIN FROM SEISMIC REFRACTION MEASUREMENTS.

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ABSTRACT

Between 1966 and 1969 thirty-three seismic refraction profiles were obtained in Lake Superior using a single ship sonobuoy technique (Halls and West, 1971). The seismic data have led to a number of conclusions concerning the shallow structure and stratigraphy of the late Precambrian Keweenaw basin that underlies the lake:

- (1) Faults with their north side downthrown at least 1-2 km bound the north shores of Isle Royale and Michipicoten Island.
- (2) The northern limb of the Keweenaw basin just southeast of Isle Royale appears to have undergone a deformation that is perhaps related to movement along the Isle Royale fault.
- (3) In addition to the main basin between Isle Royale and the Keweenaw Peninsula, there is a suggestion of a smaller one southwest of the Slate Islands in the northern part of the lake.
- (4) Late Keweenaw or early Cambrian Bayfield-Jacobsville sandstones appear to underlie most of Lake Superior. Although the site of the lake is governed by the position of the underlying basin, the principal factors determining the size and shape of the lake depression are the distribution of the Bayfield-Jacobsville sandstones and their susceptibility to erosion compared with older rocks.
- (5) For those seismic profiles that have a certain degree of geological control, such as those between Isle Royale and the Keweenaw Peninsula, refraction velocities generally agree well with those estimated (Halls, 1969) from sample measurements in the laboratory. One notable exception occurs in those profiles that lie just off the Minnesota shore. Here velocities of 5 km/s are recorded. These values are typical of Freda-Copper Harbor sandstones, but the presence of these rocks adjacent to the Minnesota coast is discounted on magnetic evidence. Instead the velocities of 5 km/s are assigned to the North Shore volcanics that crop out along the mainland. The apparently low velocities of these rocks compared to those for volcanics between Isle Royale and the Keweenaw Peninsula (5.7-6.2 km/s) can be explained if the North Shore sequence contains a greater proportion of interflow sediment and/or amygdaloidal flow top material.
- (6) The seismic penetration of the refraction profiles was generally insufficient to record the Upper Refractor (Berry and West, 1966) with velocity $6.7 \pm$ km/s. However, one profile northeast of Isle Royale recorded a velocity of 6.5 km/s at a depth of about 6 km. This observation demonstrates the existence of Upper Refractor-type velocities in the marginal parts of the Keweenaw basin.

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THE ISLE ROYALE FAULT

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ABSTRACT

A fault bounding the northwest shore of Isle Royale was originally postulated by Irving and Chamberlin (1885) on physiographic grounds. However, with the exception of recent aeromagnetic studies (Wold and Ostenso, 1966; Hinze et al., 1966) very little extra evidence has been produced as to whether the fault really exists. The aeromagnetic data show a linear anomaly that follows the northwest shore of Isle Royale and extends eastward to Superior Shoal. Although the anomaly indicates a contact between Keweenaw volcanics and sediments, it does not reveal whether the contact is a stratigraphic or faulted one (Halls, 1970). Evidence to date for the so-called Isle Royale fault has therefore been rather inconclusive. This paper discusses some lines of evidence that support the existence of the fault, in the light of new magnetic and seismic data:

(1) Seismic data (Halls and West, 1971) show that the uppermost layer that underlies the channel north of Isle Royale and also the region further northeast toward the Slate Islands has a velocity of about 3.7 km/s and a thickness of about 1-2 km. This seismic layer is all but continuous with a similar one in eastern Lake Superior that can be firmly identified as Bayfield-Jacobsville sandstones. These rocks are thus thought to underlie the Isle Royale channel and if so, their existence necessitates the inclusion of the Isle Royale fault with its downthrown side to the north.

(2) Paleomagnetic data (e.g. Books, 1968; Palmer, 1970) show a remarkably consistent pattern for Keweenaw extrusive rocks. Whereas the lower parts of the volcanic sequence (such as the Osler and South Range lavas) tend to be reversely magnetised, the upper parts such as the Isle Royale and Portage Lake lavas are normal. In the Isle Royale channel a linear magnetic anomaly (C in Fig.1), which is attributed to Keweenaw volcanics, is strongly positive with an attendant minimum to the north, signifying that the volcanics are normally magnetised. Anomaly C continues beyond the channel to both the east and west where it broadens considerably to form anomalies A and D (Fig.1). The sharpness of anomalies A, C and D together with the seismic data indicate that the volcanics are overlain by Keweenaw sedimentary rocks. Thus north of the postulated Isle Royale fault there are buried, normally magnetised, Keweenaw volcanics. If the magnetic Isle Royale 'fault' anomaly were due to a stratigraphic contact between volcanics and sediments it would imply that the sedimentary unit was sandwiched between two thick sequences of normally magnetised volcanics (i.e. the Isle Royale lavas and those causing anomalies A, C and D). Such a sequence is of course possible but it is not a known feature of Keweenaw stratigraphy. The only thick sedimentary unit that occurs in the Keweenaw volcanic sequence is that in Michigan and Wisconsin but it lies between the normal and the reversely magnetised parts of the volcanic sequence (e.g. Meshref and Hinze, 1970). Thus in northern Lake Superior a duplication of the normally magnetised volcanics through movement along the Isle Royale fault is favoured over a stratigraphic sequence of a sedimentary unit between two normal volcanic ones.

(3) The magnetic map of Fig.1 shows that the Isle Royale 'fault' anomaly (E) gradually assumes a more southerly trend toward the west. A weakening of the anomaly in this direction is more compatible with the presence of a fault rather than a stratigraphic volcanic-sediment contact (Halls, 1970).

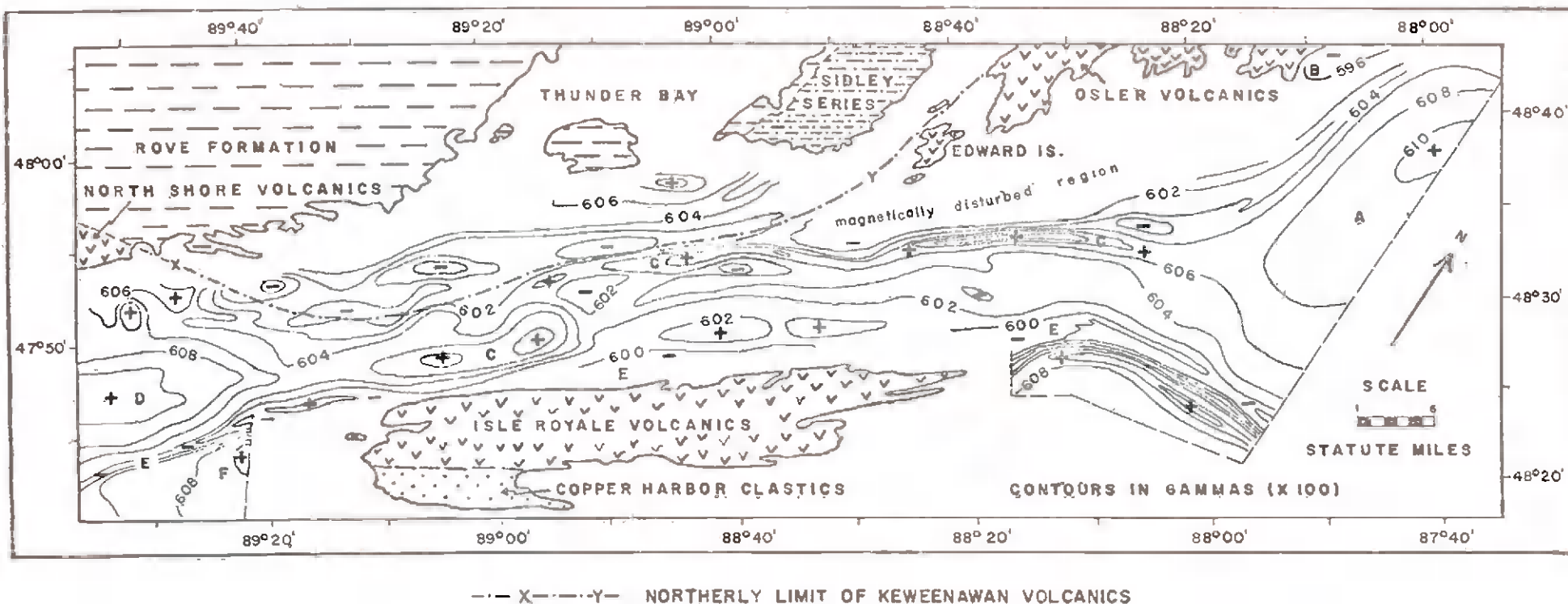
(4) Anomaly C in Fig.1 is essentially continuous with a belt of prominent positive anomalies that extends along much of the Minnesota shore before turning south and terminating in a hook-shaped anomaly over the Bayfield-Peninsula (Wold and Ostenso, 1966). White (1966) concludes that this anomaly is due to volcanics in the upper part of the Keweenaw extrusive sequence. The volcanics causing anomaly C should thus be equivalent, at least in part, to the Isle Royale lavas. Again, a fault would be necessary to explain the apparent duplication of the sequence.

The foregoing observations therefore all tend to suggest that the Isle Royale fault does exist. A two-dimensional magnetic model interpretation of the Isle Royale fault anomaly at its eastern end (Halls, 1970) suggests that the fault dips to the south. The fault is thus of reversed type as its downthrown side is to the north. The displacement along the fault is at least 1-2 km. The reversed nature of the fault and its increasing southerly trend toward the west (Fig.1) support the idea initially raised by Irving and Chamberlin (1885) that it is an easterly continuation of the Douglas fault in Wisconsin.

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FIGURE 1



Total intensity magnetic map of the Isle Royale channel. Survey by H. C. Halls and G. F. West in 1966, using a shipborne proton precession spacing: About 3 miles. Profile orientation: N 30° W., except in extreme northeast where it is more northerly

Keweenawan Geology of the Porcupine Mountains,
Western Upper Peninsula, Michigan

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ABSTRACT

The Porcupine Mountains, Michigan, are underlain by the upper northward-dipping limb of an overturned asymmetric anticline, not a dome with quaquaversal dips as usually shown. The anticline is faulted near its axis, and at the southern margin of the mountains middle Keweenawan volcanic rocks are thrust over steeply dipping to overturned upper Keweenawan sedimentary rocks. The middle Keweenawan rocks, which are younger than the Portage Lake Lava Series, can be divided into two sequences. The older sequence, which includes most of the volcanic rocks in the mountains, consists of fine-grained northward-dipping mafic to intermediate lava flows and two interbedded felsic lava flows. The southern felsic flow is nonporphyritic and constitutes about half the outcrop area. The younger sequence, which is present only in the easternmost part of the mountains, consists of gently eastward and northeastward-dipping fine-grained and aphanitic flows overlain by volcanic conglomerate and sandstone. The younger sequence is either in fault contact or unconformable on the older. Both sequences are repeated in part in imbricate fault slices in the southeastern part of the mountains. A tear fault separates these rocks from the upper Keweenawan rocks to the east.

In the north, the Copper Harbor Conglomerate consists of sandstone containing interbedded lavas. It appears to be conformable on middle Keweenawan lavas in the Lake of the Clouds valley. To the south of the mountains, the upper Keweenawan rocks are folded in an asymmetrical syncline with a steep north limb. The structural relief between the mountains and the syncline is more than 8000 feet. The size of the Porcupine Mountain structure suggests that the Keweenawan rocks of western Michigan were strongly folded in post-Freda time, and not just broadly warped.

THE KEWEENAWAN GEOLOGY OF ISLE ROYALE, MICHIGAN

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A B S T R A C T

Isle Royale lies on the north limb of the Lake Superior syncline, and the stratigraphic section exposed on the island is correlative with the much-studied middle Keweenaw Portage Lake Lava Series and upper Keweenaw Copper Harbor Conglomerate on the Keweenaw Peninsula, on the south limb of the syncline. Dips of the strata range from less than 10° to over 50° ; they are generally steeper on the north side of the island than on the south and average less than 20° .

Exposures on Isle Royale indicate a minimum thickness of 10,000 feet for the Portage Lake Lava Series at this locality. The base of the series is not exposed. As on the peninsula, the series consists largely of basaltic and andesitic lava flows, with lesser amounts of interflow sedimentary and tuffaceous rocks. No felsic flows are known from outcrops, although one has been reported from diamond drilling, about 6,200 feet below the top of the lava series. The interflow clastic rocks generally do not crop out, and most of the individual units are known only from diamond drilling. Within the lava series, which probably contains over a hundred flows in the exposed section, certain stratigraphic units representing individual lava flows or groups of flows can be identified and traced on the basis of characteristic textures or structures, and relative stratigraphic position. Twelve such units have been distinguished within the sequence and provide stratigraphic and structural control for geologic mapping.

On both the Keweenaw Peninsula and Isle Royale, the Copper Harbor Conglomerate is largely derived from lowermost Keweenaw volcanic source terranes, which shed debris into the subsiding Lake Superior basin from opposite sides; for Isle Royale, this would be from the North Shore Volcanic Group of Gehman (1958) in Minnesota. The depositional environment is interpreted as being one of a combination of fluvial and lacustrine conditions resulting in piedmont conglomerates and playa lake or flood plain deposits.

On Isle Royale, various sedimentary features indicate that the general direction of sediment transport was easterly, with a range from northeast to southeast. In this same direction the Copper Harbor Conglomerate increases in thickness and in textural and compositional maturity--namely from a boulder conglomerate, through a mixture of cobble and pebble conglomerates and sandstone, to sandstone and mudstone. In a distance of 20 miles this clastic wedge thickens from a minimum of 1,500 feet to over 6,000 feet between stratigraphic marker horizons; the top of the formation is nowhere exposed and the total thickness must be appreciably greater.

SOME PRIMARY SEDIMENTARY STRUCTURES IN THE LOWER CHERTY MEMBER OF THE
BIWABIK IRON FORMATION : VIRGINIA HORN AREA

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A B S T R A C T

The writer discovered and collected some unusual sedimentary structures in the Lower Cherty Member of the Biwabik Iron Formation at a locality near the Midway addition of Virginia, Minnesota. Polished sections and x-radiographs reveal overturned and disturbed bedding resembling convolute-type bedding, load casts with flame structures, and other structures characteristic of soft sediment deformation. Small-scale cross-bedding and small local thrust faults also are present. Recent experiments on the formation of contorted structures (McKee and Goldberg, 1969) show that convolute-type bedding and small-scale thrust faults, similar to those found in the Biwabik, can be formed by loading a semi-cohesive mud which was deposited on an existing slope of 15-20 degrees.

The preservation of the fine alternating dark and light laminae, small-scale cross-bedding, and possible graded bedding, suggest that these rocks were deposited below wave base with only periodic current activity.

The alternation of the laminae is generally attributed to seasonal changes (Hough, 1958), or periodic influxes of iron-rich and iron-impooverished layers due to tectonic activity coupled with isostatic adjustment of a semi-rigid crust, or a combination of the two processes (Cullen, 1963). Cullen's idea that banded iron formations can be regarded as corresponding to a syn-orogenic "flysch" type of deposition may have applications in explaining some of the structures found in the Lower Cherty Member. Similar sedimentary structures are found in the laminites of documented flysch facies.

The presence of allochthonous black chert pebbles within the beds poses a problem as to mode of emplacement. Turbidity currents, subaqueous sliding or gliding down a slope, or ice rafting mechanisms have to be invoked to explain their presence.

If iron formations represent the products of chemical weathering under warm humid conditions in semi-restricted basins, then ice rafting is not a very likely possibility. If, however, the iron formations were

deposited in a cool polar climate as suggested by paleomagnetic data (Symons, 1966), then these pebbles may be the product of ice transport. If these sedimentary structures are characteristic of the entire formation, and iron formations in general, then a detailed regional study could produce some enlightening results.

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ZEOLITE AND PREHNITE-PUMPELLYITE FACIES IN THE KEWEENAWAN BASALTS OF NORTHERN MICHIGAN II: THE ROLE OF VOLATILES

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A B S T R A C T

The tholeiitic lava flows of the Keweenaw peninsula, Michigan, have undergone metamorphism of the zeolite and prehnite-pumpellyite facies. In the latter, rocks along fractures and upper flow contacts have been transformed to monomineralic rocks (metadomains) composed of either pumpellyite or epidote, depending on stratigraphic position in the pile. These metadomains are enriched in CaO and Al_2O_3 relative to their unaltered basalts through albitization of pre-existing plagioclase. Bulk compositions of the altered parts of the flows, deduced through weighted averages of the rock compositions, are similar to the parental basalts. Thus, little or no material was added from extraneous sources. This metamorphic differentiation occurred as a result of migration of both volatile and non-volatile components over short distances through a fluid pressure gradient with $P_f < P_{total}$. Calcium-aluminum silicates were formed preferentially near rupture zones, where P_f was at its lowest levels. Theoretical considerations suggest that metamorphic differentiation of essentially homogeneous bodies of rock may occur only when P_f is less than P_{total} . During the Keweenawan metamorphic event, the rocks underwent extensive dehydration. As a result, water content of secondary phases decreases with depth from water-rich chlorites and zeolites ($H_2O=12\%$ or more) to water-poor epidote (H_2O about 2%). At lowest exposed levels PO_2 may have reached levels sufficient to subdue formation of pumpellyite in favor of pistacitic epidote. PCO_2 was very low during the peak of the metamorphic event.

AN AEROMAGNETIC SURVEY OF THE SOUTHERN PENINSULA OF MICHIGAN

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A B S T R A C T

Only fragmentary direct information is available on the basement complex underlying the Phanerozoic sediments of the Michigan Basin because of the limited and poorly distributed basement drill tests. To supplement this limited information a regional aeromagnetic survey has been conducted of the Southern Peninsula. Approximately 17,000 miles of total magnetic intensity data were recorded along north-south flight lines spaced at three mile intervals.

A basement configuration map prepared from magnetic depth estimates and basement drill tests confirms that the basement surface under the Southern Peninsula of Michigan has the form of an oval depression reaching a maximum depth of approximately 15,000 feet below sea level on the western shore of Saginaw Bay. A basement high underlies the Howell Anticline and a roughly north-south striking regional basement trough plunges into the basin from the common boundary point of Indiana, Ohio, and Michigan to the vicinity of 42°30'N. The map shows a broad basement platform striking northwest in the extreme southwest corner of the peninsula.

Interpretation of the residual aeromagnetic map in conjunction with geologic and other regional geophysical data from the Southern Peninsula and adjacent areas indicates that the basement of the Michigan Basin has had a complex geologic history. Several basement provinces are defined on the basis of magnetic and gravity anomalies, lithologies and isotope ages of samples obtained from basement drill holes, and extrapolation of known Precambrian geology from the margin of the basin. The Penokean province can be traced from northern Michigan and Wisconsin into the northern portion of the Southern Peninsula. In this area the province is characterized by east-southeast striking anomalies. Central and southwestern Michigan is underlain primarily by felsic rocks correlating with the Central Province.

Basement rocks in southeastern Michigan, which strike generally north-northeast are interpreted as mafic and felsic gneisses and amphibolites. They are correlated with the Grenville province which is bounded on the west by a line extending south-southwest from Saginaw Bay to west of the Howell Anticline and then due south to the Michigan-Ohio boundary. A Keweenawan rift zone characterized by mafic intrusives, extrusives and uplifted gneisses transects the Peninsula from the Traverse Bay area to southeastern Michigan. Keweenawan igneous activity may also be reflected in the numerous local magnetic anomalies in southwest Michigan which occur along northwest striking trends which parallel the regional gravity anomaly pattern.

PRECAMBRIAN CLASTIC PALEOTIDAL SEDIMENTATION

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ABSTRACT

The Precambrian Lower Fine-grained Quartzite of Scotland and both the Precambrian Sterling Quartzite and Precambrian part of the Wood Canyon Formation of eastern California and Nevada are characterized by primary sedimentary features which are indicative of sediment transport and deposition by tidal currents. Sedimentary structures which occur in these formations are grouped into seven associations which are produced by seven phases of tidal sediment transport:

ASSOCIATION 1: Cross-stratification organized into herringbone sets, with bipolar-bimodal orientation; parallel laminae; these features indicate tidal current bedload transport with bipolar reversals of flow directions (Reineck, 1963).

ASSOCIATION 2: Reactivation surfaces: Multimodal frequency distributions of cross-strata set thickness and of dip angles; unimodal orientation of directional current structures parallel to basin topographic strike; all produced by time-velocity asymmetry of tidal current flow (Klein, 1970a).

ASSOCIATION 3: Interference ripples; superposition of current ripples at 90° and 180° on crests and slip faces of dunes, sand waves and internal cross-strata; "B-C" sequences of cross-strata overlain by micro-cross-laminae; highly-variant orientation of current ripples; all produced by late-stage emergence runoff prior to emergence of an intertidal flat (Klein, 1963, 1970a, 1970b).

ASSOCIATION 4: Cross-stratification with flasers and clay drapes; flaser bedding; lenticular bedding; "tidal bedding"; convolute bedding; all produced by alternation of bedload and suspension sedimentation associated with alternating bedload and slack-water tidal current flow (Reineck and Wunderlich, 1968a, 1968b; Wunderlich, 1970).

ASSOCIATION 5. Washout structures, some filled with mud-chip conglomerates; rill marks; flute casts; all produced by tidal scour (Van Straaten, 1954; Reineck, 1967; Klein, 1970a).

ASSOCIATION 6: Mudcracks; intraformational conglomerates; birdseye structure; all produced by exposure and evaporation (Shinn, 1968).

ASSOCIATION 7: Tracks and trails; burrowing structures, "escape" burrows; all produced by burrowing organisms adapted to a tidal regime (Rhoads, 1967; Reineck and others, 1968).

Precambrian paleotidal ranges can be approximated in these rock units from analysis of fining-upward sequences similar to those occurring in prograding tidal coastlines. To date, Late Precambrian paleotidal ranges from 0.3 to 13.0 meters have been measured. This Late Precambrian paleotidal range variation is less than the known variation measured along Holocene tidal coasts (variation of tidal ranges from 0 to 17.5 meters). Perhaps Precambrian paleotidal range variation is not greatly different from present-day variation. If further work substantiates such a limited paleotidal range variation from the Precambrian, it poses critical problems for various geophysical problems that have been proposed for the origin and age of the earth-moon system.

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SOME GEOLOGY OF THE MARATHON COUNTY VOLCANIC BELT

by

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A B S T R A C T

The area east of Wausau in Marathon County consists largely of volcanic rocks which range in composition from basaltic to rhyolitic. The basaltic rocks are mainly to the southeast and the rhyolitic rocks to the northwest, suggesting that the top of the sequence is northwest; however, no definite evidence of stratigraphic top was found. Trachytes are also present at the northwestern edge of the mapped area. Sedimentary rocks are virtually absent.

The volcanic rocks have been intruded by various sized masses of gabbro, diorite, granite, and syenite. There appears to have been several ages of granitic intrusion. Available radiometric ages indicate that the rocks are late Middle Precambrian.

Structurally, the area is characterized by at least two directions of large scale faulting with major fault zones trending approximately N80°E to N60°E. The faulting, which also shows up well on the aeromagnetic map covering the area mainly west of Wausau, has resulted in many of the lithologic units being in fault contact. Perhaps the most significant fault zone is the N30°E trend which has produced a zone nearly a mile wide in the Eau Claire River valley in which mylonite is a major rock type. This zone truncates the N80°E-N60°E trend more prevalent to the west.

The current mapping project, funded by the Wisconsin Geological Survey, has revealed significantly more volcanic rocks than are shown on Weidman's 1907 map. This has important implications for mineral exploration programs. A previously unreported gold prospect, on which mining was attempted about 1920, is probably the most interesting locality from an economic point of view.

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HEMATITE PSEUDOMORPHIC AFTER BIOGENIC
PYRITE IN THE NEGAUNEE IRON FORMATION

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A B S T R A C T

Spherules of hematite (limonite), ranging in diameter from 5 microns to 20 microns but generally of similar size in each particular population, as well as disseminated octahedral crystals of pseudomorphic hematite occur in many laminations of the Negaunee iron formation. Mineral associations include chert, magnetite, iron carbonate, and iron silicates. A common associate is fossil filamentous mat algae. A tentative conclusion based on two microprobe analyses indicates carbon in the filaments. Thermal experiments result in considerable removal of the filamentous material suggesting the presence of both amorphous carbon and graphite.

Framboidal pyrite with diameters ranging from 5 microns to 20 microns and pyrite octahedra, occurring in two unconsolidated sediments with contrasting environments, one a Pleistocene fresh water lake deposit, the other a Recent marine tidal lagoon, unequivocally demonstrate their biogenic origin.

Paleozoic analogs of somewhat similar lithology to iron formation have the following associations: chert, carbonate, biogenic euhedral pyrite, biogenic framboidal pyrite 5 microns to 20 microns in diameter, sparse euhedral magnetite and fossil microfauna and/or microflora. They further demonstrate the biogenic origin of pyrite.

A finely laminated chert carbonate specimen from the Pennsylvanian Dimple formation, Texas, clearly shows the transition of biogenic pyrite to pseudomorphic hematite (limonite) by oxidation.

These various features are illustrated by photomicrographs to support the hypothesis that the spherules of hematite (limonite) and possibly other hematite in the Negaunee iron formation are pseudomorphic after biogenic pyrite, and together with the presence of probable algal mat strongly support the biogenic (in part) genesis of the Negaunee iron formation.

DISTRIBUTION OF URANIUM AND THORIUM IN PRECAMBRIAN
ROCKS OF THE WESTERN GREAT LAKES REGION

by

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ABSTRACT

Prospecting during the 1950's resulted in the discovery of several uranium and thorium prospects in Precambrian rocks in the western Great Lakes region of the United States. No economic deposits were delineated by the few small exploration efforts that were undertaken. Since then there has been very little exploration for radioactive minerals in that region.

In Wisconsin and in upper Michigan, Lower, Middle, and Upper Precambrian silicic and hyperalkalic plutonic rocks contain anomalous amounts of disseminated radioactive minerals. In upper Michigan, the Middle Precambrian Animikie Series contains uranium veins in slate, monazite placers in conglomerate, and irregular concentrations of uranium in iron formation adjacent to slate. These prospects do not contain important reserves of uranium or thorium that are economically mineable at present but some may contain large long-range, low-grade resources. For example, limited sampling indicates that masses of silicic igneous rocks in northeastern Wisconsin may contain 50 to 100 parts per million uranium. This is greater than the uranium content in any of about 250 bulk samples of igneous rocks that have been analyzed in a recent study of the distribution of uranium and thorium in Precambrian rocks in the western United States. A potentially great low-grade resource of thorium may exist in the monazite placers in Animikie conglomerates in the Marquette Range, upper Michigan.

In other areas of the world, stratiform uranium deposits in Middle Precambrian coarse clastic sediments are of major importance. The world's greatest known resource of uranium is in basal conglomerates of the Middle Precambrian Huronian Series in the Elliot Lake - Blind River district in southern Ontario. Important stratiform uranium deposits have not been discovered in the Animikie Series which is in part correlative with the Huronian;

however, limited sampling in the Marquette Range, upper Michigan, indicates that anomalous amounts of uranium are present in coarse clastic facies. Also uranium/thorium ratios in the Animikie in the Marquette Range and in the Huronian in the Elliot Lake - Blind River area increase in descending stratigraphic positions. More study of the distribution of uranium and thorium in the Animikie is warranted.

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LOWER KEWEENAWAN SEDIMENTS OF THE LAKE SUPERIOR REGION

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A B S T R A C T

Lower Keweenawan sediments directly underlie the Keweenawan volcanic series in the Lake Superior region. Studies of the quartz-rich Puckwunge Formation (Minnesota) and the Bessemer Formation (Michigan and Wisconsin), which include thin section petrography, heavy mineral analysis, and measurement of paleocurrent indicators, provide new data on Lower Keweenawan events.

The Puckwunge Formation of Cook County, northeastern Minnesota, is intermittently exposed along a 25 mile belt extending westward from Pigeon Point on Lake Superior. Although the lower contact of this formation is not exposed, outcrops of the formation thicken from 30 feet on Grand Portage Island to over 100 feet in the westernmost exposures. Fifteen feet of basal conglomerate exposed on Grand Portage Island contains flat chips and pebbles of argillite and slate, probably derived from the underlying Rove Formation, and rounded pebbles of quartzite. Thin section examination indicates total feldspar content ranges from 20 percent in the eastern exposures to only a trace in the western outcrops. Unit quartz is the dominant quartz type, with up to 20 percent polycrystalline quartz being present. Zircon, apatite, and epidote are the common nonopaque accessory heavy minerals, with tourmaline also present in the central portion of the outcrop belt.

At Nopeming, just west of Duluth, 25 feet of quartzite and quartz- and quartzite-pebble conglomerate are exposed beneath the basal (?) Keweenawan flow over a distance of half a mile. In the sand-sized fractions, unit quartz is the dominant quartz type, with polycrystalline quartz also present. Zircon is the principal nonopaque accessory heavy mineral, with minor amounts of apatite and tourmaline present. Gravity and magnetic profiles across the area suggest the presence of a tabular, dike-like mafic body beneath the Puckwunge exposures at Nopeming; a greater degree of recrystallization in the lowermost sediments may be related to this probable intrusive.

The Bessemer Formation of Michigan and Wisconsin is intermittently exposed along a 40 mile belt extending eastward from Mellen, Wisconsin. The formation is over 150 feet thick where both the upper and lower contacts are visible. A basal conglomerate contains rounded pebbles of quartz, quartzite, flint, and jasper in a quartzite matrix. In the sand-sized fractions, unit quartz is the dominant quartz type, with polycrystalline quartz also present. The average total feldspar content is less than 10 percent. Zircon is the dominant nonopaque accessory heavy mineral, with apatite, rutile, and tourmaline also present.

Exposures of the lower Keweenawan sediments along both limbs of the Lake Superior Syncline suggest the deposition of a thin sheet of sediment throughout the region. The cross-bedded, ripple-marked, well sorted quartz-rich sediment composed of well rounded grains suggests a shallow water environment. Cross-bedding, ripple mark, and parting lineation measurements in these sedimentary rocks indicate a general southerly direction of sediment transport, with the sediments being derived from the Pre-Keweenawan rocks to the north. Thus, these Lower Keweenawan sediments were probably deposited during the northward transgression of a sea into the region, and were apparently the final sediment deposited in the Lake Superior region prior to formation of the Lake Superior Syncline.

EXPLORATION GEOLOGY OF DOUGLAS COUNTY, WISCONSIN

by

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A B S T R A C T

The oldest bed rock units in Douglas County are the Keweenawan basaltic fissure flows of the St. Croix horst south of the line Brule, Maple, Wentworth, South Range, Pattison State Park, Patzau. These flows have a N60E35S attitude along the north margin of the horst and N50E15S along the south. They are intruded by "red rock" in 15-47N-13W, K/Ar dated at .95 b.y. and by a gabbro mass in 32-48N-12W.

Basaltic flows occur again south of the line Totagatic River-Ounce Creek where the attitude is N45E30N and there are extensive conglomerate and sandstone interbeds with the lavas.

Native copper and copper sulfides are found in amygdaloidal horizons and along fractures wherever the Keweenawan lavas outcrop. Almost all lava outcrop is within the following limits:

- (1) A 2 mile wide band south of the line Brule-Patzau
- (2) A 2 mile wide band north of the line Winnebaujou-St. Croix River in 43N-14W and 44N-13W
- (3) The NW half of 43N-15W
- (4) The south half of 44N-15W and SW quarter 44N-14W
- (5) The NE quarter of 45N-12W
- (6) The SE half of 43N-10W, especially along the valley of Dingle Creek in sections 12 and 13 where an extensive section is exposed

During the last century and a half the properties listed below have all been the locus of shafts and/or test pits and drilling for copper in the lavas.

<u>Location</u>	<u>Property</u>	<u>Nature</u>
NE 12-43N-10W	Weyerhaeuser	Amygdaloid and in assoc. sediments
SW 28-43N-10W	Williams	Ashbed amygdaloid
NW 6-43N-13W	Superior Copper Mines	C.F. Irving Mon 5, pl. 25
SW 8-43N-13W	Copper Mine Dam	Amygdaloid (?)
SE 34-44N-14W	Nowell (Crotty Brook Arnold)	Amygdaloid (?)
SE 14-44N-13W	Arnold	Amygdaloid
NE 31-47N-14W	Culligan	Amygdaloid
SE 28-47N-14W	Bardon	Amygdaloid (?)
SW 14-47N-14W	Copper Creek	Amygdaloid
NE 8-47N-13W	Fond du Lac	Amygdaloid
SE 2-47N-13W	Starkweather Wisconsin Edwards	Fissure vein 4-6' wide NE strike 75 NW dip
Center 11-47N-13W	Amnicon	Narrow steeply dipping vein
4-47N-12W	Houghton	Amygdaloid
NE 8-47N-12W	Badger	Amygdaloid (?)
NW 10-47N-12W	Chippewa	Fractured Amygdaloids
SW 10-47N-12W	Copper King	Amygdaloid (?)
NE 23-48N-10W	Cascade	Amygdaloid (?)
NE 24-48N-10W	Percival, Jr.	Amygdaloid
NE 27-48N-10W	Percival	Veinlets in amygdaloid
NW 28-48N-10W	Astor	Amygdaloid
SE 29-48N-12W	Amnicon	Amygdaloid (?)
SE 34-48N-13W	Catlin	Amygdaloid

The U. S. Bureau of Mines reported on extensive tests of the Weyerhaeuser Property in 1947 and the Chippewa Property in 1955.

The Keweenaw-Oronto Group occupies the Lake Superior syncline south of the line Winnebougou, Solon Springs - St. Croix River. Reportedly the Copper Harbor Conglomerate, the Nonesuch Shale, and the Freda Sandstone units are all present in this area. Prospecting in the syncline has centered on attempts to locate a copper-bearing facies of the Nonesuch Shale, but has been hampered by complete absence of outcrop except along the lower portion of the St. Croix River Valley. Conglomerates have been reported from exploration tests in: NWNW 10-44N-11W, SW corner 31-44N-10W, W half 10-45N-10W, SWSW 16-45N-11W, NE corner 27-45N-10W, NENE 34-45N-11W, SE 10-46N-11W, NESE 25-46N-11W; Shale from near the center of 34-47N-11W; and Sandstone from NE 3-45N-10W, SW 8-46N-10W, NWSW 11-46N-10W, W half 15-47N-10W, SE 19-47N-10W. Waterwells do not penetrate the estimated 200 foot depth of sandy overburden in this area.

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REVISED KEWEENAWAN SUBSURFACE STRATIGRAPHY SOUTHEASTERN MINNESOTA

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ABSTRACT

The Mid-continent Gravity High is the major tectonic feature of the northern mid-continent region. Detailed geophysical surveys over the 600 mile-long belt show that the structure consists mainly of a sequence of basaltic lava flows which form steep-sided blocks that are an average of about 40 miles wide and several miles thick. Clastic rocks occur in flanking basins and in grabens and axial basins on top of the blocks. Because much of the structure is covered by Paleozoic rocks, little is known about the rocks away from their outcrop area around Lake Superior. However, the Paleozoic cover is relatively thin in southeastern Minnesota, and several drill holes have penetrated considerable thicknesses of Keweenawan strata. Of particular interest here are the sedimentary rocks which flank and overlie the St. Croix horst, an uplifted basalt block in southeastern Minnesota.

Keweenawan sandstone and shale have been known from the subsurface for a hundred years. Because of their red color, they have been grouped together under the Red Clastic Series, a "temporary" name proposed by Hall and others in 1912. Mooney and others (1970, J. Geophys. Res., v. 75, p. 5056-5086) have subdivided these rocks into a number of seismic units, and concluded that several of their subdivisions could be correlated with already named formations. A detailed petrographic study of 4,000 feet of diamond drill core from a number of localities has demonstrated the presence of at least three lithologically distinct intervals which more-or-less correspond to seismic units. Therefore, it will be recommended (Morey, in prep.) that the term Red Clastic Series be abandoned and replaced by a more suitable nomenclature. Accordingly, three formations will be recognized: (1) Hinckley Sandstone, a buff to tan rock containing 95 percent or more quartz. (2) Fond du Lac Formation, consisting of intercalated moderate red shale and sandstone containing 60 percent quartz, 30 percent orthoclase, microcline and sodic plagioclase, and 10 percent "granitic" rock fragments. (3) An as yet unnamed formation, consisting of dark reddish-brown mudstone and sandstone containing variable amounts of quartz, plagioclase of intermediate composition, and aphanitic igneous rock fragments. The first two formations are known from surface exposures, however the third formation is confined entirely to the sub-surface.

A stratigraphic analysis indicates that in the flanking basins, the unnamed formation is overlain by the Fond du Lac Formation, which in turn is gradually overlain by the Hinckley Sandstone. On top of the horst, the unnamed formation overlies basaltic rocks and is locally overlain by Hinckley Sandstone; at places, a regolith as much as 100 feet thick separates the two formations. Either the Fond du Lac Formation was never deposited on top of the horst, or was removed prior to Hinckley deposition.

Any attempt to explain the geologic evolution of this structure must take into account these stratigraphic relationships.

LIMNOGEOLOGICAL STUDIES OF THUNDER BAY,
LAKE SUPERIOR, ONTARIO

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A B S T R A C T

Limnogeological studies were carried out in Thunder Bay, Lake Superior during the 1970 field season. Ponar grab samples and Phleger cores were taken at one hundred and forty-seven stations on a 1.5 mile grid for geochemical and mineralogical analyses. In addition three echo sounding traverses were carried out using an MS 26F metric echo sounder.

Thunder Bay which is partly silled to the south by an east-northeast trending horst from Victoria Island to Spar Island contains three separate basins. Recent sediments which cover the bay-floor grade from a thin veneer of sand, less than 3 centimeters thick, to a sequence of clay-silts, up to 14 meters thick, in the central parts of the basins. Tight folding of the Recent clay-silts in the deepest part of the central basin is probably caused by gravity slumping. Geochemical investigations of the bottom-sediments show that there appears to be a tendency towards negative Eh and low pH values in the deep-water areas. In the vicinity of the Kaministiquia Delta anomolous Eh and pH measurements were recorded which were probably caused by industrial pollutants entering the bay from the Kaministiquia River.

The Recent sediments unconformably overlies Pleistocene varved sediments of undetermined thickness. The Recent clay-silt section and the Pleistocene varved section each form a typical syndiagenetic sequence with a relatively thin upper oxidized zone (initial stage) and a lower reduced zone (early burial stage). The oxidized zone is caused by the dissolved oxygen in the trapped waters of the upper layers of sediment and the action of aerobic bacteria. The depletion of oxygen results in the underlying reducing zone with anaerobic conditions and a sharp increase in pH.

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REINVESTIGATION OF "RED ROCKS" IN THE
PIGEON POINT AREA, MINNESOTA

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A B S T R A C T

Keweenawan granitic rocks of reddish color as exemplified by the "red rocks" of the Pigeon Point, Cook County, area are divisible into red quartzites, porphyritic red rocks and granular red rocks. Remapping with this division reduces the problem of excess granophyre abundance associated with the Pigeon Point sill.

Reddish quartzites contain abundant recrystallized quartz with minor interstitial sericite-biotite and granophyric feldspar-quartz intergrowths. A faint foliation defined by biotite lineation and relict bedding can be discerned in quartzite inclusions found in intermediate rock of dioritic composition.

Porphyritic red rock displays euhedral feldspar phenocrysts in a granophyric quartz-feldspar groundmass. This rock type cuts the Rove formation and intrudes the Pigeon Point gabbro. Micro-litic cavities are found filled with calcite and zeolite minerals.

Granular red rock contains granoblastic quartz and feldspar set in a granophyric groundmass of quartz and feldspar with minor sericite-biotite and rounded grains of sphene and epidote.

Phase relations and overgrowths on quartz suggest that a sedimentary parentage is possible, however intrusive relations on Pigeon Point require that the granular red rocks must have been a crystal mush.

The abundance of red rock in the Pigeon Point area in excess of that to be expected by differentiation has been noted since 1893, and is part of a reinvestigation of the eastern exposures of Keweenawan rocks in Minnesota.

THE SEDIMENTOLOGY AND TECTONIC SIGNIFICANCE OF THE
BAYFIELD GROUP, WISCONSIN AND MINNESOTA

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A B S T R A C T

A study of the mineralogical and physical characteristics of the Bayfield Group was made to determine 1) depositional environment, paleogeography, and source terrane during Bayfield time, 2) the nature of the contact of the Bayfield Group with the older Oronto Group, and 3) the early history of the Douglas fault.

Field study included detailed mapping of Bayfield and Oronto Group rocks to establish the location of all outcrops, the lithology and stratigraphy of all formations, the geographic and stratigraphic distribution of sedimentary structures and the structural relationships between rock bodies. Analyses of rock specimens in the laboratory included 1) petrographic study of the bulk mineralogy and textural characteristics of sandstone specimens, 2) x-ray diffraction study of the clay mineralogy of shale beds and chemical analyses of the boron concentration of the clay mineral illite, 3) x-radiography study of the internal stratification of selected sedimentary structures, and 4) statistical study of directional sedimentary structures.

Petrographic studies of Bayfield Group sandstones indicate that quartz constitutes approximately 80 percent of framework grains, that the feldspar population is dominated by microcline, and that Bayfield Group sandstones are better sorted and exhibit a higher degree of rounding than the Freda Sandstone of the Oronto Group.

The high compositional and textural maturity of the Bayfield Group suggests that the source area for these sediments was not a simple volcanic terrane. Petrographic data indicate that the Bayfield and Freda sandstones had a similar source; possibly recycling of the Freda Sandstone was an important source of sediments during Bayfield time.

The sedimentary structures of the Bayfield Group are those which are typically developed in fluvial environments, including trough cross-bedding, current ripple marks, channel sandstones, mudcracks, and associated structures. The stratification and bed forms of the Bayfield Group are characteristic of those formed in the upper part of the lower-flow regime (Harms and Fahnestock, 1965). By analogy with modern alluvial channels the general geologic setting of the Bayfield Group can be inferred to have been an alluvial plain characterized by low-gradient, meandering, perennial streams. The strong N40°E trend of trough cross-bedding indicates the direction of sedimentary transport was from the southwest to the northeast. This inference is supported by the orientation of parting lineation and current ripple marks.

The contact of the Bayfield and Oronto Groups is not exposed; petrographic data provide the clearest evidence of the nature of this boundary. On the basis of the high compositional and textural maturity exhibited by Bayfield Group sandstones, it is suggested that these clastics represent a new cycle of sedimentation in the synclinal Lake Superior basin. This interpretation is supported by the contrasting clay mineralogy of the two sequences (illite- and chlorite-rich Oronto rocks, but kaolin-rich Bayfield rocks).

There is no compelling evidence that the Douglas fault was active during Bayfield time. Conglomerates are known at only two exposures of the Douglas fault, and in each case their distribution is restricted to the zone immediately adjacent to the fault. Furthermore, the conglomerates do not resemble true tectonic conglomerates either texturally or compositionally. Additional evidence is provided by the orientation of directional sedimentary structures at the Douglas fault localities. These structures which include parting lineation and cross-bedding, show no apparent relation to the Douglas fault. Thus, there is no geologic evidence of major faulting during Bayfield, or at least Orienta, time.

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A B S T R A C T

The Precambrian basement complex beneath Lake Michigan, which lies on the western and northern flank of the Paleozoic Michigan Basin, is only known from a few widely scattered basement drill holes around the perimeter of the Lake and a single drill hole within the Lake on Beaver Island. Nevertheless, the basement geology of Lake Michigan is significant to the Precambrian framework of the Midcontinent and is critical to the extrapolation of basement structural trends from Lake Superior, Northern Michigan, and Wisconsin into the Michigan Basin. To fill this gap an aeromagnetic survey consisting of 7,000 miles of total magnetic intensity data were collected along flight traverses separated by six mile intervals. Flight traverses were flown over northern Lake Michigan in a general north-east direction and over southern Lake Michigan in a northwest direction.

The residual total magnetic intensity map prepared from the collected data exhibits three regional magnetic positives. In general the magnetic anomalies are related in a direct manner to gravity anomalies on the perimeter of the Lake. The southernmost positive strikes northwest from the Michigan shore from 42° to $43^{\circ} 30'N$. This anomaly is associated with a southeast striking gravity positive and local magnetic positives extending across southwestern Michigan and northeastern Indiana into Ohio. It is on strike with the positive gravity and magnetic anomaly in northeastern Indiana which has been found by basement drilling to be underlain by basalts similar to Keweenaw flows of the Lake Superior region. The central regional positive, which is made up of several individual anomalies, strikes roughly east-west across the Lake between 44° and $45^{\circ} 15'N$. The northern components of this anomaly can be traced into Wisconsin and across the southern Peninsula of Michigan except where they are transected by the Mid-Michigan rift zone. These trends are believed to be associated with the Penokean basement province. A marked regional magnetic anomaly minimum striking east-west occurs to the north of the regional positive. The anomaly is on strike with the felsic rocks of the Mountain-Amberg area of Wisconsin which is also characterized by magnetic minimums. The minimum reappears east of the Mid-Michigan rift zone anomaly and strikes east-southeast across to Lake Huron. The northern regional positive magnetic anomaly strikes north-south from Traverse Bay to north of Beaver Island where it bifurcates with one limb extending north-northwest through Lake Superior to the Keweenaw basalts on Keweenaw Point. The other limb continues into the eastern portion of the Northern Peninsula of Michigan and another segment of this branch connects to the Keweenaw flows on Mamainse Point. In the Traverse Bay area the regional positive becomes strongly negative and connects to the south with the mid-Michigan gravity and magnetic anomaly.

GEOCHRONOLOGY OF THE GIANTS RANGE GRANITE

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A B S T R A C T

Seven whole rock samples of two-mica, foliated quartz monzonites from the central part of the Giants Range Granite, north of Hibbing, Minnesota, give a Rb-Sr isochron age of 2670 ± 65 m.y. ($\text{Rb } ^{87}\lambda_8 = 1.39 \times 10^{-11} \text{ yr }^{-1}$) and a $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio of 0.7002 ± 0.0019 at the 95% confidence level. Epidote, plagioclase, potassium feldspar, biotite-chlorite, apatite and muscovite separates from one of these whole rock samples give mineral-whole rock ages ranging from 2350 m.y. for epidote to 2640 m.y. for muscovite. The lowered mineral-whole rock ages suggest that at least one event occurred after intrusion of the granite, but that the individual mineral phases were not completely homogenized with respect to their $\text{Sr}^{87}/\text{Sr}^{86}$ ratios. The 2350 m.y. epidote-rock age probably is a maximum for the time of the last event. The mineral data provide no conclusive evidence for the sequence of events after intrusion, but are not inconsistent with a regional low-grade metamorphism at around 1600 m.y.

This whole rock age is in agreement with U-Pb data on sphene and zircon from the Giants Range Granite which suggest an age of 2700 m.y. and also with K-Ar ages for hornblende from the Giants Range Granite which generally are 2600-2700 m.y. These ages however are older than most of the Rb-Sr and K-Ar ages for biotite which range from 2280-2630 m.y. The age of the post-kinematic Linden Syenite just to the north also limits the age of the syn- to late-kinematic Giants Range Granite. $\text{Pb}^{207}\text{-Pb}^{206}$ data on sphene and a Rb-Sr mineral-whole rock isochron with an initial ratio of 0.7009 ± 0.0004 suggest an age for the Linden Syenite of about 2700 m.y.

The low $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratios from both the Linden Syenite and the Giants Range Granite suggest a source with a low Rb/Sr ratio, perhaps the mantle, and it is unlikely that appreciable mixing with preexisting continental crust took place.

THE GREAT LOGAN PALEOMAGNETIC LOOP - THE POLAR
WANDERING PATH FROM CANADIAN SHIELD ROCKS DURING THE HELIKIAN ERA

by

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A B S T R A C T

Normally magnetized dykes and reversely magnetized sills of Neohelikian age near the north west shore of Lake Superior form two distinct paleomagnetic groups with mean pole positions of 179W, 35N, and 140W, 47N respectively. Thermal and alternating field paleomagnetic studies and the study of magnetic properties and opaque minerals indicate that directions of magnetization of these rocks were acquired at the time of their intrusion. Field evidence indicates that the reversely magnetized sills are older than the normally magnetized dykes and radiogenic age determinations indicate intrusion between 1000 and 1100 m.y. ago.

These pole positions, together with those for the Franklin intrusions pole at 167E-08N, assigned age 675 m.y., the Abitibi dykes, at 134W, 27N, assigned aged 1150 m.y. and the MacKenzie Igneous events, at 171W, 4N, assigned age 1200 m.y. are used to define Logan's Loop, the path that the pole took in Neohelikian time relative to the Canadian Shield. Other poles well defined magnetically, but less well dated, from rocks of this era fit the curve quite well.

Analysis of available data supports the hypothesis that the relative polar movement that gave rise to Logan's Loop was preceded and followed by polar stability vis a vis North America, whereas polar movement may have been quite rapid during the formation of the loop. The depositional environment of Neohelikian rocks of the Canadian Shield should be tested against their probable paleolatitude as indicated by the 5 key points on Logan's Loop.

CHARACTERISTICS OF SOME ALTERATION MINERALS,
PORTAGE LAKE LAVA SERIES, MICHIGAN

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ABSTRACT

Many silicate, carbonate, and oxide minerals are associated with copper mineralization in the Portage Lake Lava Series and associated conglomerates. A complete listing was published by Butler and Burbank¹. Amygdule zoning patterns associated with mineralization were studied by Stoiber and Davidson². Chemical and x-ray diffraction studies are being carried out at Michigan Technological University on a continuing basis. In the past some of these studies were supported by the Calumet Division, Universal Oil Products Company.

Epidote is characterized by wide ranges in unit cell dimensions. In general, epidotes from amygdaloids have larger unit cell volumes than those from conglomerates.

Calcites show wide ranges in trace element composition, especially in concentrations of Fe, Mg, and Mn. There is a positive correlation between Mn content and copper mineralization in the Kearsarge amygdaloid, and therefore is potentially useful as an exploration tool in the district.³

Chlorite occurs in many forms and at virtually every stage of the alteration sequence in the district. An interesting occurrence is as an essentially pure clay mineral in the fault gouge in the Allouez Gap Fault and hanging wall slip of the Kingston Mine⁴. This is one of the few, if not the only occurrence of pure clay chlorite known. It consists essentially of the type IIb polytype⁵. In much of the hanging wall slip, chlorite is intimately mixed with hematite. The water absorption properties (plastic and liquid limits) are greater for chlorite-hematite mixtures than for pure chlorites, suggesting the possibility of some mixed layering of chlorite and hematite.

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THE GENERAL STRATIGRAPHY OF THUNDER BAY,
LAKE SUPERIOR

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A B S T R A C T

Petrographic studies of the sediments taken from Thunder Bay combined with x-ray diffractometer analysis have indicated distinct lithologic types in the bottom sediments of Thunder Bay. Stratigraphic correlation of the bottom sediments from Thunder Bay has been developed with the aid of echo sounding traces. These traces indicate the boundaries, nature and thickness of the various lithofacies.

The sediments in Thunder Bay can be divided into five categories; (1) Varved Clay, (2) Weathered Varved Clay, (3) Intermediate Clay, (4) Upper Deltaic Sediment, (5) Upper Trough Sediment. The Varved Clay is of Post Valders glacial origin and is disconformably overlain by the Weathered and Intermediate Clays. The latter are products of weathering of the older Varved Clay. The Intermediate Clay is conformably overlain by Upper Deltaic and Upper Trough Sediment. The latter units are sediments derived dominantly from the Kaministiquia River. Thin iron and manganese beds are formed through diagenetic solution, upward migration, and precipitation at a chemical interface in the Upper Sediments.

CHERT IN SEDIMENTS

by

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A B S T R A C T

Amorphous silica is produced when a silica solution becomes super-saturated and a precipitate forms or when some silicates are dissolved in acids. In either case the silica is in a colloidal form and remains so for long periods of time. Eventually crystallization begins, and heating the substance can speed up the process to a great extent. In natural conditions opal is the first step followed by chalcedony and finally cristobalite. All of these forms of silica have been termed chert.

Chert has long been regarded as a chemical precipitate. This view is sufficient to explain hot spring deposits and hydrothermally deposited chert or opal near the surface. Cooling volcanic waters become supersaturated with silica in solution and amorphous is deposited as a sinter or in thin layers.

There are, however, many other environments in which chert is found such as:

- a) black slate with chert lenses or beds
- b) limestones with chert nodules or joint fillings
- c) bedded cherts containing sponge spicules or Radiolaria
- d) chert stringers and crusts in oxidized sulphides
- e) agate fillings of vesicles in lava flows
- f) chert as a matrix for iron oxide granules
- g) opal or chert replacing organic matter

The author ascribes chert to the decomposition of clays, detrital silicates, volcanic ash or sand grains in carbonates. In acid environments alumina and alkalies are removed and a silica gel is left. In alkaline waters silica is dissolved and is deposited in a more neutral zone or will replace a dissolving particle such as organic matter. The relative solubility of alumina and alkalies compared to silica is the determining factor.

Murata (1946) investigated many silicates which produced gels when treated with acid. He found that a silica to alumina ratio of 1:1 or 2:3 was common to gel forming silicates. Other silicates produced silica particles larger than colloidal size or were not affected by acids. Any silicate structure from which alumina has been removed is halfway along to becoming chert.

In carbonate and silicate iron formations mixed with quartz, minerals become unstable when the temperature is raised and CO_2 is removed from the sediment. The ionization of water increases up to 230°C at which point silica both in quartz and silicates becomes increasingly soluble. Sand grains in oolites might dissolve and secondary silicates such as

minnesotaite and stilpnomelone would appear. Chert in this case is clearly diagenetic and came from a breakdown of original clastics even if the original texture remained the same.

Precambrian iron formations would appear to be examples of late diagenetic chert although they would also contain early diagenetic silica as well. Silica and iron oxide content is higher in these rocks because of the loss of carbon dioxide, water, and small amounts of alkalies in solution.

IMPLICATIONS OF CARBON ISOTOPE RATIO VARIATIONS IN CARBONATES FROM THE BIWABIK IRON FORMATION, MINNESOTA

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A B S T R A C T

Carbon isotope ratios from carbonates of the Biwabik Iron-formation obtained from core samples of Mesabi Deep Drilling Project (Pfleider and others, 1968) show the following significant features.

(1) δC^{13} values of carbonates associated with magnetite from holes 5 and 7 show a range of from -7 to -19 per mil (relative to a Cretaceous belemnite standard calcite PDB) in comparison with the carbonates from the magnetite-free horizons (0 to -7 per mil). δC^{13} is strongly correlated with magnetite content in hole 7.

(2) The δC^{13} values of carbonates from magnetite and non-magnetite horizons of hole 2 with one exception, do not show significant difference in contrast with holes 5 and 7. They exhibit a δC^{13} range of from -7 to -19 per mil.

(3) The δC^{13} values do not show any significant stratigraphic correlation with the percent iron.

(4) There appears to be a correlation between δC^{13} values and the individual members of the Biwabik Iron-formation.

In explaining the observed correlation between magnetite and the δC^{13} values based on our preliminary results, we proposed (Perry and Tan, 1970) that a diagenetic oxidation-reduction reaction producing magnetite from hematite permitted exchange between organic carbon and carbonate carbon reservoirs:



Our recent detailed studies have strengthened our previous observation on hole 7 but have found anomalously low δC^{13} values (-18 per mil) from the non-magnetite horizons of hole 2 (Lower Slaty Unit). These anomalous values may be related to metamorphic reactions accompanying the intrusion of the Duluth Complex because hole 2 is located near metamorphic zone (1) of French (1968).

Our observation that there is a correlation between δC^{13} values and the individual members of the Biwabik Iron-formation would suggest that the δC^{13} variations are depositional or early diagenetic features and bear no relationship to the genesis of magnetite (model above). The

differences in δC^{13} values may be explained by the variable contributions of organic carbon and oceanic bicarbonate to the depositional or diagenetic environments.

We are currently investigating the δC^{13} values of co-existing graphite-carbonate pairs and oxygen isotope fractionation between co-existing quartz-magnetite at various stratigraphic levels of holes 2 and 7 to see if they have different diagenetic or metamorphic histories. Co-existing quartz-carbonate oxygen isotope fractionation in samples from hole 2 compared to that in holes 5 and 7 suggests that the post-depositional history of these two areas is indeed different.

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Oxygen isotopic studies of Early Precambrian granitic and
metamorphic rocks from the western part of the
Giants Range batholith, Northeastern Minnesota

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A B S T R A C T

The paper has two main objectives: (1) to demonstrate that oxygen isotope geochemistry is a valuable tool in elucidating granite petrogenesis, provided it is integrated with detailed field and laboratory studies, and (2) to give values for $\delta(0^{18}/0^{16})_{\text{quartz}}$ in the Early Precambrian granitic and metamorphic rocks, data for which are rather scarce in the literature.

Geologic mapping of a 500-square mile area in the western part of the 2.7 b.y. old Early Precambrian Giants Range batholith of northeastern Minnesota has revealed eleven distinct granitic phases (Sims and others, 1970). Field observations, petrography, petrochemistry, and trace element geochemistry suggest that five of the phases are magmatic, four are metasomatic, and two are anatexitic.

The $\delta 0^{18}/0^{16}$ ratios of quartz separated from 28 rocks, relative to Standard Mean Ocean Water (SMOW), are presented in the accompanying table. The values are consistent with the postulated genetic grouping for the Early Precambrian granitic succession. The following conclusions can be drawn from the data:

(1) Values of 9 to 10 permil are characteristic of relatively uncontaminated, probable mantle-derived granites and granodiorites. These are consistent with the $\delta(0^{18}/0^{16})_{\text{quartz}}$ values that have been reported for plutonic granites, granodiorites, and tonalites, which range from about 9 to about 11 permil (Taylor, 1968, p.34).

(2) Values greater than 10 permil require one of several special explanations, such as:

- (a) syntexis of large amounts of 0^{18} -rich country rocks into a primitive or first-cycle granitic magma
- (b) co-mingling of an 0^{18} -enriched magma and a primitive or first cycle granitic magma
- (c) anatexis of 0^{18} -rich sediments

- (d) potash metasomatism of O^{18} -rich sediments
- (e) simple recrystallization (treptomorphism) of relatively O^{18} -rich clastic sediments such as arkoses and graywackes, which thereby assume a granitic fabric and composition
- (f) recrystallization of granites under shearing and crushing to produce aplogranites, accompanied by late-tectonic metasomatism in mobile zones
- (g) post-consolidation cataclasis, and other metamorphic episodes which facilitate exchange between granitic rocks of magmatic origin and O^{18} -rich country rocks through a pore-fluid medium
- (h) post-consolidation endoblastesis/autometamorphism involving O^{18} -enriched fluids
- (i) processes such as petroblastesis and imbibition in which the participants are O^{18} -rich sediments and O^{18} -enriched fluids
- (j) selective exchange between granitic intrusions and O^{18} -rich host rocks
- (k) tectonic styles of emplacement, whether synkinematic, post-kinematic or late-kinematic, and
- (l) early segregation of O^{18} -depleted minerals which results in O^{18} -enrichment in late granitic differentiates.

(3) The values observed in granitic rocks of anatectic origin are nearly identical to those of their source rocks. They are either low or high depending on whether such granitic rocks were formed from O^{18} -poor or O^{18} -rich sources, respectively. The values will be grossly different only if: (i) the anatectic melt undergoes subsequent differentiation, and (ii) the consolidated anatectic melt is subjected to later metasomatism (see data under "C" and "D (2)", of table).

(4) The main intrusive phases of granites and granodiorites of magmatic origin have values nearly identical to those of their satellitic phases (see data under "A" of table). Interestingly, a value of 9.2 permil was obtained for a leucogranite (satellitic late-magmatic differentiate) that transgresses an O^{18} -rich metasedimentary host rock having a value of 12.4 permil. This result indicates that there was hardly any oxygen communication between the satellitic late-magmatic differentiate and its O^{18} -rich metasedimentary host rock. This is in sharp contrast to the conclusion of Shieh and Taylor (1969, p.353) who report that: "Samples from tiny intrusive bodies and dikes and from the marginal portions of most of the larger plutons have unusually high O^{18}/O^{16} ratios relative to "normal" igneous rocks from

the central portions of plutons. This is interpreted to be the result of large-scale oxygen isotopic exchange between essentially molten igneous rock and metasedimentary country rock, either through a medium of aqueous fluids or by contamination with xenolithic blocks of country rock."

(5) The sequence: sedimentary parent $\rightarrow$ partially granitized sediment $\rightarrow$ granitic rock of metasomatic origin reflects a progressive decrease in the O^{18}/O^{16} ratio, and encompasses only a narrow range of 1 to 2 permil, and

(6) Global comparisons of oxygen isotopic ratios from granitized sequences should not be attempted, unless: (i) the O^{18}/O^{16} ratios of the parent rocks of two widely separated granitized sequences are comparable, and (ii) their geological settings are nearly identical.

Problems involving a possible time-dependence of the O^{18}/O^{16} ratios in minerals from specific rock-series, representing the entire geological column, are under study by one of us (Perry).

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Table

$\delta(^{18}\text{O}/^{16}\text{O})_{\text{SMOW}}$ ratios of quartz in Early Precambrian granitic

and metamorphic rocks from the western part of the
Giants Range batholith of Northeastern Minnesota

	<u>Range</u> (permil)	<u>Average</u> (permil)
<u>A. Rocks of magmatic origin:</u>		
(1) Granodiorites (main intrusive phase, two samples)	9.4 - 9.9	9.7
(2) Leucogranodiorite (satellititic phase of (1), one sample)		9.8
(3) Granites (main intrusive phase, two samples)	9.5 - 9.6	9.6
(4) Leucogranites (satellititic phase of (3), two samples)	9.2 - 9.6	9.4
<u>B. Rocks of metasomatic origin:</u>		
(1) Granites (five samples)	10.7 - 11.4	10.9
(2) Aplogranite (one sample)		10.2
(3) Partially granitized volcanogenic metasediments (three samples)	10.4 - 12.5	11.1
<u>C. Rocks of anatectic origin:</u> (derivatives of relatively O^{18} -poor source rocks)		
(1) Quartz tonalites (four samples)	9.2 - 10.1	9.6
(2) K-feldspathized tonalite (one sample)		12.1
<u>D. Parent volcanogenic metasediments of:</u>		
(1) Group B (four samples)	11.1 - 12.9	12.2

CHEMICALLY ZONED NATIVE COPPER AND CHALCOCITE FROM
WHITE PINE, MICHIGAN

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A B S T R A C T

A microprobe study of the copper ore minerals at White Pine, Michigan, has shown that zoned copper-mineral grains occur in the ore-bearing horizons of the Nonesuch Shale. This zoning is developed in both chalcocite and native copper, and the most prominent type of zoning is iron enrichment towards the edge of the grain. Some chalcocite grains are highly zoned, containing about four times as much iron (at least 10%) on the edge of the grain as in the core. Aluminum, magnesium and silicon show the same type of zoning, but are developed to a lesser extent.

Many native copper grains are also zoned with respect to iron, with the edge of the grain containing about twice as much iron (about 1%) as the core. All zoned copper minerals show an enrichment of iron towards the edge of the grain; however, both within and between samples, the amount of zoning and the relative proportion of zoned to unzoned grains is highly variable. This variation does not appear to be controlled by the major lithologic variations in the ore zone, but may be controlled by subtle differences in lithology or by variations in the local chemical environment at the time of deposition.

Any model of ore genesis must take into account the occurrence, distribution and type of zoning in these copper minerals.

KEWEENAWAN STRATIGRAPHY OF WESTERNMOST MICHIGAN

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A B S T R A C T

Recent geologic and aeromagnetic surveys provide a skeletal framework for throughgoing stratigraphic correlations of the Keweenaw rocks of westernmost Michigan. The stratigraphy of the middle and upper Keweenaw rocks of the Keweenaw Peninsula has long been known in great detail, thanks to the large amount of drill-hole and surface geologic information. The recent work permits certain key horizons to be traced, with moderate certainty, westward into Wisconsin.

Stratigraphic relationships for the middle and upper Keweenaw rocks are best shown in a longitudinal stratigraphic section drawn along the general strike of the middle Keweenaw rocks and having the base of the Nonesuch Shale as a datum plane. The most striking features of such a diagram are the following: (1) The predominantly basaltic Portage Lake Lava Series maintains a thickness of 10,000-12,000 feet from Houghton to the Black River and is thinnest near the Ontonagon River. It is about 8000 feet thick at the Montreal River. (2) An unnamed lenticular unit, 10,000 feet thick at the Presque Isle River and pinching out near the Ontonagon River on the east and the Montreal River on the west, lies above the Portage Lake Lava Series and below the predominantly sedimentary Copper Harbor Conglomerate. The unit is mainly composed of thin aphanitic to fine-grained andesitic flows and contains minor rhyolite and intermediate rocks, particularly near the top. It seems to represent accumulation within a few miles of a volcanic center south of the Porcupine Mountains. (3) The Copper Harbor Conglomerate is less than 500 feet thick over the thick part of the unnamed unit, and 4000-5000 feet thick near the pinchouts of the unnamed unit. (4) The combined thickness of the three units suggests a strongly asymmetric basin, deepening from a minimum near the Ontonagon River to more than 25,000 feet between the Black and Presque Isle Rivers, and then, in the next 15 miles to the west, thinning rapidly to less than 10,000 feet at the Montreal River. These findings reinforce the concept that the middle Keweenaw lavas accumulated in separate tectonic basins rather than in a single large one.

The lower Keweenawan lavas, which form the so-called South Trap Range, lie unconformably beneath the Portage Lake Lava Series, from which they differ in lithology, metamorphic grade, and magnetic properties. The lowermost 5000 feet consists predominantly of very thin basalt flows, and the next 4000 feet mainly of aphanitic to fine-grained flows of intermediate composition. The uppermost part of this sequence is everywhere concealed by the Jacobsville Sandstone or deep overburden, but is inferred from gravity and magnetic data to consist largely of felsic flows. This lower sequence is 10,000 and perhaps 20,000 feet thick, the difference reflecting uncertainty about the location of the top.

The lower Keweenawan rocks are more metamorphosed than the middle Keweenawan. Their metamorphic grade appears to increase westward -- actinolite is found in Wisconsin but is rare near Ironwood.

Kenneth Books has found that the lower and middle Keweenawan rocks also differ from one another in magnetic direction.

In contrast with the belts of middle and upper Keweenawan rocks, dips of bedding generally decrease with stratigraphic depth in the lower Keweenawan belt. If this represents southward thickening rather than folding, it suggests that the axis of the lower Keweenawan basin lay to the south.

THE NORTH SHORE VOLCANIC GROUP

May 5 and 8, 1971

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The North Shore Volcanic Group

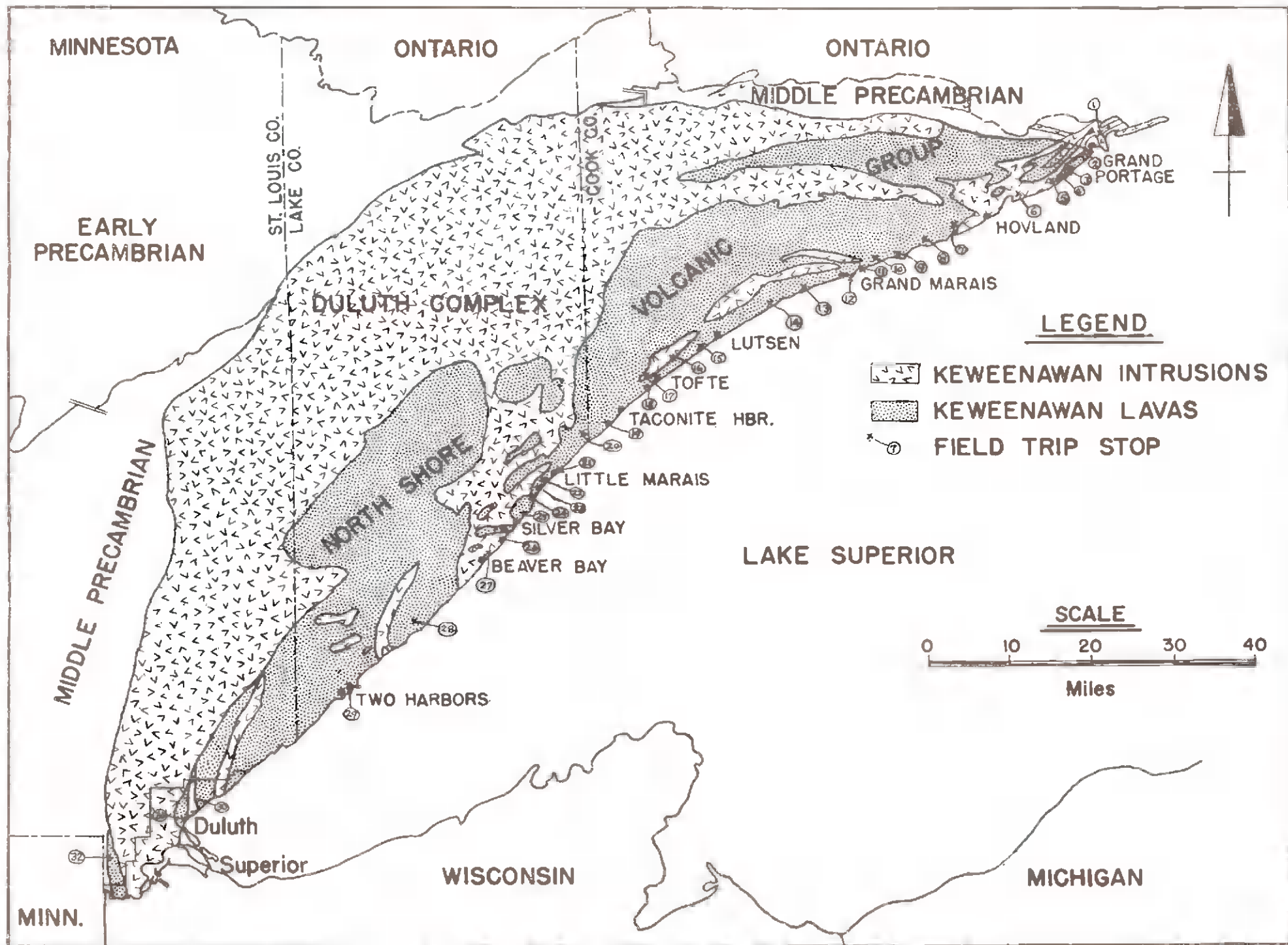
John C. Green

Introduction

Previous Work and Acknowledgments. Detailed mapping of the Minnesota shore of Lake Superior began with A. E. Sandberg's study (1938) of the section between Duluth and Two Harbors. Grout and Schwartz (1939) and Gehman (1957) studied the intrusions and flows in eastern Lake County; Grogan (1940) mapped the lakeshore between Two Harbors and Split Rock River; Schwartz (1949) studied the Duluth area; and Grout and others (1959) mapped most of Cook County. Most of the data reported in this account derive from studies by the writer who, starting in 1965, has mapped the shoreline between Silver Bay and Grand Portage, with considerable reconnaissance inland (Green, 1966; 1968a; 1968b; 1970). The report does, however, also lean considerably on Grout et al. (1959) and, for the Duluth-Two Harbors area, on Sandberg (1938). The field studies have been supported by the Minnesota Geological Survey, and most of the laboratory studies have been supported by the National Science Foundation. Sincere gratitude for this support is extended to both agencies. The writer's ideas have benefitted from discussions with many other geologists concerned with Keweenaw rocks, especially including Bill Bonnicksen, D. M. Davidson, Jr., H. Hubbard, G. B. Morey, W. C. Phinney, P. W. Weiblen, and W. S. White.

Regional Setting. The name "North Shore Volcanic Group" has been used by Goldich et al. (1961) for the lavas and interbedded sediments of Late Precambrian age in northeastern Minnesota. These rocks, as well as all other Late Precambrian volcanic and sedimentary rocks in the Lake Superior district, have traditionally been called "Keweenaw" by general lithic and structural correlation with rocks exposed on the Keweenaw Peninsula of Michigan, but recent radiometric and paleomagnetic investigations as well as geologic mapping indicate that a more precise stratigraphic framework is needed to adequately describe the complex series of Late Precambrian events and deposits in this area.

In the northeast corner of Minnesota (Grand Portage area) the lowest Upper Precambrian flows overlie a thin quartzite (Puckwunge) which in turn overlies, apparently disconformably, the shales and graywackes of the Middle Precambrian Rove Formation; here both sequences strike nearly east-west and dip at approximately 10° to the south. At the southwest end of the basin immediately west of Duluth (155 miles away), the lowest Upper Precambrian flows also conformably overlie a thin quartzite (Puckwunge?) which there overlies the vertically folded slates and metagraywackes of the Middle Precambrian Thomson Formation, which is correlated with the Rove. Here the flows strike north and dip at about 25° to the east. The angular unconformity here reflects the diastrophism and subsequent erosion associated with the Penokean orogeny, which evidently did not affect the northeastern corner of the state. Across the axis of the Lake Superior Syncline in northern Wisconsin and Michigan the lowest flows



conformably overlie a similar quartzite (Bessemer) that in turn overlies Middle Precambrian shale and graywacke with only minor discordance. These quartzites have always been referred to as Lower Keweenaw, but no radiometric age determinations are available and they may be much older than the volcanic rocks of the Keweenaw Peninsula.

The North Shore Volcanic Group is cut by a great variety of intrusive rocks that are also of Late Precambrian age. These range from the great Duluth Complex, dominated by anorthositic and troctolitic rocks, to smaller sills, stocks, dikes, and irregular plutons of diabase, ferro-gabbro, troctolite, syenogabbro, trachybasalt, granodiorite, and granophyric adamellite. Some of these bodies also cut the older rocks to the north, northwest and west of the main Late Precambrian outcrop area (e.g. the Logan intrusives of Cook County and the Thunder Bay District of Ontario).

Paleomagnetism and Age. Recent paleomagnetic studies (Dubois, 1962; Beck and Lindsley, 1969; Books, 1968; Palmer, 1970) have shown that two reversals of magnetic polarity occur within the Late Precambrian volcanic rocks of the Lake Superior district. The lowest strata show "normal" (north-seeking) polarity similar to orientations in the underlying Middle Precambrian rocks, but this group of rocks has not been recognized in Minnesota. Books (1968) has proposed that the Lower - Middle Keweenaw boundary be redefined at the second magnetic reversal where rocks of reversed polarity are succeeded by rocks of normal polarity. The North Shore Volcanic Group contains at the base of the section at Grand Portage about 5000 feet of lavas that show reversed polarity, and are thus Lower Keweenaw as magnetically defined. The thick wedge of flows west of Duluth that underlie the Duluth Complex but overlie the Puckwunge (?) quartzite have not been adequately tested in the laboratory, but on regional magnetic maps give a negative magnetic anomaly which implies reversed polarization. Furthermore they are lithically very similar to the reversed-polarity lavas of Grand Portage. The remainder of the North Shore Volcanic Group has normal magnetic polarity, similar to the bulk of the associated intrusive rocks and to the rocks of the Keweenaw Peninsula.

Only limited radiometric age determinations are yet available on rocks of the North Shore Volcanic Group. Goldich et al. (1961) found a 1.1 ± 0.1 b.y. age for associated intrusive rocks of the Duluth Complex by Rb/Sr and K/Ar methods, and Silver and Green (1963) found an isotopic age of 1.125 by U/Pb isotopes in zircons of both lavas and intrusive rocks from the Duluth and Mellen, Wisconsin areas. Faure et al. (1969) determined the age of the Endion sill, which cuts the flows at Duluth, as 1.092 b.y., and that of the Duluth Complex at Duluth as 1.115 b.y. by the Rb/Sr method. However, all of these sampled rocks are in areas of normal magnetic polarity, so no data are available as to the age of the Lower Keweenaw lavas of, for instance, the Grand Portage area. Hanson and Malhotry (1970) have recently found a 1.380 b.y. age (K/Ar) of a "Logan Intrusive" in southern Ontario, which may indicate the possible age span of the Lower Keweenaw. Isotopic U/Pb studies over the range of Upper Precambrian rocks in the district are currently in progress.

Structure

The general structure of the North Shore Volcanic Group is that of a great nest of dishes tilted gently to the southeast into Lake Superior. At the northeast end the strata at the base strike slightly north of west and dip about 10-12° south, whereas at the southwest end, 155 miles away, they strike north and dip about 25° east. In between the strikes gradually converge along the shore of Lake Superior as higher stratigraphic levels are reached, until the flows strike parallel to the shore in the vicinity of Schroeder, Tofte, and Lutsen in southwestern Cook County. Here the highest stratigraphic units are exposed, and the dip is approximately 12° to the southeast.

The lavas are intruded by a great variety and bulk of intrusive rocks, including several large diabasic sills at Duluth, the Beaver Bay Complex, the Hovland and Reservation River diabase complexes and the Logan intrusions. Where these intrusions are discordant and abundant they have deformed the lavas considerably, with local strongly divergent strikes and steep to overturned dips. Along with the thick glacial cover inland, they have also made difficult to impossible the long-distance tracing of stratigraphic units in the lava series. Several major flows or groups of similar flows, however, can be traced inland from the lakeshore for at least 15 to 25 miles. Faulting is common in the flows near the areas of abundant intrusions (such as from Silver Bay to Little Marais). These faults appear to be of minor displacement and are mostly transverse and steeply dipping with no strongly preferred strike or displacement, but a few longer strike-faults have been found, one of which probably extends for at least five miles.

The thickness of the lava succession has been measured and estimated by Sandberg (1938) and Grogan (1940) as 23,148 feet between Duluth and Split Rock River (the beginning of the Beaver Bay intrusive complex) by adding the individual flow thicknesses intersected along the lakeshore. Whether this conforms to the true thickness of the pile at Split Rock River is not known. Northeast of the Beaver Bay Complex about 5000 feet of lavas are estimated from recent mapping to form the lakeshore section between Silver Bay and the uppermost flows at Tofte. Northeast of Tofte and Lutsen, where the flows are parallel to the shore, lavas totalling about 16,500 feet have been measured down to the Reservation River diabase near Hovland. Below (northeast of) this is an older section of about 5,000 feet of lavas, for a total on this limb of about 21,500 feet.

Estimates of volcanic thicknesses by constructing cross-section profiles give between 11,000 and 18,000 feet at Tofte, above the Duluth Complex, depending on assumed dips between 12° and 20°. Although the average dip at Tofte is about 12°, there is very little control on dips near the base of the section as the few inland outcrops rarely expose flow contacts. Farther northeast at the Cascade River, about 15,000 feet of lavas above the Duluth Complex are calculated with an average dip of 12°; another thick section, possibly as much as 5,000 feet thick, here lies beneath the Complex.

General Description

The North Shore Volcanic Group bears many resemblances, both physically and chemically, to plateau lava sequences of various geologic ages. Similarities to the Tertiary plateau lavas of eastern Iceland are particularly striking. The lavas are almost entirely subaerial, showing highly vesicular (now amygdaloidal) upper portions and massive interiors, and various types of jointing, surface features, and textures depending on their specific composition. Evidence of submarine extrusion is almost entirely limited to the base of the section both at Grand Portage and at Duluth; at Nopeming, west of Duluth, the lowest flow is pillowed and on Grand Portage Island the lowest flow shows spheroidal forms that could possibly be pillows, but excellent, thick-rinded, vesicular pillows constitute a flow on the lakeward side of the island a few flows above the base of the section. Unequivocal but less well-formed pillows and pillow-breccia have been seen only rarely higher in the section. These could have formed in local lakes or stream beds on the lava surface. The flows are in general tabular, and since some individual flows or flow groups can be traced along strike for at least 20 miles, the general impression is that of a broad, rather flat volcanic terrain. In contrast to the situation in eastern Iceland, however (Walker, 1964), no clear evidence of volcanic centers, representing shield or composite volcanoes contemporaneous with the plateau volcanism, has yet been found. White (1960) has drawn attention to the remarkable extent of some Keweenaw flows (especially in Michigan) and with ample justification calls them flood basalts.

Interflow sediments make up a minor part (1-3%) of the section. They are principally red, cross-bedded sandstones, that occur sporadically as beds a few inches thick between flows, but a few local accumulations of over 100 feet are found. Conglomerate is rare. Some sand has filtered down into cavities in the upper parts of flows, and also forms a matrix for flow-top breccia in others. These sediments appear to have been deposited by occasional temporary streams winding across the volcanic surface. There is little evidence of erosion. Pyroclastic deposits are extremely scarce, but welded tuff and mixed sand and shards have been reported from the Cascade River in Cook County (Johnson and Foster, 1965) and basaltic to andesitic breccia, other than flow top breccia, is present in a few localities.

With the exception of a high potassium content in some mafic and intermediate members and the relative abundance of rhyolite, the compositions of the lavas are also very similar to those of plateau lava series in Iceland and elsewhere. Table 1 shows the general characteristics and abundance of the major types.

The most abundant general type is olivine basalt of several varieties; one widespread, important, and distinctive variety is mottled (ophitic), and is similar to what has been called olivine tholeiites in other areas. These typically have ropy surfaces and were very fluid. Rough columnar joints are common. Other olivine basalts are coarser, some with diabasic and some with other characteristic textures. In the Tofte-Lutsen area, high in the section, is a group of olivine basalts with abundant, small (1-3 mm) bytownite phenocrysts or crystal clots. At the base of the section both at Duluth and on Lucille Island east of Grand Portage are distinctive basalts that contain abundant phenocrysts, 2-3 mm across, of augite and

TABLE 1

Generalized Characteristics of Major Lava Types of North Shore Volcanic Group

Characteristic	Olivine Tholeiite	Quartz Tholeiite	Andesite-Trachyandesite	Intermediate Quartz Latite	Quartz Latite Rhyolite
Wt % SiO_2	46-49	50-51	52-57	62-65	72-75
Wt % K_2O	0.1-0.5	0.6-0.9	1.9-2.7	2.8-5.0	3.9-6.2
Wt % MgO	5.9-6.8	4.3-5.9	1.9-4.5	0.9-1.9	0.0-0.4
Textures	Ophitic Occasionally porphyritic (plagioclase)	Very fine-grained, intergranular. Some flow structure, fine oxidation-banding	Very fine-grained, commonly porphyritic (plag., augite)	aphanitic, mostly porphyritic (plag., augite, ol.)	aphanitic to felsitic; aphyric or porphyritic (plag., orthoclase, quartz, mag., pyrox.) occas. spherulitic
Thickness, feet					
Range	<1 to >100	30-150	50-240	80-200	50-1300 perhaps 3500
Common	10-40	80	variable	120	50-500
Structures					
flow tops	smooth, ropy	scoriaceous rubble	scoriaceous, rubbly	vesicular wrinkled	vesicular, rolled, flow-banded
jointing	sheeted tops, columnar centers	small, irregular	small, irregular	irregular to subhorizontal, platy	platy, sub-horizontal big columns in thick flows
vesicles	round or irregular	stretched	stretched or round	stretched or round	stretched, round
Other Characteristics	very fluid pipe amygdules at base segregation veins, vesicle cylinders	more viscous some contain more K_2O , <u>Kspar</u> ; quartz, agate common in cavities	brown-weathering somewhat variable	few flow contacts exposed	pink, red, or light gray

(serpentinized) olivine: these are particularly unusual in having ferromagnesian instead of plagioclase phenocrysts. Another moderately abundant and distinctive rock type is the "quartz tholeiite" which is aphanitic or very fine grained and slightly more siliceous and viscous than the olivine basalts. The quartz-tholeiites characteristically have a rubbly or brecciated top with the highly vesicular fragments set in a matrix of washed-in red sand or occasionally calcite and zeolites. They also commonly show narrow oxidation bands, 1-3 mm thick, along subhorizontal flowage planes. This quartz-tholeiite grades into more potassium-rich varieties (trachybasalt, trachyandesite) that can be distinguished only by chemical analysis and microscopic study; patches of interstitial K feldspar are present in these rocks but are invisible in hand specimen.

Intermediate varieties are nearly all porphyritic with plagioclase, augite, magnetite, and in some specimens iron-rich olivine phenocrysts; they have the compositions of andesites, trachyandesites, and intermediate quartz latites. Most are aphanitic, but one unusual flow, here called the Manitou trachybasalt, is exceptionally thick (at least 300 feet) and granular, and can be traced for 5 miles although it originally continued for an unknown distance in both directions. These flows are commonly brown or red and irregularly jointed or with platy, subhorizontal joints.

The felsic lavas are anomalously abundant for a simple differentiation series from a basaltic parent magma. They are red, pink, or light gray, and have the composition of quartz latites. These flows tend to be much thicker than the other types: the thickest is 1300 feet, a few miles east of Grand Marais; the 3500' Brule River rhyolite west of Hovland may be a lava dome. Their top surfaces are mostly strongly flow-banded, vesicular, and contorted, but not brecciated, and their bases are commonly flow-banded and locally brecciated. Spherulites are occasionally present. Jointing ranges from large columns 4 feet across in the thickest flows to subhorizontal platy joints; small tectonically-produced parallel fracture sets a few mm apart commonly break up the cooling joint fragments into small pieces. Most of the felsites are porphyritic, with quartz and feldspar phenocrysts (oligoclase-andesine and/or orthoclase) but some are only weakly porphyritic or aphyric. Poikilitic quartz surrounding stout alkali-feldspar laths ("snowflake texture") is a common microscope texture in the thicker flows. Even these siliceous lavas have evidently flowed a great distance; one lava or flow group can be traced for at least 23 miles west from the Devil Track River, Grand Marais (see map, fig. 1).

Alteration

The lavas have been strongly but irregularly affected by secondary solutions that have deposited low-temperature minerals in vesicles, fractures, and other cavities, and altered some of the minerals of the lavas themselves. For instance, no fresh olivine has been detected in any of the lavas, although it is common in the intrusive diabases. A broad zonation of this alteration is apparent; at Duluth and at Grand Portage (in the lower parts of the lava section) much of the groundmass pyroxene has been converted to actinolite (although many larger augites are unaffected) and some plagioclase has been saussuritized. Here also the amygdale minerals are characteristically quartz, prehnite, calcite,

epidote, and chlorite, the same basic assemblage as is found in the Portage Lake Lava Series on the Keweenaw Peninsula (Stoiber and Davidson, 1959). In and northeast of Duluth K-feldspar is also occasionally found, and laumontite becomes abundant. Higher in the section various zeolites, along with calcite, are dominant except in the quartz tholeiites and similar lavas where agate, crystalline quartz and chlorite are common. The most abundant zeolites are laumontite, stilbite, heulandite, thomsonite and scolecite but analcite, natrolite, mesolite, mordenite, and apophyllite have also been found. Saponite is common in olivine basalts. Andradite garnets have been discovered in several localities in amygdules and veins from a wide range of lava types (basalts to rhyolites) and levels in the sequence, and traces of native copper have been found in several localities. Thus the secondary zonation in the North Shore Volcanic Group spans both the deeper-level, higher-temperature type of the Keweenaw Peninsula and the higher-level, cooler type characteristic of the lower parts of the Tertiary plateau lavas of eastern Iceland as described by Walker (1960). Walker's upper, zeolite-free zone is apparently not represented in Minnesota. According to his estimates, the presently exposed top of the section on the Lake Superior shore could have been approximately 5,000 feet below the surface during mineralization. Although detailed work has not yet been done, no clear cross-cutting relations of zeolite zones to stratigraphy within the lavas have been recognized, but the evident Upper Precambrian, postvolcanic unconformity which probably follows the North Shore must have postdated the mineralization, since it does crosscut the zeolite zones.

It should be stressed, however, that none of the flows has been entirely converted to secondary minerals. In fact, the plagioclase and augite are typically unaltered or only locally altered in most mafic and intermediate rocks, although no fresh olivine has been discovered. There has typically been some oxidation of the opaque minerals, especially of magnetite, and niobonite is commonly oxidized at its borders. In many intermediate and felsic lavas, plagioclase phenocrysts have been albitized and/or zeolitized; some of this alteration could be deuteric. Fresh, undevitrified volcanic glass is still present in occasional samples, notably in a basalt from about two miles west of the mouth of the Brule River.

Stratigraphy

The lavas of the North Shore Volcanic Group can be conveniently divided into several lithostratigraphic units of coherent petrographic character primarily on the basis of exposures at or near the Lake Superior shore. Many of these units can be traced for a considerable distance inland, but interruptions and structural complications by intrusive bodies as well as glacial deposits prevent the reconstruction of a complete, continuous sequence. No clear trend of compositional change is evident from base to top; in fact, although the most ferromagnesian lavas occur at the base, the uppermost flows, in the Tofte-Lutsen area, are entirely olivine basalts. It should be kept in mind also that a major stratigraphic break may occur between the Grand Portage lava section (showing reversed magnetic polarity) and the higher strata.

Table 2 lists the informal stratigraphic units proposed for the northeast limb (Tofte to Grand Portage) North Shore Volcanic Group, with their estimated thicknesses and general lithic characters, and Table 3 gives similar data for the southwest limb. This latter table depends largely on the work of Sandberg (1938) and Grogan (1940), pending restudy.

Table 2

Stratigraphy of Northeast Limb (Tofte-Grand Portage)
North Shore Volcanic Group
(Exclusive of interflow sediments)

<u>Approx. Thickness(ft.)</u>	<u>Lithostratigraphic unit</u>	<u>Lithic character</u>
Top		
1020	Lutsen basalts	olivine basalts, olivine tholeiites
160	Terrace Point basalt flow	thomsonite-bearing ophitic basalt
310	Good Harbor Bay andesites	brown, porphyritic andesite, trachyandesite
360	Breakwater trachybasalt flow	brown, columnar, granular trachybasalt
500	Grand Marais rhyolite flow	pink, red, gray porphyritic rhyolite
600	Croftville basalts	various fine-grained basalts
1020	Devil Track felsites	aphyric and porphyritic rhyolite flows
400-900	Red cliff basalts	amygdaloidal, ophitic olivine basalts
1300	Kimball Creek felsite	pink to tan, porphyritic felsite
1800	Marr Island lavas	mixed tholeiitic basalt, intermediate, felsic lavas
1000	Brule River basalts	granular-diabasic basalts
3500	Brule River rhyolite flow	pink to gray porphyritic rhyolite
4000 (est.)	Hovland lavas	mixed porphyritic basalt, trachybasalt, rhyolite
200	Red Rock rhyolite flow	red, porphyritic rhyolite
260	Deronda Bay andesite flow	gray-brown, aphyric andesite
4500	Grand Portage basalts	mixed tholeiitic to diabasic basalts
<u>Base</u>		

Table 3

Generalized Stratigraphy of Southwest Limb (Tofte-Nopeming)

North Shore Volcanic Group

(exclusive of interflow sediments)

<u>Approx. Thickness (ft)</u>	<u>Lithostratigraphic Unit</u>	<u>Lithic character</u>
Top		
4000	Schroeder basalts	amygdaloidal ophitic olivine tholeiites
> 300	Manitou trachybasalt flow	red-brown granular trachybasalt to basalt
	(more of the Schroeder basalts)	
> 280	Bell Harbor lavas	mostly quartz tholeiites, other basalts
> 300	Palisade rhyolite flow	gray to pink, porphyritic rhyolite
few 100's	Baptism River lavas	mixed lavas, mostly basalts
— — —	Beaver Bay intrusive complex —	— — — —
3200	Gooseberry River basalts	mixed basalts, one felsite
— — —	LaFayette Bluff, Silver Creek Cliff intrusions —	— — — —
1025	Two Harbors fine-grained basalts	"melaphyres", some quartz tholeiites
1615	Larsmont ophitic basalts	amygdaloidal ophitic olivine basalts.
— — —	Knife River diabase intrusion —	— — — —
4930	Sucker River basalts	mixed basalts, mostly ophitic
4400	Lakewood basalts	mixed basalts, mostly non-ophitic
— — —	Lester River diabase sill —	— — — —
3600	Lakeside lavas	mixed basalts, andesites, felsites
— — —	Endion diabase sill — — —	— — — —
2560	Leif Erickson Park lavas	mixed basalts, andesites
— — —	Duluth Complex — — —	— — — —
2300	Nopeming basalts	porphyritic melabasalts, diabasic basalts
<u>Base</u>	Puckwunge Sandstone	

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Field Trip A

The North Shore Volcanic Group

Leader: John C. Green
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The stops described below are intended to give a broad picture of the chemical, petrographic, and structural varieties of lavas of the Group, some representative exposures of the minor intrusions that cut the flows, and the general structural characteristics of these Upper Precambrian rocks. The area northeast of Silver Bay, where Green has done most of his work, is stressed. The trip excludes the Duluth Complex, aspects of which have been or are covered elsewhere (GSA 1956 Guidebook, ILSG 1968 Guidebook, and Field Trip B of this program). Many more stops are listed below than will be possible to examine in a one-day trip, but they are included for the benefit of those who can visit or revisit the area at a later time. The U.S.G.S 7 1/2 minute quadrangle name is given for each stop. The stops which are planned as a minimal framework for Field Trip A are designated with an asterisk after the number. Mileages are listed for distances between easily identifiable points along US Highway 61 (not cumulative mileage for whole trip), for travel either southwest (starting at the U.S.A./Canada border - Pigeon River: left-hand column) or northeast at the Midway Road, (St. Louis Co. 13), Nopeming, west of Duluth: right-hand column). Mileages for side trips off Hwy 61 are in parentheses or not given. All stops are shown on Fig. 1. Descriptions between stops are written for southwestward travel. The total distance covered is approximately 160 miles each way.

At several stops volcanic structures are well preserved. Visitors are urged to refrain from loosening, removing or otherwise destroying them, since they constitute irreplaceable evidence for flow direction, etc., and are valuable teaching features for local students and future visitors.

GoingGoing

SW	NE
0.0	7.4

Start of Trip A - Pigeon River, Minnesota-Ontario (Pigeon Point, Minn. - Mich. quad.). Travel SW along flat post-glacial lake bed, then rise along shoulder of a large NE-trending dike of the Keweenawan Logan Intrusions. Several road cuts in Middle Precambrian Rove Formation shales cut by small branch dikes. Excellent views from parking rest areas to the east over Wausaugoning Bay, Pigeon Point (thick complex Keweenawan sill), Susy Islands (Rove Fm. and Lower Keweenawan flows), Isle Royale (Keweenawan flows), Hat Point with Mount Josephine (Logan dike).

3.7 3.7

Stop 1. Logan dike and Rove Formation (Grand Portage quad.) At the top of the rise is a deep cut through the thick Keweenawan diabase dike that forms Mt. Josephine and Hat Point. Farther down the highway to the southwest are good cuts in the Rove Formation which is here dominated by graywacke.

Going SW	Going NE	
		(At the base of the slope an interesting detour can be made to the SE to Grand Portage Chippewa village and bay and Grand Portage National Monument. The base of the Upper Precambrian sequence forms Grand Portage Island. Continue out the west end of the village to Highway 61).
7.4 0.0	0.0 14.8	Stop 2.* <u>Basal Lower Keweenawan basalts</u> , Grand Portage (Grand Portage quad.). At the top of the next rise (at the Junction of Cook Co. 17) are low cuts exposing basalts near or at the base of the Keweenawan reversed polarity sequence. These basalts have a somewhat diabasic texture and have been strongly though not completely retrograded to prehnite-pumpellyite facies minerals. Amygdules contain weathered agate, prehnite, and epidote.
		The basal Upper Precambrian sandstone (Puckwunge) underlies the gentle slope to the north but is not exposed at the highway. It can be seen by bushwhacking about 1/4 mile to the NNW. It is a clean-looking, somewhat feldspathic quartz sandstone, in marked contrast to the red, immature, volcanic interflow sandstones above. The lowland beyond is underlain by the Rove Fm., and all the ridges are held up by large Logan dikes.
3.0	11.9	Stop 3. <u>Tholeiitic basalt and porphyry dike</u> (Grand Portage quad.). Walk or drive off Highway 61 on an inconspicuous, unmaintained little branch on the lake side to an old cabin site at a small cove (1/8 mile). On R (SW) is the basal, massive portion of a fine-grained tholeiitic basalt of the Lower Keweenawan Grand Portage lavas. On the L is a thick, compound dike of porphyritic trachybasalt that trends E into lake. A large swarm of similar dikes is present in this area and is being studied. They are unusually rich in Fe and K.
3.7	11.1	Stop 4. <u>Red Rock rhyolite</u> (Mineral Center quad.). At Deronda Bay the beach leads out to the SE to the breccia-rubble base of a thick (over 600 feet) porphyritic rhyolite flow which is the uppermost flow found to show magnetic reversal by Books (1968). More scenic exposure can be seen by climbing up the ridge and walking out to the point on the open lake. Less scenic but more accessible exposure is in a road cut 1/2 mile beyond.
4.6	10.2	Stop 5. <u>Reservation River Diabase</u> and abandoned beach ridges. (Mineral Center quad.) At the top of the next rise is the eastern edge of the extensive Reservation River diabase complex: one characteristic phase is exposed here that shows faint banding on some surfaces. Large gravel pits in the lowland to the northeast, mined out for the new highway, were large abandoned beaches of late postglacial Lake Superior. Excellent smaller, later ridges can still be seen on a little track that goes to the lake shore from the base of the slope.

Going	Going
SW	NE
<u>9.0</u>	<u>5.8</u>

Cross Reservation River and out of Grand Portage Indian Reservation. Slope is at contact of Reservation River diabase complex and lavas (a rhyolite here).

10.0	4.8
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Stop 6.* Hovland porphyry lavas. (Hovland quad.) Opposite a house on the lake side are exposures of a remarkable porphyritic trachyandesite lava flow with platy plagioclase phenocrysts up to 10 cm across. By following the low scarp to the NE behind a house (private property) two flows can be seen, the top of the lower one being vesicular and showing a slightly uneven crust. These are near the base of the Middle Keweenawan (normal polarity) lava sequence, and are assigned to the Hovland lavas. They are here cut by a large dike, at least 2 miles long, of brown trachyandesite with small clinopyroxene phenocrysts, that also crops out across the road.

<u>14.8</u>	<u>0.0</u>
0.0	4.0

Highway descends to old lake-bed flat; then, past Big Bay, rises onto higher ground of Hovland Diabase complex. Cross Flute Reed River, pass through village of Hovland at Chicago Bay, and up onto a large sill-like body of syenogabbro. Many road cuts; some show good foliation of plagioclases, dipping gently S.

<u>4.0</u>	<u>0.0</u>
0.0	10.6

Stop 7. Syenogabbro, basalt pillow-breccia, and rhyolite at Brule River (Marr Island quad.). Opposite Naniboujou Lodge, park in lot of Judge Magney State Park. Walk up trail, cross river on footbridge, and follow fisherman's trail and bushwhack up W bank. Take care - steep and unstable slope in places. At footbridge is medium-grained, foliated syenogabbro of "Hovland diabase complex." This is cut by a later basalt dike, then gives way to a rather coarse-grained basalt lava with chlorite scraps and amygdules. Soon this is overlain by basaltic-scoriaceous tuff-breccia. After a short gap in exposure, steep bank resumes which is made of basalt pillow-breccia, with altered volcanoclastic matrix. This is one of the few places where evidence for underwater extrusion can be seen in the North Shore Volcanic Group (others are on Grand Portage Island and W of Duluth in the Lower Keweenawan). Farther upstream this can be seen to overlie the altered, flow-banded and swirled top of a very large porphyritic rhyolite flow through which the Brule has cut a deep gorge above. Return by fisherman's trail at top of bank.

After crossing the Brule (Arrowhead) River, the highway rises over and cuts through three basalts of the Brule River group, then crosses a porphyritic trachyandesite or intermediate quartz latite of the Marr Island lavas at Paradise Beach. A few more low cuts of this mixed group are passed in next 3 miles.

3.8	5.8
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Stop 8.* Porphyritic intermediate quartz latite of Marr Island lavas one mile past Cook Co. 14 (Kadunce Creek quad.) Two large road cuts on N. side of a thick, intermediate quartz latite lava (62% SiO₂, 4.1% K₂O) with plagioclase, ferroaugite, and rare ex-olivine and magnetite phenocrysts. Contacts not exposed.

Going SW	Going NE
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1 1/2 miles to the west at Kadunce Creek (Kodonce River) State Park a thick porphyritic felsite is exposed, especially in a deep and narrow canyon that begins about 1/8 mile upstream from highway — this is part of the Kimball Creek felsite group, also exposed in Kimball and Cliff creeks farther west. Excellent abandoned wave-cut cliffs of Nipissing stage.

7.3	3.2	Stop 9. <u>Olivine basalts</u> of Red Cliff series (Kadunce Creek quad.). Just past large gravel pit and creek gully, highway rises onto a series of 5 or 6 ophitic olivine basalt flows totalling between 400 and 900 feet in thickness. Amygdules contain saponite, laumontite, calcite, quartz, and agate. Plagioclase phenocrysts have floated to top in some, sunk to bottom in others. 47% SiO ₂ , 0.5% K ₂ O.
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Past Durfee Creek (near top of Red Cliff basalts) highway (and Nipissing cliff) pass onto Devil Track felsite group, here composed of two thick flows.

9.6	1.0	Stop 10.* <u>Felsite</u> of Devil Track series, at promontory of abandoned Nipissing wave-cut cliff. N side of highway, 0.85 miles west of Durfee Creek (Kadunce Creek quad.). Pink, non- or weakly porphyritic rhyolite or quartz latite (72% SiO ₂ , 5.5% K ₂ O) with slabby jointing and faint flow-banding. Bushwhacking along old cliff to E for 1/4 mile one eventually passes down into vesicular, locally spherulitic and flow banded top of a porphyritic flow of similar composition. These two flows total about 1020 feet in thickness. Five Mile (Guano) Rock, a mile out in Lake Superior, is made of diabase.
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10.6 0.0	0.0 3.7	Cross <u>Devil Track River</u> . This cuts a deep gorge just upstream in the upper felsite flow. Continue on Hwy 61 into Grand Marais, or alternatively turn off just before rise on small side road (Cook Co. 87) toward lake to Croftville settlement and optional Stop 11.
(off Hwy 61) (1.3) (0.0)	(0.45)	Stop 11. <u>Spherulitic</u> basal phase, <u>Grand Marais rhyolite</u> , Croftville (Grand Marais quad.) Drive about 1.1 mile along Nipissing terrace over Croftville basalts (about 0.45 mi. from <u>W</u> end of this road). <u>Private Property</u> . Ask permission at the house in birches on lake side, examine outcrops at modern beach-back. Slabby, spherulitic red rhyolite is exposed here (73.4% SiO ₂ , 4.65% K ₂ O) that contains andesine-oligoclase and rare hedenbergite, ex-fayalite and magnetite phenocrysts. Nearby is cross-bedded, calcite-cemented interflow sand. Strata have been steeply tilted by diabase intrusions. Continue on Croftville road until it re-joins Hwy 61.
(0.45)	(0.0) (2.1)	

Continue SW to Grand Marais.

(off Hwy 61)	Stop 12. <u>Breakwater trachybasalt</u> (Good Harbor Bay quad.). Drive to Coast Guard Station at E end of Grand Marais harbor. Tombolo here is made by gravel bar connecting mainland to resistant island and ledges of a massive, locally columnar-jointed, porphyritic trachybasalt or basalt with small phenocrysts of plagioclase, augite, and rare olivine. It is about 360 feet thick. It is not known for certain whether this is a big flow or sill; to the west it has a sharp, chilled basal contact against felsite but its top contact is covered. It becomes amygdaloidal and zeolitized near
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Going
SW

Going
NE

its top and is assumed to be a flow. As can be seen from this vantage point, it forms one of the major strike-ridges of the "Sawtooth Range" to the west (as does the big "thomsonite flow" starting at Good Harbor Bay). The harbor at Grand Marais is probably eroded from rhyolite.

3.7
0.0

0.0
9.2

Highway 61 passes corner of harbor, near start of Gunflint Trail (Cook Co. 12).

Then highway rises to W past a good porphyritic rhyolite cut onto higher level (Breakwater trachybasalt cuesta ahead), then back down across the Breakwater trachybasalt and across Fall River (Rosebush Creek). About 1 mile past this creek, low road cuts start in two thick porphyritic trachyandesite to andesite flows (55% SiO₂, 2.7% K₂O) with small plagioclase and clinopyroxene phenocrysts and vesicular-rubble tops. Big cuesta ahead is held up by Terrace Point thomsonite-bearing basalt flow. Continue across Outface (Good Harbor) Creek.

5.2

3.9

Stop 13.* Thomsonite-bearing basalt, interflow sediments (Good Harbor Bay quad.). In this large road cut one of the major cliff formers of the "Sawtooth Range" overlies a thick (130') section of interflow sediments. The Terrace Point basalt is dominantly a massive, fine-grained, ophitic basalt that characteristically contains thomsonite in amygdules, but in its lengthy exposure (including in this cut) several flow units of varying character show complex relations with the major, massive part of the flow.

The interflow sediment is here mainly thin-bedded siltstone and silty shale, but by walking up the bed of Outface Creek at the bottom of this hill one passes outcrops of the basal contact of the sediments resting on the amygdaloidal-scoriaceous top of an andesite flow and eventually reaches large banks cut into well-bedded sandstone showing abundant ripple marks.

Highway 61 passes low cuts of the complex upper parts of the Terrace Point flow complex, with big cuesta on this flow visible ahead, then at jct. of Cook Co. 7 passes into coarse-grained olivine basalt of the Lutsen basalt series. Cross Cascade River in State Park. Trail up W side provides access to good river outcrops of Terrace Point thomsonite basalt, the underlying sandstones, and several andesite flows of the Good Harbor Bay series. Drive past Cascade Lodge.

9.2
0.0

0.0
16.9

0.5

16.4

Stop 14* Cascade olivine basalt of Lutsen basalt series (Deer Yard Lake quad.). 0.5 miles W. of Cascade River. Shore outcrops of a thick (100 feet or more), relatively coarse-grained olivine basalt of a distinctive group in this Cascade-Lutsen area. Segregation cylinders up to 6" or so in diameter and segregation lenses or sills can be seen within this flow.

Highway continues on long straight stretch roughly parallel to strike of Lutsen basalts, topmost series of the North Shore Volcanic Group. Pass through Lutsen village (big ridges to W held up by Leveaux trachybasalt sill), to Poplar River.

Going	Going
SW	NE
9.8	7.1

Stop 15. Porphyritic olivine basalts of Lutsen series (Lutsen quad.), Poplar River. Watch your step - dangerous. Private land. Several flows of a distinctive ophitic olivine basalt characterized by abundant small (1-3 mm) blocky bytownite phenocrysts are exposed from the mouth of the Poplar River at Lutsen Resort, up through an impassable canyon to the highway bridge and upstream to left bend (1/10 mile from highway). Take fisherman's trail on W side. This flow type has the most "primitive" composition (lowest K, highest Mg) of the North Shore lavas (47% SiO₂, 0.12% K₂O). At L bend in river it overlies breccia-rubble top of a basaltic andesite flow; red sand has been washed into all the interstices between the lava blocks, a typical situation.

12.3	4.6
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Stop 16. Leveaux - Onion Mtn. trachybasalt porphyry sill (Tofte quad.). 2.5 mi. SW of Poplar R. at slight L bend cross Rollins Creek and immediately turn up U. S. Forest Service gravel road (No. 336). Continue on it as it contours back to SW, then cuts up into Onion River gap in big ridge held up by a big trachybasalt porphyry sill. This sill forms Leveaux Mtn., the high ridge with a fire tower on it to the SW, and comes out to the lake shore to form the islands at Taconite Harbor SW of Tofte. Its contacts are not exposed but it crosscuts the lavas. Park as near as possible to the S corner of the hill on the NE side of the gap, and bushwhack a short distance N to the steeper, rocky rise. Here the lower part of the sill is exposed - a fine-grained, pigeonite-augite trachybasalt to trachyandesite. Farther up the slope a bit abundant large (1 cm) blocky labradorite phenocrysts appear abruptly; they appear to have floated. This porphyritic phase forms the upper part of the sill throughout its extent.

16.9	0.0
0.0	12.1

Continue SW past Sawbill Trail (Cook Co. 2) at village of Tofte. Town park on lake shore 0.3 mi. SW of Edgewater Motel has good exposures of thin-bedded ophitic olivine basalts. DO NOT DESTROY FEATURES. These lie at the top of the section of the North Shore Volcanic Group.

1.7	10.4
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Stop 17. Carlton Peak anorthosite in diabase (Tofte quad.) 1.7 mi. SW of Sawbill Trail jct., opposite large Superior National Forest Sign, turn up road of Erie Mining Co. to large quarry in side of Carlton Peak, which is held up by massive anorthosite xenoliths in a gabbroic intrusion. Private Property. The complex relations between the anorthosite and various phases of olivine gabbro are well exposed.

2.5	9.6
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Stop 18. Thin-bedded ophitic olivine tholeiites of Schroeder basalts, Temperance River (Tofte quad.). Park at State Park lots, walk down trail to bridge near river mouth. Note excellent erosional potholes. Several thin flows or flow units, with ropy surfaces, pipe amygdulæ and lensing shape are well exposed here. If more time is available, walk up NE side of river above highway to the main gorge where the river has cut a very deep and narrow slot with larger potholes into thicker olivine basalts. Warning: people have been killed trying to jump across. Large joint columns visible on trail and overlooks, and vesicle cylinders are present in thicker flows.

Going SW	Going NE	
3.8	8.3	Drive SW through <u>Schroeder</u> and Taconite Harbor (power plant and taconite pellet shipping facility of Erie Mining Co.) with occasional low cuts of amygdaloidal or ophitic olivine tholeiite.
9.4	2.7	Stop 19*. <u>Thin-bedded ophitic olivine tholeiite</u> of Schroeder basalts at Sugar Loaf Point (Little Marais quad.). Private property. Drive down side road (just opposite gravel road from uphill) at Consolidated Paper Co. pulpwood storage and handling facility. Drive down to cove, and ask permission to walk on point at office. Notice great old pine boom-logs used to raft pulpwood across lake. Walk around Sugarloaf Point clockwise from end of beach. Excellent examples of thin flow units (6" and up) and thicker flows of ophitic "olivine tholeiites," with ropy surfaces, bent pipe amygdules, and clastic dikes where sand was washed into open joints in the tops of flows. <u>Please do not remove or destroy these structures!</u> On the sides of the high knob at the end can be seen vertical tube-like concentrations of amygdules ("vesicle cylinders") in the massive lower part of the topmost flow.
11.7	0.4	Cross Cook/Lake County line.
12.1 0.0	0.0 11.0	Stop 20. <u>Ophitic olivine tholeiites, Manitou trachybasalt,</u> and strike-fault, Caribou River (Little Marais quad.) Park at Caribou Falls State Park lot on the NW side of the highway and walk up the trail. (Between the highway and Lake is private property including falls over typical ophitic olivine basalts). In the river and along the trail are a few outcrops of the red volcanic breccia and basalt that underly the "Manitou trachybasalt," then at a L bend is the NE-most outcrop of the trachybasalt. As the trail approaches the falls the river has cut through a thick section of volcanic breccia, but a large strike-fault intervenes between this and the typical ophitic olivine tholeiites ($\text{SiO}_2=45-47\%$, $\text{K}_2\text{O}=0.3-0.5\%$) that form the cliff over which the river falls. Several flows, 10-30' each, are visible in the cliff each with a massive lower part and an amygdaloidal and slabby-jointed top. These are typical of nearly all the lavas between Little Marais and Lutsen, the uppermost sequence of the North Shore Volcanic Group.
2.2	8.8	Drive SW, cross Manitou River, which has cut a deep gorge through drift and olivine basalts (trail up stream in State Land accessible on SW side via gravel pit road). Commercialized gorge downstream has falls, sea arches.
		Continue SW almost to R bend at Little Marais R.
4.5	6.5	Stop 21. <u>Manitou trachybasalt</u> (Little Marais quad.). Turn down road at Ben Fenstad's Resort. Private property; ask permission for entry at office. Continue down to lakeshore, bearing left to end of driveway loop at fishhouse. Here at the end of the slip is exposed the base of a large flow of granular trachybasalt, at least 300' thick and 5 miles long, that forms much of the shoreledges from this breakwater on, both SW and NE of Manitou River. It contains about 52% SiO_2 and 2.3% K_2O , and has labradorite, augite, and altered rare olivine phenocrysts and abundant K feldspar and pigeonite in the groundmass. Higher in the flow it is coarser-

Going SW	Going NE	
		grained, less potassic and less porphyritic. Its top is not exposed. It overlies a sequence of interbedded basalts and red volcanic breccia or conglomerate.
		Continue SW past Little Marais. High ridge inland is held up by a thick intrusive diabase sill containing some anorthosite blocks.
8.0	2.6	Stop 22.* <u>Quartz tholeiite-trachybasalt</u> , Kennedy Landing (Finland quad.) Good cuts for about 1/3 mile through several typical quartz tholeiites to trachybasalts. They show the characteristic fine-grained, aphyric texture, oxidation lamellae, and scoria-rubble tops. They contain interstitial alkali feldspar and about 51-53% SiO ₂ and up to 2% K ₂ O. Red sand, locally cross-bedded, fills the interstices between fragments. Large knob overlooking the bay is made of the thickest of these flows.
9.1	7.8	Stop 23.* <u>Anorthosite in syenogabbro; overturned lavas</u> (Illgen City quad.). After crossing Kennedy Creek come to deep vertical cut in an irregular discordant intrusion (part of Beaver Bay complex) of altered syenogabbro that contains a great, massive block of rather pure anorthosite. After examining this, walk or drive SW downhill to lower cut that is composed of a sequence of several basaltic lavas with an interflow sediment bed - all of which have been overturned, probably as a result of forceful intrusion of nearby diabbases. These basalts show a variety of structures, including some lobes that look like pillows and at the NE end some red scoria-rubble that is characteristic of the top part of the fine-grained tholeiites, basaltic andesites, and trachybasalts.
<u>11.0</u> 0.0	<u>0.0</u> 4.9	Continue SW to Illgen City, jct. with Minn. Rte. 1 to Ely. Just to NE are cuts in quartz tholeiite flows, to SW cuts in altered rhyolite.
0.45	4.5	Stop 24.* <u>Palisade Head porphyritic rhyolite</u> , Shovel Point (Illgen City quad.). 0.45 mile SW of Illgen City jct., or 0.45 mile NE of Baptism River, search for unmarked trail leading to shore at Shovel Point in Baptism R. State Park. Here is well exposed the upper-middle part of the thick (>300') porphyritic rhyolite (quartz latite) that also forms Palisade Head to the SW and the road cuts at Illgen City. Take care on clifftop. View to SW over underlying lavas ("Baptism basalts") and some mafic intrusive bodies, to Palisade Head. Follow trail down dip slope to end and NE corner: view NE toward overlying quartz tholeiite flows. Return on same trail.
		Drive SW across Baptism River to Palisade Head (big hill with radio beacon).
2.1	2.7	Stop 25. <u>Palisade Head rhyolite</u> (Illgen City quad.). Drive up narrow, winding road (just past Palisade Creek) to top of cliff next to radio beacon. <u>Careful</u> - joint columns are separating from rest of hill. Excellent views to N, NE, SE, SW. Ridges to

Going	Going
<u>SW</u>	<u>NE</u>

N. NE are held up by intrusions of Beaver Bay complex. Up lakeshore to NE is columnar-jointed Shovel Point, made of same rhyolite flow, and far beyond is smoke from Taconite Harbor power plant and Carlton Peak anorthosite knob at Tofte. To S across lake are Apostle Islands and Bayfield Peninsula, Wisc. To SW is Reserve Mining Co. taconite plant at Silver Bay and humpy topography of Beaver Bay complex. Palisades made of thick, porphyritic rhyolite with quartz and feldspar phenocrysts, flow-banded at the base. Return to highway.

<u>4.9</u>	<u>0.0</u>
0.0	14.8

Drive 2.75 mi. to traffic light at Silver Bay, site of Reserve Mining Co.'s taconite plant where about 100,000 tons of rock from the eastern Mesabi Range are processed per day.

0.4	14.3
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Stop 26. Anorthosite in diabase of Beaver Bay complex, Silver Bay (Silver Bay 15' quad.). Stop at road cut directly opposite the main building of the Reserve Mining Co.'s taconite plant (after the 2nd traffic lights). Here several large blocks of anorthosite are included in diabase, a typical assemblage in the Beaver Bay complex. Large patches of interstitial, poikilitic olivine occur in some parts of the anorthosite. No definite source for the anorthosite is known. Small red veins and dikelets of "granophyre" cut the diabase and anorthosite.

Continue SW 2.8 miles across Beaver River to Beaver Bay.

3.2	11.6
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Stop 27. Beaver Bay ferrogabbro and Black Bay gabbro (names after Gehman) of Beaver Bay complex (Silver Bay 15' quad.). Drive or walk down to shore on gravel road opposite the main restaurant in Beaver Bay. Walk E through woods across little point to shore ledges. These are well-foliated ferrogabbro of the Beaver Bay Ferrogabbro, one of two similar plugs in this area. On walking NE along the shore, the contact with an enclosing ring-dike of Black Bay Gabbro is reached; such rings surround both ferrogabbro plugs. It is rather inhomogeneous and locally contains very abundant apatite. The ophitic Beaver River Gabbro can be seen farther along the shore below some cabins. Return to highway.

Continue SW through Beaver Bay complex; most outcrop is of coarsely mottled, ophitic olivine gabbro ("Beaver River Gabbro" of Gehman), well seen opposite Kings's Landing Marina 3 miles from Beaver Bay. After 2.2 more miles road branches to Split Rock Lighthouse, built on anorthosite in diabase. At Day Hill (parking and trail), 1.0 mile beyond, is last exposure of Beaver Bay complex. Re-enter volcanics, continue 5.4 miles to Gooseberry Falls State Park.

<u>14.8</u>	<u>0.0</u>
0.0	13.1

Stop 28. Smooth-surfaced olivine basalt, Gooseberry Falls State Park (Split Rock Point quad.). Below highway bridge are good exposures, in and between falls, of columnar-jointed olivine basalt lavas with amygdaloidal tops, and smooth, gently billowing surfaces.

Continue SW through Castle Danger (2.4 mi.), across Crow Creek (a diabasic intrusion here returns soon to SW at deeply weathered Lafayette Bluff), through Encampment Forest (privately owned old-growth forest with summer homes) to Silver Cliff (another thick

Going
SW

Going
NE

gabbroic intrusion) to outskirts of Two Harbors.

12.7 0.5 Stop 29. Quartz tholeiite basalt, Two Harbors city park (Two Harbors quad.). Just before entering town, turn toward lake at road to city camp ground and Wa-Ke-Ya Motel. Drive past Burlington Bay, and up a hill. Park at hilltop picnic area, walk E to shore, then S. Well exposed contact between amygdaloidal, weathered (ex-laumontite) top of one basalt and massive basal part of an analyzed fine-grained, aphyric quartz tholeiite (50% SiO₂, 0.6% K₂O). Local thin sand lenses near and at contact; traces of Cu have been found. The tholeiite shows occasional small quartz-agate and chlorite amygdules and typical incipient sheeting-fractures with thin bands of oxidation. Upper zone of this thick tholeiite can be examined to S. toward power plant; it becomes rubbly, vesicular, brecciated, with abundant laumontite. Return to Hwy 61.

13.1 0.0
0.0 20.6 Continue SW to traffic light in Two Harbors. At west end of town take express highway to Duluth. Many cuts of basalts and minor diabase intrusions. At about 17.7 miles Moose Mtn. is seen inland, held up by Lester River diabase sill. At 20 miles jct. with old Hwy 61 (now St. Louis Co. 61), and at 20.6 miles Lester River bridge. Just beyond, either continue straight on Hwy 61 (London Rd.) direct to downtown 6 miles ahead, or turn uphill on Minn. 23 (60th Ave. E) across RR tracks to Superior St; go left.

20.6 0.0
0.0 5.9

(3.0) (3.0) Stop 30. Tischer Creek felsite and Endion sill, Congdon Park (Duluth quad.). Examine outcrops beneath bridge; then walk up trail that starts on W side of creek. There are some impassable places where you must climb up to a bank-top trail on W side. Lower part of section cuts through orange, foliated felsite with flow structure, quartz veinlets, occasional inclusions, cut by two or three basaltic dikes. Upstream at top of steeper part of gorge the stream cuts down into red granophyre top of Endion sill. Upstream the creek cuts gradually down into intermediate, then gabbroic rocks of main part of Endion sill. At Vermilion Road bridge (second bridge above Superior St.) still in lower-middle part of sill; return via trail or Congdon Parkway on W. side. See Ernst, 1960.

Continue SW on Superior St. over rise held up by Endion Sill.

5.0 0.9 Stop 31. Basaltic-andesitic lavas, interflow sandstone, Leif Erickson Park, Duluth (Duluth quad.). At 10th Avenue E. turn off Superior St. toward lake to London Road at Leif Erickson Park. Walk over footbridge near "viking ship" to shore. Weakly porphyritic basalt or basaltic andesite ledges behind stage. Rubbly (weathered?) top to NE is directly overlain by a thick cross-bedded sandstone, strongly epidotized, that is cut by a small dike at NE end of beach. Several more flows exposed along shore to SW.

5.9 0.0
0.0 11.2
(approx.) Lake Avenue and Superior Street, downtown Duluth.

11.2 0.0
(approx.) Drive SW on Hwy 61 past Point of Rocks through Duluth Complex up Thomson Hill to Nopeming. Turn R at Midway Road (St. Louis Co. 13), drive uphill about 0.9 mi. almost to top of rise.

Stop 32. Basal (Puckwunge?) sandstone, basal basalts of Lower Keweenawan ("Grandview Golf Course" locality, Esko quad.). Drive or walk E on road toward Cloquet city water supply tank on hill. Pass low outcrops of vertical Thomson slate and graywacke (Middle Precambrian: more are exposed on rise and roadcuts to N.). At slope, go either R or L along base of slope to outcrops of basal Upper Precambrian quartzite and conformably overlying mafic, porphyritic basalt with small augite and altered olivine phenocrysts identical to rocks on Lucille Island at Grand Portage. Note pillows subtly outlined by small vesicles and color zones.

GUIDE TO THE PRECAMBRIAN ROCKS
OF NORTHWESTERN COOK COUNTY
AS EXPOSED ALONG THE GUNFLINT TRAIL

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Geology of Northwestern Cook County, Minnesota

INTRODUCTION

An exceptionally complete Precambrian section is exposed in the vicinity of the Gunflint Trail in northwestern Cook County. Rocks of Early Precambrian age, represented by a volcanic succession and the Saganaga Granite, are unconformably overlain by the Middle Precambrian Animikie Group, consisting of the Gunflint and Rove Formations. A low angular unconformity separates the Middle Precambrian strata from the overlying Puckwunge Formation of Late Precambrian age. The Logan Intrusive Rocks and the Duluth Complex, which intrude and truncate the Middle Precambrian strata, comprise the major part of the Upper Precambrian section. However, possible remnants of the North Shore Volcanic Group occur at the top of Duluth Complex rocks.

The geology of the area was summarized in 1959 by Grout and others. Because geologic mapping since 1962 has considerably revised the geologic history of the area, and because much of this work is as yet unpublished, a comprehensive summary is presented here. This discussion is meant to provide a framework for the specific aspects of the geology which the chosen stops illustrate.

Lower Precambrian

Introduction

The Lower Precambrian rocks in Cook County are the eastern extension of the Vermilion greenstone belt (Sims and others, 1971, in press). Gruner (1941) has shown that the district contains many major longitudinal faults that divide it into long segments or belts, each with distinct characteristics. They cannot be connected stratigraphically with each other in any simple way. One segment extends from Gabimichigami Lake across the Gunflint Trail (Fig. 1). It includes a metavolcanic assemblage consisting of metabasalt, metaandesite, agglomerate and tuff, hornblende andesite porphyry, and intercalated metagraywacke and slate. To the north, the Saganaga Granite has intruded and metamorphosed the volcanic succession; it is overlain to the south by younger rocks of Middle and Late Precambrian age.

The metavolcanic assemblage constitutes a homoclinal sequence which dips southward toward what Gruner inferred to be the axis of a southeastward-plunging synclinorium. Pillow-top directions indicate that the sequence also becomes stratigraphically younger to the south. However, some pillows top to the north indicating folding, but poor exposure precludes detailed evaluation of the structure.

Previously, an unconformity was thought to separate the mafic and more felsic rocks; thus the succession was subdivided into two formations. The metabasalts were referred to as part of the Ely Greenstone whereas the more felsic volcanic and clastic rocks were placed within the Knife Lake Group. Recent mapping (Morey and others, 1969) has shown these two lithologies to be gradational, and mapping in other parts of the Vermilion district (Morey and others, 1970; Green, 1970; Sims and others, 1968; 1971, in press) has shown that specific rock types are not diagnostic of any particular stratigraphic horizon - i.e., lithologic units are not time-stratigraphic units - therefore no formal stratigraphic nomenclature is now used for these rocks.

Descriptive Stratigraphy

Volcanogenic Rocks

Detailed mapping in the Long Island Lake quadrangle, reconnaissance mapping as far west as Fay Lake in the Gillis Lake quadrangle, and Gruner's work in the area have indicated that the volcanogenic sequence consists of approximately 60 percent metabasalt and associated fragmental rocks, 30 percent metaandesitic agglomerate, conglomerate, tuff, and flows, and 10 percent intercalated metagraywacke and slate.

Metabasalts and associated rocks: Over 95 percent of the metabasalt is extrusive; there are several tabular bodies of metadiabase, too small to show at a scale of 1:24,000. Many of the metabasalts exhibit pillow structure. The pillows are as much as three feet in diameter, but many have been deformed so that they are now two or three times as long as they are wide. Chilled rinds are well-developed and are as much as one-half inch thick; typically they are lighter in color than the dark green or dark greenish-gray interiors. Inter-pillow material locally is well developed and consists of tuffaceous material chert, or pillow-rind fragments.

The metabasalts show intense retrograde alteration; many thin sections are nearly opaque. Recognizable minerals include relict augite and calcic plagioclase, and secondary sodic plagioclase, actinolite, chlorite, epidote, calcite, quartz, leucoxene, and opaques.

The tabular bodies of metadiabase have a relict poikilitic texture — actinolite pseudomorphs after augite — and a mineralogy much like that of the metabasalts.

Thin beds of texturally and mineralogically immature metaclastic rocks are locally intercalated with the metabasalt. Several beds are crudely graded and have a texture suggestive of a pyroclastic origin. Most layers, however, appear to be epiclastic with pebble- to silt-size clasts of locally derived metadiabase in a finer-grained matrix of chert, plagioclase, hornblende, chlorite, and sericite.

Hornblende andesite prophyry and related rocks: There are two types of hornblende-biotite phenocryst bearing rocks. Both are light greenish-gray in color. One type lacks internal structure. The ground mass consists of plagioclase, lesser amounts of biotite, opaques and rare quartz and secondary calcite. The other type has similar phenocryst and groundmass mineralogy but is composed of angular to rounded, cobble-size clasts and is inferred to be a volcanic breccia or agglomerate.

Metagraywacke and slate: In the vicinity of Fay Lake in the Gillis Lake quadrangle, the felsic volcanic rocks apparently interfinger, or are infolded with agglomerate or conglomerate, metagraywacke, and slate.

Amphibolites: The metamorphic effects of the Saganaga Granite on the metabasalts becomes apparent only within several hundred feet of the contact. Away from the contact, the metabasalt contains incipient hornblende; nearer the contact, the rock becomes granular and consists of hornblende and calcic plagioclase; at the contact, the rock is strongly schistose. The schistosity parallels the granite contact, as does a well-developed foliation within the granite.

Saganaga Granite

General Statement: The Saganaga Granite (A. Winchell, 1888) (Fig. 1) is a late-kinematic composite intrusion emplaced around 2,700 m.y. ago in older volcanic rocks and the Northern Light Gneiss. Inch- to foot-sized inclusions of both rock types are found in the granite. The main phase, which comprises 85 percent of the outcrop area, is a medium-grained "quartz-eye" hornblende-biotite tonalite. Other phases include: 1) a border phase, found along the southern margin of the batholith and along the base of a roof pendant of the Northern Light Gneiss; 2) a younger fine-grained tonalite which lacks conspicuous "quartz-eyes"; 3) a coarse-grained biotite-fluorite-bearing granodiorite; and 4) a quartz-feldspar pegmatite which occurs as veinlets as much as three feet wide in the main phase.

Main Phase: This phase is a "quartz eye"-bearing tonalite containing 20 percent quartz, 60 percent oligoclase, 1-6 percent microcline, up to 8 percent biotite, 6 percent hornblende, and 1-4 percent epidote. Other minerals include clino-pyroxene, muscovite, chlorite, sphene, apatite, zircon, calcite and opaque oxides. Cataclastic deformation of the tonalite is indicated by strong undulose extinction and granulation of the quartz and abundant mortar and mylonite zones.

Border Phase: The border phase is a quartz bearing, hornblende diorite that is gradational with the "quartz-eye" tonalite. This phase is well developed along the southern edge of the batholith in the Long Island Lake quadrangle where it is as much as 1000 feet wide, and in the Moose Bay area in Ontario where it is found along the underside of a roof pendant of the Northern Light Gneiss. Foliations in the border phase and in the country rock are everywhere similar, and it is inferred that the border phase was produced by partial assimilation of country rocks of mafic composition (Halford, 1969).

Younger Tonalite: A tonalite characterized by a lack of "quartz-eyes," a fine-grained equigranular texture, and abundant hornblende and biotite crops out in the Horseshoe Island area of Saganaga Lake. This tonalite is not sheared which indicates that it was emplaced after deformation of the main phase.

Internal Structure: Linear structural elements marked by an alignment of "quartz eyes" and/or elongate hornblende grains are well developed only in the border phase. Lineations in the border phase plunge gently southeastward. In contrast, lineations in the main phase are random.

Structure

All the minor structural elements in the pre-Saganaga rocks in the Long Island Lake quadrangle reflect a southeasterly plunging synclinorium. In addition, a major, northwesterly-trending fault (Lookout Fault, Sims and others, 1969) separates rocks showing no metamorphic effect of the Saganaga Granite from those that do. The fault is marked by a topographic low developed in a breccia zone as much as 50 feet wide. The breccia consists of highly sheared metabasalt in a matrix of massive quartz and calcite. Fracture cleavage is present throughout the area and commonly parallels the Lookout Fault. Southeastward plunging lineations formed by bedding/cleavage intersections are locally well developed. These lineations are consistent in orientation with mineral lineations developed in the amphibolites and in the granite itself; obviously all of these structures are related to the same tectonic event.

The Lookout Fault also apparently was related to the final emplacement of the Saganaga Granite. Previously it was assumed (Grout, 1936) that the granite was emplaced into its present position via a westward rotation of about 70° about a north-south axis. This implies that the eastern part of the granite and the Northern Light Gneiss represent roots of the batholith that were once as much as 25 miles deep. However, Goldich and others (1968) have suggested that the granite was originally intruded at a shallow depth—an observation more consistent with the regional Abukuma greenschist facies metamorphism (Mudrey, 1969) — and brought to its present relative position by dominantly vertical movements along several westerly-trending border faults. The granite-greenstone contact mapped by Harris (1968) on the north shore of Saganaga Lake was interpreted to be the northern border fault, and it is here inferred that the Lookout Fault is its southern analog.

The block was emplaced during Early Precambrian time, in as much as detritus now found in the Knife Lake Group of Gruner (1941) was derived from the Saganaga Granite. Although there has been later movement on the Lookout Fault, it is dominantly a Lower Precambrian structure.

MIDDLE PRECAMBRIAN

Introduction

The Animikie Group consisting of the Gunflint and Rove Formations comprises the entire Middle Precambrian in this area. These rocks unconformably overlie Lower Precambrian rocks and in turn are intruded and truncated by gabbroic rocks of Middle Keweenawan age.

The time of Animikie deposition has not been completely documented. Hurley and others (1962) have suggested that deposition of the iron-formation occurred around $1,900 \pm 200 \times 10^6$ years. Although this K-A age includes an arbitrary and perhaps unnecessary correction of 20 percent assumed argon loss, it nevertheless has been widely quoted in the literature. In contrast, Faure and Kovach (1969) obtained a Rb-Sr whole-rock isochron age of $1,685 \pm 24 \times 10^6$ years from the Gunflint Iron-formation. They interpret this age to be the time of diagenesis, however, it is similar to other ages obtained from rocks metamorphosed during the Penokean orogeny. Later Misra and Faure (1970) showed that argillite from three Gunflint Iron-formation localities have Rb-Sr ages that decrease from "...1.7 b.y. at the eastern end to 1.2 b.y. near... the western...this systematic variation of apparent ages may be related to metamorphic effects caused by Keweenawan diabase sills....". Thus there is no unequivocal depositional age for these rocks.

Descriptive Stratigraphy

Gunflint Iron-formation

The Gunflint Iron-formation crops out in a northeasterly-trending belt that extends from Thunder Bay on Lake Superior to a point in Minnesota 12 miles west of Gunflint Lake where it is truncated by the Duluth Complex.

In Canada the iron-formation is only slightly, if at all, metamorphosed and consists of silica, much of which is chalcedonic, iron oxides, iron carbonates, and greenalite. Consequently, Goodwin (1956) recognized six sedimentary facies which serve to subdivide the iron-formation into four members. In Minnesota the original nature of the iron-formation is obscured by metamorphism by the Duluth Complex. The carbonates and greenalite are replaced by amphibole, pyroxene, fayalite, and locally by garnet and other silicates. In addition, many of the small-scale sedimentary textures have been almost completely destroyed; however larger structures, and especially complex bedding relationships are still preserved. Therefore the four-fold nomenclatural scheme — originally outlined in the Biwabik Iron-formation (Wolff, 1917) and later extended to the Gunflint Iron-formation (Broderick, 1920) — was retained by Morey and others (1969) because it emphasizes various bedding aspects. Accordingly, four members are recognized; Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty. Although the boundaries of these members do not coincide with those recognized by Goodwin (1956), the two schemes can be equated with only slight difficulty.

Lower Cherty Member: The Lower Cherty Member is thin, ranging in thickness from 15 to 45 feet. Feldspathic quartzite that contains granite and greenstone cobbles is present locally at the base of the formation; these beds are equivalent to Goodwin's basal conglomerate member. A persistent magnetite-rich, silicate-bearing unit five to 15 feet thick occurs within this member and serves as an excellent marker-horizon. Most commonly it lies directly upon basement rocks, but locally it overlies either the feldspathic quartzite or a chert-cemented conglomerate containing fragments of algal structures; it in turn is overlain by a massive, chert-rich, magnetite-poor unit about 15 feet thick.

Lower Slaty Member: This member is 80 to 95 feet thick. The lowermost, nearly magnetite-free 10 feet is a black, thin-bedded argillite composed dominantly of volcanically derived material. It is equivalent to the Intermediate slate on the Mesabi range and to the lower tuffaceous shale facies in Canada. The beds immediately above the Intermediate slate are massive and cherty and resemble the upper part of the Lower Cherty Member. This unit passes abruptly upward into cherty silicate-bearing beds with sparse magnetite intercalated with a few thinly-laminated silicate-rich beds. The remaining 50 feet is a thin-bedded to laminated rock containing various silicates and from 20 to 35 percent magnetite. A few cherty-silicate beds, definitely subordinate in amount are intercalated in this interval.

Upper Cherty Member: There is a complete gradation between the Lower Slaty and Upper Cherty Members. The Upper Cherty Member, as presently defined, is approximately 50 feet thick. The lower part consists of irregularly bedded to lenticular cherty layers intercalated with thinly-laminated silicate-rich layers that increase in abundance upward. Thin irregular layers of magnetite are common in the cherty beds near the bottom of the member, but become less abundant upward. The top of the member—equivalent to Goodwin's upper algal chert facies—is characterized by several granular chert beds containing algal structures, conglomerate fragments, and abundant magnetite.

Upper Slaty Member: The Upper Slaty Member is approximately 150 feet thick. Thick lenticular chert beds with disseminated magnetite characterize the lower few tens of feet, but most of the member consists of a thin-bedded to laminated quartz-silicate rock interbedded with thinly laminated layers of graphitic argillite, and one to two inch thick beds of relatively pure chert. The upper 10 feet is nearly magnetite free and consists of limestone and chert interbedded with argillite.

Rove Formation

The Rove Formation gradationally overlies the Gunflint Iron-formation and is intruded by Logan Intrusive Rocks and truncated by the Duluth Complex. A detailed description of the formation is presented by Morey (1969). In the Long Island Lake, Gunflint Lake, Southlake, and Hungary Jack Lake quadrangles, the formation is characterized by intercalated black to grayish black, locally carbonaceous argillite, argillaceous siltstone and fine-grained graywacke. In general the silt and sandstone beds become coarse-grained, thicker, and more abundant upward in the formation. In addition, there are several lenses and irregular bodies of limestone, dolomite, and chert and a number of calcite-dolomite concretions of various shapes and sizes, similar to those described in the formation by Tanton (1931) and Moorhouse (1963) scattered near the base of the formation.

Morey (1969) has suggested that deposition started in a deep basin in which fine-grained sediment accumulated under reducing conditions. The siltstone and sandstone beds contain many primary sedimentary structures indicative of turbidite deposition. There is also evidence of an increase infrequency of this type of deposition upward in the section. The graywackes contain abundant framework grains of quartz, feldspar and "granitic" rock fragments indicative of a granitic source area. Sedimentary structures including cross-bedding and various kinds of sole marks indicate that sediment transport dominantly was from north to south. These observations and the graywacke mineralogy led Morey (1969) to conclude that the source area was the Lower Precambrian terrane now exposed north of the outcrop area of the Rove Formation.

Structure

The Animikie strata form a homocline that dips 10° - 15° SE except where intrusive bodies and secondary structures have distorted or disturbed the beds. For example, complex folding commonly occurs in narrow zones adjacent to many of the Logan Intrusive Rocks and is most likely related to the forceful emplacement of the sills into restricted space. There is a fairly regular increase in dip to as much as 60° near the Duluth Complex. However, this structure is most likely pre-Duluth Complex in age. Lack of marker beds in the Animikie strata makes recognition of faults difficult; however, a number of northwesterly- and northerly-trending faults have been mapped.

Most faults have displacements of less than 50 feet; however, the Lookout fault has a displacement in the iron-formation of at least 200 feet. All faults so far recognized displace Logan Intrusive rocks, but none extend into the Duluth Complex; thus movement apparently occurred in Middle Keweenawan time prior to emplacement of the Duluth Complex. The fault pattern is similar to that in Canada (Moorhouse, 1960; Goodwin, 1960) near what can be inferred to be the northern hinge of the Lake Superior syncline. This structure must have formed at least in part prior to emplacement of the Duluth Complex.

Movement on the Lookout fault during Keweenawan time duplicates the iron-formation west of the Gunflint Trail, and a northerly-trending segment of the fault separates the iron-formation into two structurally distinct terranes. East of the Gunflint Trail, the Animikie rocks dip gently southward; accordingly the outcrop area of the iron-formation is relatively wide and most of the apparent irregularities in the map pattern result from the super-position of a rugged topography on gently-dipping strata. The south side of the Lookout fault is upthrown, and the Animikie strata on this side dip steeply and thus form a narrow outcrop belt.

A number of smaller structures also can be recognized. Just east of the Gunflint Trail the iron-formation and the sills are folded into a southeasterly plunging anticline with a steeply dipping north limb and a gently dipping south limb. This structure which is obviously post-Logan in age has an anticlinal axis which projects into the trace of the Lookout Fault.

Metamorphism

In the Animikie rocks there is no textural or mineralogic evidence for a pervasive regional metamorphism beyond minor recrystallization of the clay-size detrital fraction. The obvious metamorphic effects in the Animikie strata are associated with the emplacement of the Duluth Complex and Logan Intrusive Rocks of Middle Keweenawan age.

The contact aureole of the Duluth Complex has not been studied in detail in the Gunflint Trail Area. Preliminary work in the Gunflint Iron-formation shows there are a number of metamorphic facies similar to those described from the Biwabik Iron-formation by French (1968) and Bonnichsen (1969). Unmetamorphosed iron-formation like that described by Goodwin (1956) is found in Minnesota only in a small area between Gunflint and North Lakes. There the iron-formation consists of chert, iron carbonates, greenalite, abundant amounts of finely disseminated hematite, and traces of magnetite. However, west of Gunflint Lake, the iron-formation has been metamorphosed and three metamorphic zones have been distinguished by changes in mineralogy along the strike of the formation toward the Duluth Complex.

Zone 1, or slightly metamorphosed iron-formation, occurs in the area immediately west of Gunflint Lake. It consists of quartz, iron carbonates, greenalite, minnesotaite, and stilpnomelane. Finely-divided hematite occurs in the east end of the zone, but disappears mid-way in it. Disseminated and interlocking grains of magnetite are abundant, especially as rims around granules. This part of the iron-formation is much like that described by French (1968) in "unmetamorphosed" Biwabik Iron-formation.

Zone 2, or moderately metamorphosed iron-formation, is about 1.2 miles wide and extends to within 0.3 miles of the Duluth Complex. Grunerite-cummingtonite, hornblende and actinolite, as well as quartz and magnetite characterize this zone. As in zone 1, much of the magnetite is between 0.002 and 0.02 mm in diameter; a size-range similar to that observed in various other Lake Superior iron-formations. Small-scale pre-metamorphic sedimentary structures such as granules and oolites are partly destroyed, but larger-scale primary structures and bedding features are little affected.

Zone 3, or highly metamorphosed iron-formation, occurs adjacent to the Duluth Complex and is characterized by a wholly metamorphic fabric. The rock is composed chiefly of quartz, magnetite, iron-rich pyroxenes, and fayalite. Very commonly, euhedral or subhedral grains of magnetite are poikilitically enclosed within large silicate grains; they are of essentially the same size as in the lower grade rocks. However a significant part of the magnetite is extensively recrystallized, and grains as much as a millimeter in diameter are concentrated along bedding planes. Actinolite is common in magnetite-rich layers, and both prograde and retrograde cummingtonite is abundantly present. In general this zone is very similar to that described in the Dunka River area on the Mesabi range by Bonnichsen (1969).

Preliminary work on the contact aureole of the Duluth Complex in the Rove Formation indicates a complex mixture of rock types suggesting partial melting, and mineral and textural variations due to original inhomogenities and degree of metamorphism. The metamorphosed rocks are commonly layered and have a granoblastic texture. Individual layers contain; 1) cordierite and hypersthene with minor biotite and ilmenite, 2) hypersthene, plagioclase, biotite, and ilmenite, 3) augite, plagioclase + minor olivine, biotite, and ilmenite, or 4) hypersthene, plagioclase, K-feldspar, and biotite. Calcareous beds near the contact have a skarn-mineralogy consisting of wollastonite, diopside, tremolite, and grossularite garnet. Away from the contact - and from place to place

this distance varies from several tens to several hundreds of feet — most pelitic rocks are rich in biotite, and cordierite may or may not be present.

The Logan Intrusive Rocks also have metamorphosed the Gunflint and Rove Formations. The width of the metamorphic aureoles are related to sill thicknesses and range from less than one foot to more than 30 feet. In the Gunflint Iron-formation it is difficult to recognize unique metamorphic assemblages adjacent to sills. In zone 2, mineral assemblages characteristic of zone 3 occurs in aureoles around the sills. Similarly in zone 1, minnesotaite, which is characteristic of zone 2 metamorphism is found next to the sills.

In the Rove Formation thick sills have assemblages that can be assigned to the pyroxene-hornfels facies whereas thinner sills have assemblages characteristic of the hornblende-hornfels facies. Locally andalusite (Morey, 1969) and chloritoid (Grant, 1971) have been identified in certain beds.

UPPER PRECAMBRIAN

Introduction

In northeastern Minnesota two units are recognized in the Upper Precambrian: the Lower Keweenaw represented by the Puckwunge Formation and the Middle Keweenaw which consists of the Logan Intrusive Rocks, the North Shore Volcanic Group (Green, this volume), and the Duluth Complex.

Puckwunge Formation

The Puckwunge Formation consists of conglomerate and sandstone which unconformably overlie the Rove Formation and underlie the North Shore Volcanic Group. The type locality was described by N. H. Winchell (1897) on the Stump River in Sec. 25, T. 64 N., R. 3 E. where about 18 feet of section is exposed. Exposures of similar lithology are found in the Grand Portage area (Grout and others, 1959).

If these isolated exposures are equivalent to the Sibley Series in Canada (Tanton, 1931) they represent a period of sedimentation around 1376 ± 36 m.y. ago (Franklin and Kustra, 1970) followed by possible uplift and erosion prior to the onset of volcanic activity in Middle Keweenaw time.

Logan Intrusive Rocks

The name Logan sills was applied to tabular, diabase intrusive rocks in the Rove Formation (Lawson, 1893, p. 48). Similar intrusive rocks in Animikie and Lower Keweenaw formations are currently referred to as Logan Intrusive Rocks. As now defined, they include sills and dikes of diabasic gabbro which range in measured age from 1300 m.y. (Hanson and Malhotra, 1971) to 963 m.y. (Franklin, cited in Wanless and others, 1970, p. 57). Thus the Logan Intrusive Rocks,

units of the Duluth Complex, and the North Shore Volcanic Group may have overlapping time-stratigraphic relationships.

In Cook County the predominant exposed volume of the Logan rocks is sill-like, and the present sawtooth topography results from the differential erosion of the inclined sills and Rove Formation. The sills range in thickness from a few feet to over a thousand feet and thick sills can be mapped along strike for several miles. In three dimensions they form a boxwork pattern, their emplacement having been controlled by bedding, joint and possibly fault plane connections between sills but in the Grand Portage in northeastern Cook County area there are major northwest-trending dikes comparable in size and extent to the sills (Grout and Schwartz, 1933, p. 36-59).

Early detailed studies of the petrogenesis of the Logan Intrusive Rocks were primarily restricted to the sill on Pigeon Point (Bayley, 1893; Daly, 1917; Grout and Schwartz, 1933). Reinvestigation of these rocks is currently in progress and the following generalized description of textures, and mineralogy is based on the unpublished work of J. A. Grant, E. Mathez, G. B. Morey, M. Mudrey and P. Weiblen.

Texture: Rock types include aphyric chilled margins, fine- to medium-grained diabase with ophitic clinopyroxene enclosing plagioclase, porphyritic diabase with plagioclase phenocrysts, plagioclase cumulates, and granophyre. Chilled margins form sharp contacts with country rocks. Diabase grades from fine to medium toward the center of sills. Clinopyroxene remains ophitic even though the grain size changes and enclosed plagioclase crystals rarely exceed 5 mm in length. Plagioclase phenocrysts however are as much as 10 cms long in thick sills. Diabasic rocks with plagioclase phenocrysts grade into accumulations of essentially coarse-grained plagioclase. Such accumulations are found in the upper parts of some large sills and their origin has been attributed to the floating of plagioclase (Grout and Schwartz, 1933, p. 50).

Mineralogy: Minor olivine is found in the lower part of some sills. Plagioclase both as phenocrysts and as small grains enclosed in pyroxene is generally highly sericitized. Clinopyroxene is altered to amphibole within single oikocrysts. The remnant pyroxene varies in composition from pigeonite through augite and has a mottled birefringence which resembles that of the complex lunar pyroxenes. Ilmenite and minor magnetite appear at distinct horizons in some sills. The ilmenite is commonly skeletal. Minor interstitial quartz is characteristic of much of the diabase. Biotite is ubiquitous in the diabase and texturally appears to be of both igneous and metamorphic origin. Granophyric intergrowths are common in the upper part of the diabase where they impart a pink mottling which can be recognized in hand specimen. Separate occurrences of granophyre in mappable units are rare, except for the Pigeon Point sill (Mudrey and Weiblen, 1971).

Structure: In plan view the Duluth Complex truncates the various Logan sills along strike at a low angle (Fig. 3). Where exposed, the base of the Duluth Complex dips gently southward, whereas both the Logan sills and country rocks may dip as much as 60° to the south. Drilling in the vicinity of the contact indicates that the base of the Complex steepens to as much as 60° and levels off to about 30° 1 km. down-dip (Johnson, 1970, p. 82). This structural configuration is much like that described by Mancuso and Dolence (1970) in the East Mesabi district. They suggested that the emplacement of the Duluth Complex in that area was in part controlled by a pre-Complex structure.

Mineralization: Minor hydrothermal mineralization is found within the Logan Intrusive Rocks. The mineralization is probably similar to the Thunder Bay silver deposits, but no commercially important occurrences have been found in Minnesota. On Susie Island where a shaft was sunk along a fracture zone filled with calcite-barite and lesser amounts of quartz, bornite, chalcocite, chalcopyrite, pyrite, covellite and malacite, ore was recovered which contained 6.22 percent copper and trace amounts of silver (Grout and Schwartz, 1933, p. 64). At Loon Lake, R. Blankenburg has investigated a prospect in a quartz-calcite vein that contains arsenopyrite with minor cobalt (Johnson, 1968).

Duluth Complex

The Duluth Complex consists of a variety of anorthositic, troctolitic, granodioritic, and granophyric rocks which crop out in an arcuate belt from Duluth to east of the Gunflint Trail (Fig. 1). A brief review of the early literature and recent work up to 1969 is given by Phinney (1969). The results of subsequent mapping and study of the northeastern limb of the Complex are presented by Nathan (1969), Morey and others (1969), Johnson (1970), and Davidson (1970).

Nathan (1969) mapped a layered series of sheet-like intrusions across the Gunflint, South Lake and Hungry Jack Lake quadrangles (Fig. 2). To the west, in the Long Island quadrangle, Nathan's layered series is truncated by the Tuscarora Intrusion and other associated rocks.

Layered Series of Nathan

The layered series extends from the east edge of the Hungry Jack Lake quadrangle across the South Lake quadrangle and into the Gunflint Lake quadrangle where it is truncated by the Tuscarora Intrusion. This truncation is marked by an irregular northwest trending scarp (Fig. 3). For the most part, the series consists of a sequence of conformable sheets having a regional dip of $15-25^\circ$ to the south. The sheets thicken to the west and are locally interrupted by minor crosscutting stock- and dike-like bodies. On the east side of the Hungry Jack Lake quadrangle a northwest trending fault offsets the series with an unknown amount of displacement, but as much as 140 feet of vertical displacement of the northeast side is inferred (Fig. 3).

The series consists of troctolitic, gabbroic, and associated felsic rocks. Several of the major units represent unique occurrences in the Duluth Complex of oxide-rich gabbros and two-pyroxene gabbros. For the most part, fine-grained rocks are not chilled margins but occur principally as separate intrusions or inclusions of mappable size. Planar orientation of minerals is common, indicating flow or crystal setting. Differentiation resulting from these processes can be demonstrated within some units, however the layered series does not form a regular stratigraphic sequence. Intrusive relationships for 27 different units were established using cross-cutting structures, fine-grained margins, inclusions and thermal effects, the latter being principally a development of dark clouded plagioclase near intrusive contacts, Nathan (1969, p. 99). On the basis of field relationships, mineralogy, and composition, Nathan concluded the 27 units could be combined into eight cogenetic groups.

Detailed rock descriptions and interpretations are given by Nathan (1969, p. 38-185) and are summarized here using his nomenclature. The descriptive rock names have several textural prefixes that characterize the primary mineral assemblages. A size classification for these rocks, based on visually-estimated mean grain diameters, is: >10 mm, very coarse-grained; 4-10 mm, coarse-grained; 1-4 mm, medium-grained; 1/2-1 mm, fine-grained; <1/2 mm, very fine-grained. Four basic fabrics are recognized. A "granular" rock has only equidimensional minerals. If elongate grains are present and are randomly oriented, the rock is "decussate," if the grains define a plane, the rock is "foliated," and if the grains are aligned, the rock is "lineated." All rocks are named by the characterizing primary mineral assemblage, in order of increasing abundance; the primary mineral assemblage refers to early crystallizing phases in contrast to late interstitial phases. Modes are indicated by subscripts. If a significant part of the primary assemblage was transported in the magma the rock is referred to as an allocrystallate, a cumulate being a special case in which gravity settling has occurred. Rocks formed by crystallization in place are called autocrystallates. Subscripts are used to indicate modal composition. Thus a descriptive rock name for a troctolite formed by gravity settling could be a fine-grained foliated olivine₂₀-plagioclase₇₀ cumulate with minor interstitial augite₅ and oxides₅.

<u>Group 1</u> da db dc	The oldest unit (da) in the layered series now appears in the upper part of the section as dilated septa as much as 200 feet thick. It is a fine-grained foliated olivine₂₅-plagioclase₆₃ cumulate with minor pigeonite₉ and augite₃, which are also cumulus in the middle of the unit. This unit grades into a 1,000 foot-thick sheet of medium-grained, foliated augite₁₅-pigeonite₂₆-plagioclase₅₉ cumulate (db). A very fine-grained olivine₁₀-augite₂₇-plagioclase₆₁ rock (dc) occurs as masses of various shapes and sizes near the base of the layered series. Nathan speculated that it might represent a chilled margin of the Group 1 intrusive rocks.
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Group 2

- dg This group comprises the major oxide-rich part of the layered series. The main unit (dg) is a coarse-grained foliated ilmenite-titanomagnetite₁₁-augite₁₉-olivine₁₄-plagioclase₅₆ cumulate. Within this unit the following sequence of crystallization appears: (1) ilmenite-olivine-plagioclase; (2) ilmenite-titanomagnetite-olivine-augite-plagioclase; and finally (3) apatite-pigeonite-titanomagnetite-ilmenite-olivine-augite-plagioclase.
- dd Very fine-grained foliated olivine-oxide-augite-plagioclase
- de (dd) and fine-grained granulo-decussate augite - plagioclase (de) rocks occur in unit dg as inclusions as much as 400 feet across. A number of mappable units are gradational with unit dg: (1) at the base of the complex, a fine- to coarse-grained decussate augite-olivine-plagioclase autocrystallate
- df (df) grades into rocks having a texture and mineralogy similar to that in unit dg, and may be the base of the cumulates of unit dg. Unit df shows sulfide mineralization similar to unit ttf of the Tuscarora Intrusion (Johnson, 1970, p. 68). (2) A fine-grained, olivine₂₀-plagioclase₆₆-olivine₂₀ cumulate with minor augite₅-oxide₄-pigeonite₄-apatite₁ occurs as a thin sheet within unit dg. (3) A fine-grained, decussate, oxide₂₃-augite₂₈-plagioclase₄₅ autocrystallate containing minor₂₃ olivine₂ and apatite₂ intrudes unit dg and is presumed to be a late differentiate (di). (4) Unit dg grades upward into 100-200 foot-thick discontinuous sheets of coarse-grained, foliated pigeonite₄-titanomagnetite₄-augite₆-plagioclase₈₃ cumulates containing minor potassium feldspar₂ and quartz₁ (dj). A fine-grained granular plagioclase, quartz, orthoclase rock (dk) occurs as dikes cutting other Group 2 rocks.
- di
- dj
- dk

Group 3

- dm Unit dm, the upper part of the layered series, is a 2,000 foot-thick sheet of coarse-grained decussate pigeonite₁₃-augite₂₄-plagioclase₅₉ autocrystallates and cumulates containing minor oxides₂, quartz₂ and potassium feldspar₁. This unit is thought to have been emplaced along foliation planes and thus to have dilated the earlier units. Variations in grain size and modal mineralogy suggest that this unit may be a multiple intrusion. A related intrusion may be
- dl unit dl, a medium-grained decussate pigeonite₁₇-augite₂₀-plagioclase₆₀ rock containing minor oxide, quartz, and potassium feldspar, which occurs as a small stock about 1-1/2 miles across in the central part of the Hungry Jack quadrangle. Another related intrusive unit is a fine-grained granular oxide₁₉-plagioclase₄₁-augite₄₀ rock (dn) which occurs as a sheet 6 feet thick and 4 miles long in the northern part of the South Lake quadrangle. Felsic dikes which intrude unit dm were given a separate designation (do) and may represent a late-stage differentiate of unit dj or partially fused country rock (Nathan, p. 115).
- dn
- do

Group 4
 dp The next intrusive unit (dp) occurs as a concordant sheet as much as 1,200 feet thick between units dg and db. It is a fine-grained foliated augite₃₂-plagioclase₅₈ cumulate with olivine₃-hypersthene₇ and trace amounts of oxides. Plagioclase and augite occur in a granular fabric, hypersthene as oikocrysts, and olivine as phenocrysts. The absence of late-stage interstitial material suggests the unit formed by flow or crystal settling with exchange between the magma and the inner cumulus melt. Near the top of unit dp, a 100-foot-thick sheet of medium-grained foliated olivine₁₇-plagioclase₈₃ cumulate (dq) is gradational with unit dp.

Group 5
 dr In the southwestern part of the Gunflint Lake quadrangle a heterogeneous assortment of pyroxene-plagioclase and olivine-plagioclase rocks possibly related to unit tta of the Tuscarora Intrusion truncate the layered series. A typical example is a medium-grained decussate tironals₅-olivine₅-augite₁₅-plagioclase₇₅ autocrystallate (dr). Near the base of the layered series a medium-grained foliated augite₁₇-plagioclase₇₇ rock with minor oxide₃-pigeonite₂ and olivine (ds) is intruded as a sheet 300 feet thick between units df and dg. Unit ds is highly altered with montmorillonite after plagioclase, and amphibole and chlorite after pyroxene. Locally chalcopyrite and bornite occur within interstitial, altered pyroxene.

Group 6
 dt A number of oxide-rich stock- and dike-like bodies 3/4 miles across occur near the base of the Complex in the South Lake quadrangle. Nathan recognized four varieties: (1) medium-grained granular olivine₁₆-oxide₇₃ rocks with a minor amount of plagioclase and augite (dt). The ilmenite and titanomagnetite occur as primary phases; the latter generally has exsolved coarse ilmenite lamellae with intra-titanomagnetite granules which have in turn exsolved to a fine reticulate intergrowth of magnetite and hercynite. (2) On Little Iron Lake in the South Lake quadrangle a medium-grained granular plagioclase₂₁-oxide₂₄-olivine₄₉ (du) rock having minor hypersthene and augite forms a 1/2 mile long composite sheet within unit dt. (3) A coarse-grained granular plagioclase₈-oxide₂₃-pigeonite₂₄-augite₄₄ rock containing minor olivine occurs as small discordant masses in the South Lake quadrangle. (4) Two occurrences of a coarse-grained decussate oxide₁₀-augite₃₁-plagioclase₅₅ autocrystallate (dw) were mapped within unit dg. This unit exhibits an amphibole alteration similar to that in unit ds, but is considered to be part of group 5 rocks because of its large oxide content.

Group 7 Several fine-grained decussate rocks occur as discontinuous thin sheets along the base of the complex and as small stocks and dikes higher in the section. They may represent either fused fractions of country rock or contaminated melts, but all are thought to be intrusive. They consist of: (1) fine-grained decussate oxide₇-augite₂₂-plagioclase₆₆ rock having minor olivine₂-quartz₂ and potassium₁ feldspar (dx); (2) fine-grained decussate oxide₅-hypersthene₁₁-augite₃₁-plagioclase₅₅ autocrystallite (dy); and (3) fine-grained augite₃-oxide₉ decussate quartz₁₀-orthoclase₁₅-hornblende₂₉-plagioclase₃₄ rock (dz).

Group 8 The youngest intrusive unit within the layered series occurs as dikes and stocks as much as 1-1/2 miles across in the Hungary Jack Lake quadrangle. This unit, a medium-grained granular quartz₁₈-alkali feldspar₇₇ rock with minor augite₃ and oxide₂ (daa), truncates unit dm. Across an interval over a mile wide at the east end of unit dm, there is a progressive increase in the amount of late stage interstitial material that has a composition similar to unit daa. This unit (dmaa) might be a late stage differentiate of dm. Nathan found however that unit dx has been intruded and altered by daa. Therefore, it is presumed that dm was cold when unit daa was intruded and that the gradational zone represents melt from daa that was introduced into unit dm.

Tuscarora Intrusion and Associated Rocks

In the Long Island quadrangle (Fig. 2) a sequence of rock types common to other parts of the Duluth Complex appear in the following succession away from the base: (1) a fine-grained poikilitic augite gabbro (tp), (2) a fine-grained granoblastic gabbro (hornfels) (th), (3) a fine- to medium-grained troctolite (ttf-ttm), (4) interlayered troctolite and poikilitic gabbro (tta), (5) anorthositic gabbro (ag), (6) ferrograndiorite (tg), (7) granophyre (gr), and (7) metamorphosed flows (kmv). Although the outcrop pattern suggests a simple differentiated layered sequence, the stratigraphic position of units tp, ag, tg and gr have not been unequivocally established. However, units ttf, ttm, and tta are clearly parts of a separate troctolite intrusion that truncates part of Nathan's layered series (Fig. 3).

Units ttm, ttf, and tta: The main unit of the Tuscarora Intrusion is a medium-grained troctolite (ttm, Fig. 2), consisting of 65-70 percent cumulus plagioclase (An₅₅₋₆₀), and 10-15 percent cumulus olivine (Fo₅₀). Relative amounts of poikilitic augite and iron-titanium oxides varies locally. Orthopyroxene mantles olivine and occurs in symplectic intergrowth with plagioclase. Biotite is associated with the iron-titanium oxides. Planar orientation of plagioclase and modal-mineral layering are locally well-developed and mutually concordant.

The troctolite grades into an upper unit which consists of interlayered poikilitic augite gabbro and troctolite (Fig. 3). The poikilitic augite consists of about 70 percent plagioclase (An_{50-60}), 15-20 percent augite, 5-10 percent ilmenite and is medium- to coarse-grained with well developed augite orthocrysts as much as 1-1/2" across. The troctolite within the layered interval is similar to that in unit ttm. Contacts between layers are generally sharp and in general conformable with layering in the troctolite. Interlayering occurs on a scale of several inches to several feet, and is undulatory with wave lengths of ten to twenty feet and amplitudes of two to three feet, but the gross structure is nearly flat-lying.

Unit ttp: A belt of fine-grained rocks occur beneath unit ttf. It consists of fine- to medium-grained augite troctolite with 60-70 percent cumulus plagioclase (An_{50}), 5-10 percent cumulus olivine (Fe_{35}), 15-20 percent poikilitic augite, 5-10 percent iron-titanium oxides, and minor orthopyroxene-plagioclase simplectite. As yet the upper contact of this unit has not been observed and it is not clear from outcrop data if it is a separate intrusion or the basal unit of the overlying rocks. Johnson (1970, p. 76) concluded from drill core data that it is a separate intrusion.

Unit th: Several areas of fine-grained, granoblastic gabbro consisting of 50 to 60 percent short tabular plagioclase, 30 to 40 percent rounded augite, minor subhedral iron-titanium oxides, olivine, and blades of biotite are exposed on topographic highs. These rocks may be a remnant capping over the troctolite; however there is no noticeable chilling of the troctolite next to the hornfels and they more likely represent large inclusions.

Unit ag: A distinct break in plagioclase content separates units tta and ag. Unit ag - an anorthositic gabbro - contains 75 to 85 percent plagioclase An_{55-60} (in contrast to the 50 to 70 percent of unit tta). Plagioclase is the only cumulus phase, and interstitial minerals, occurring in various proportions are augite, olivine, and iron oxides in a poikilitic texture. Orthopyroxene occurs in simplectic intergrowth with late-stage plagioclase. Biotite is associated with the iron-titanium oxides. Planar orientation of plagioclase is developed locally. At the top of unit ag, quartz and potassium feldspar occur interstitially.

The flat-lying outcrop pattern of the ferrogranodiorite (tg) and granophyre (gr) is concordant with the structure within the troctolite (ttm) and the anorthositic gabbro could be just another part of the layered intrusion. However some field evidence contradicts this interpretation. Hornfels inclusions and sulfide mineralization are found in unit tta at several localities along the contact with unit ag. Thus the troctolite may be intrusive into the anorthositic gabbro as in the Gabbro Lake quadrangle (Green and others, 1966). Phinney (1969) has extended the older anorthositic gabbro from the Gabbro Lake quadrangle eastward and this extension projects toward unit ag. Thus unit ag may be a thin wedge of an areally extensive older anorthositic gabbro. In this case, units fg and gr could be either related to the troctolite and intruded into the anorthositic gabbro or a differentiated part of the anorthositic gabbro.

Unit fg: This unit is restricted to a topographically high area in the southwest corner of the Long Island Lake quadrangle (Fig. 3). It is a medium-grained ferrogranodiorite which contains 50 to 60 percent cumulus plagioclase, 10 to 15 percent amphibole, minor clinopyroxene, and varying amounts of quartz, potassium feldspar, and magnetite. Contacts with the underlying anorthositic gabbro and overlying granophyre are gradational over tens of feet. The former could represent replacement by intrusive ferrogranodiorite or differentiation within the anorthositic gabbro. Further study is needed to clarify the stratigraphic relationships.

Unit gr: The ferrogranodiorite grades into and is cut by fine- to medium-grained granophyre. It consists of quartz, plagioclase, potassium feldspar and magnetite. The texture ranges from granophyric to granitoid.

Unit kmv: The granophyre intrudes black fine-grained meta-volcanic rocks which are interpreted to be remnants of Middle Keweenawan flows. The groundmass is highly altered. Acicular blades of ilmenite are common and plagioclase phenocrysts are clouded similar to intruded rocks in the layered series.

Mineralization: Two types of mineralization are found in the Duluth Complex in this area: (1) low grade copper-nickel concentrations are associated with the basal rocks of the Tuscarora Intrusion and several of the layered series intrusions (Johnson, 1970), (2) Ilmenite- and titanomagnetite-rich rocks occur in several units of Nathan's layered series.

With regard to the mineralization, the unpublished Ph.D. thesis of Johnson (1970) warrants special mention. The thesis summarizes the results of an exploration program conducted by the Cleveland-Cliffs Iron Company and the Amerada-Hess Corporation Company from 1966 to 1969. This program assessed the economic potential of the base of the Duluth Complex in a 38 km corridor along the Gunflint Trail adjacent to the Boundary Waters Canoe Area. The drilling program (10 holes) provides an unique opportunity to assess the effects of drilling on the area in comparison with other activities such as logging and recreation. More importantly the release of geophysical, drill core, and assay data, along with Johnson's study represents a major contribution by a mining company to the concern for the environment of the area. The correlation of geophysical and drill core data, discussed below, makes possible a more accurate evaluation of mineral resources in adjacent areas and in other areas of similar geology using less expensive and disruptive preliminary investigations.

Copper-Nickel Mineralization: Discontinuous areas of gossan and visible sulfide mineralization within unit ttf have been mapped across the Long Island quadrangle. Similar isolated exposures have been found in unit tta at the contact with anorthositic gabbro. The sulfide assemblage, consisting of chalcopyrite, pyrrhotite, and minor pentlandite occurs interstitially to plagioclase and olivine. Because of the smaller grain size of the troctolite a distinct interstitial texture, like that found in the sulfide mineralization in the Kawishiwi area in the Gabbro Lake quadrangle, is not apparent in hand specimen.

Drilling across the quadrangle (Johnson, 1969) has indicated a tabular, possibly continuous volume of low grade ore (0.3% combined copper-nickel) about 50 feet thick in the unit ttf. A thinner 10-20 foot-thick zone, 50-100 feet above the lower mineralized zone, has a higher combined copper-nickel content that approaches one percent (Johnson, p. 84). The mineralization can be correlated with a detectable resistivity anomaly on the order of 700×10^3 ohmcentimeters in the troctolite (ttf, ttm).

Titanium Mineralization: The primary titanium oxide phases are ilmenite solid solution (Fe_2O_3 - MgTiO_3 - FeTiO_3) and titanomagnetite (Fe_3O_4 - Fe_2TiO_4). Subsolidus exsolution has resulted in the complex intergrowths described above. Johnson (1970, p. 87) estimates that Ti recovered from ilmenite in unit ttf in the Tuscarora Intrusion could add \$1.50 per ton to sulfide ore from this unit.

The largest titanium concentrations however are in units dt and du at Little Iron Lake in the Gunflint Lake quadrangle and other isolated exposures in the South Lake quadrangle. Unfortunately, most of these occurrences at the surface do not exceed about 35 feet in maximum dimension.

A large low-grade titanium resource also is contained within unit dg (Fig. 3). Oxide-rich layers as much as 5 feet thick are common, although individual layers seem too thin and discontinuous to be mined separately. Unit dg should be considered in its entirety for commercial evaluation with the potential of developing a very large tonnage of low-grade ore. The unit is very heterogeneous and field exposures are scarce and discontinuous, so only widespread systematic drilling will reveal which parts have the greatest promise.

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FIELD TRIP GUIDE TO THE PRECAMBRIAN ROCKS, NORTH
COOK COUNTY ALONG THE GUNFLINT TRAIL

Stop 1 End of Trail Campground — Main Phase of Saganaga Granite

The main phase of the Saganaga Granite at this stop is a medium-grained hornblende-"quartz-eye" tonalite having quartz₂₀-plagioclase (An₂₇)₆₀₋₇₀-hornblende₆-microcline₃₋₅ and accessory muscovite, biotite, chlorite, epidote, sphene, apatite, allanite and magnetite. The apparent lineation of the "quartz-eyes" is 25-30° ENE. This structure is parodied in the hornblende-biotite inclusions. These inch-sized inclusions are probably related to the greenstones to the south of Seagull Lake.

The bay leading north to Saganaga Lake was considered by Grout (1936) to be a shatter zone. It is here interpreted as a fault in the granite. At this stop, a minor secondary east-northeast trending foliation is marked by shears and epidote veinlets, and may be related to faulting.

Stop 2 Gunflint Trail near the Campground — Lamprophyre dike in Saganaga Granite

The lamprophyre dike at this stop is 50 feet wide, and can be traced to the north shore of Saganaga Lake where it is found to cut the northern boundary fault (Harris, 1968, p. 21). This observation sets a lower age limit for faulting and uplift to the west for the Saganaga Granite. Goldich and others (1961, p. 52) date the biotite (KA-70B) from a small island to the north at 1.75 b.y.

Sundeen (1936) reviewed the petrography of the lamprophyre dikes in the Saganaga Lake area and found biotite, hornblende, and pyroxene as the mafic phenocrysts in a groundmass of either plagioclase or "orthoclase." This dike contains plagioclase₅₀-pyroxene₁₅₋₂₀-pyroxene₁₅₋₂₀-biotite₅₋₁₀ and hornblende₅. Accessory minerals include quartz, apatite, magnetite, chlorite, carbonate, sphene, pyrite, zircon, serpentine, talc and perovskite.

Stop 3a Saganaga Granite — Border Phase

The strongly foliated hornblende diorite exposed at this stop is typical of the border phase of the Saganaga Granite. The foliation is defined by a layering characterized by various proportions of dark and light minerals; it is nearly vertical and strikes N70°W. Elongate hornblende needles within the foliation plane define an elongate lineation that plunges gently to the east.

A transition from the border to the main phase involving an increase in quartz — with the development of "quartz-eye" structure — and a decrease in hornblende can be seen in a number of outcrops on either side of the Gunflint Trail to the north of this stop.

Stop 3b Metabasalt and associated rocks

In the general vicinity of this stop, vaguely pillowed metabasalt and thin-bedded to laminated pyroclastic material typical of the mafic part of the volcanic succession are exposed. Layering is nearly vertical and strikes in a northwesterly direction. Fracture cleavage also is near vertical and strikes in a northeasterly direction parallel to the trace of the Lookout fault.

The mafic rocks are cut by conformable layers of fine-grained graphic feldspar granite. Locally a thin layer of iron-formation composed of magnetite and chert unconformably overlies the older rocks.

Iron-rich strata typical of the lower part of the Gunflint Iron-formation are exposed on the steep north-facing slope immediately to the south of these exposures.

Stop 4 Along Magnetic Rock Trail - metamorphosed Gunflint Iron-formation of Zone 2

Thin-bedded, fine-grained, chert-amphibole-magnetite-bearing strata assigned to the upper part of the Lower Slaty member are exposed along Magnetic Rock Trail at this locality. These exposures are near the transition between moderately and strongly metamorphosed iron-formation; small, poorly developed pyroxene porphyroblasts can be seen, especially in the more massive beds at the top of the member.

Along the power line trail to the south, the iron-formation is locally deformed with beds dipping northward at 15°.

Approximately 75 feet farther to the south a northwesterly-trending, medium-grained diabase sill cuts slaty iron-formation. Approximately 200 feet to the south the slaty beds again dip to the south and are interlayered with coarse-grained, magnetite-rich cherty beds. On the same knob, algal chert-bearing beds characteristic of the Upper Cherty Member also are exposed.

Stop 5 Along the Kekabeic Trail - Metamorphosed Gunflint Iron-formation at Zone 3.

The Kekabeic Trail more or less parallels the base of the Gunflint Iron-formation and the north-facing slope immediately south of the trail contains exposures of the Lower Slaty Member. The iron-formation everywhere in this area has been extensively metamorphosed and now consists of various assemblages of quartz-cummingtonite-grunerite-fayalite-magnetite and quartz-cummingtonite-grunerite-pyroxene-magnetite.

Test pits can be seen along the Trail. Most are in the lower magnetite-rich part of the Lower Cherty Member. Various sulfides, especially pyrrhotite, also are associated with the magnetite.

Stop 6 Along the Paulson Mine railcut — Basal Contact of the Duluth Complex

The Paulson Mine railcut exposes the base of the Duluth Complex from the Kekabeic Trail to the Tuscarora Lodge road, a distance of about 1-1/4 miles. Contacts between beds of the Upper Cherty Member of the Gunflint Iron-formation and fine-grained poikilitic augite troctolite, unit tp of the Duluth Complex, are exposed at the west end of the railcut. Also at the west end truncation of a thin sill of the Logan Intrusive Rocks can be seen. About half-way along the railcut, argillite and graywacke of the Rove Formation are in contact with the base of the Duluth Complex. The contact aureole here is narrow with no visible recrystallization of Rove Formation rocks except within a few feet of unit tp. This is inferred to be a reflection of the thickness of unit tp 100-1,000 feet. The dip of the Gunflint and Rove Formation varies from 15-60° to the south along this part of the contact.

Stop 7a Scenic overlook on the Gunflint Trail above Gunflint Lake — Copper-nickel mineralization at the base of the Tuscarora Intrusion

The base of unit ttf of the Tuscarora Intrusion is exposed on the northeast side of the Gunflint Trail at the overlook. The fine- to medium-grained troctolite shows no regular increase in grain size away from a contact with unit tp and the upper part of a Logan sill. Visible chalcopyrite, pyrrhotite, pentlandite occur interstitial to plagioclase and olivine in the troctolite. This is a typical example of the copper-nickel mineralization of unit ttf, which was found by Cleveland-Cliffs Iron Company (in five holes along the base of the Complex) to occur constantly in a 150 feet thick interval near the base of unit ttf. The combined nickel-copper content is about 0.3 percent in this interval. A slightly richer zone 10 to 20 feet thick was intercepted about 50-150 feet above the lower zone.

Stop 7b 2000 feet northeast of Stop 7a — Logan Intrusive Rocks and the Rove Formation

Thin bedded argillite is exposed on the north face of a ridge capped by diabase. The argillite is recrystallized to a biotite-bearing hornfels over an interval of a few inches at the contact. The diabase is typical of fine- to medium-grained diabase in thin sills and in the lower parts of thick sills.

Stop 8 Northwest arm of Poplar Lake on the Gunflint Trail

At this stop typical exposures and intrusive relationships of four of Nathan's units will be examined. On the north side of the unit df, a fine-grained decussate augite-olivine-plagioclase rock (troctolite) similar to unit ttf of the Tuscarora Intrusion intrudes unit dc, a very fine-grained granular olivine-augite-plagioclase rock (gabbro) which may represent a chilled margin of the oldest unit of the layered series (da). About 50 feet north of the Trail at the east end of the northwest arm of Poplar Lake, a small mass of unit dt, a medium-grained granular olivine oxide rock, occurs within unit dc. A small isolated exposure of unit ds with uncertain contact relationships occurs between units dc and df about 500 feet northwest of Poplar Lake and 400 feet north of the Gunflint Trail. South of the Gunflint Trail there are exposures of the large oxide-rich sheet unit dg (coarse-grained, foliated oxide, augite, olivine, plagioclase rock).

Stop 9 Gunflint Trail south of Bear Club Lake — Late granitic rocks of the Duluth Complex

Unit daa, a medium-grained granular quartz-feldspar rock, is exposed as a dike in unit dm on the north side of the Gunflint Trail. The main mass of daa occurs south of the Trail as a stock 1-1/2 miles across. Unit dm, a cumulate sheet of pigeonite-augite-plagioclase rock has visible interstitial quartz and alkali feldspar in an aureole as much as 1 mile wide around the stock of daa. This interstitial material is interpreted as replacement associated with the intrusion of unit daa.

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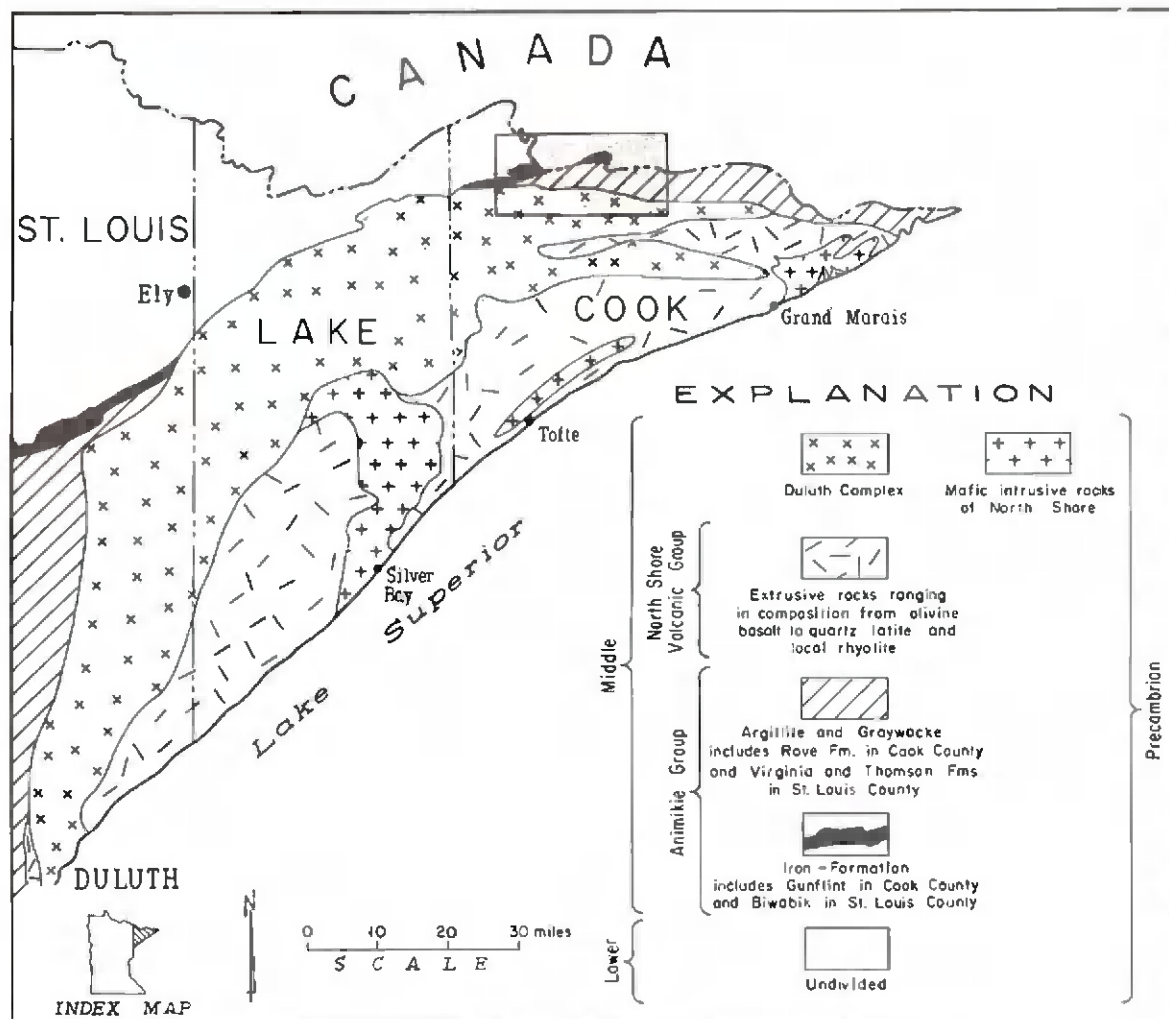


Figure 1 Map of northeastern Minnesota showing the geologic setting of Cook County and the location of Figure 2.

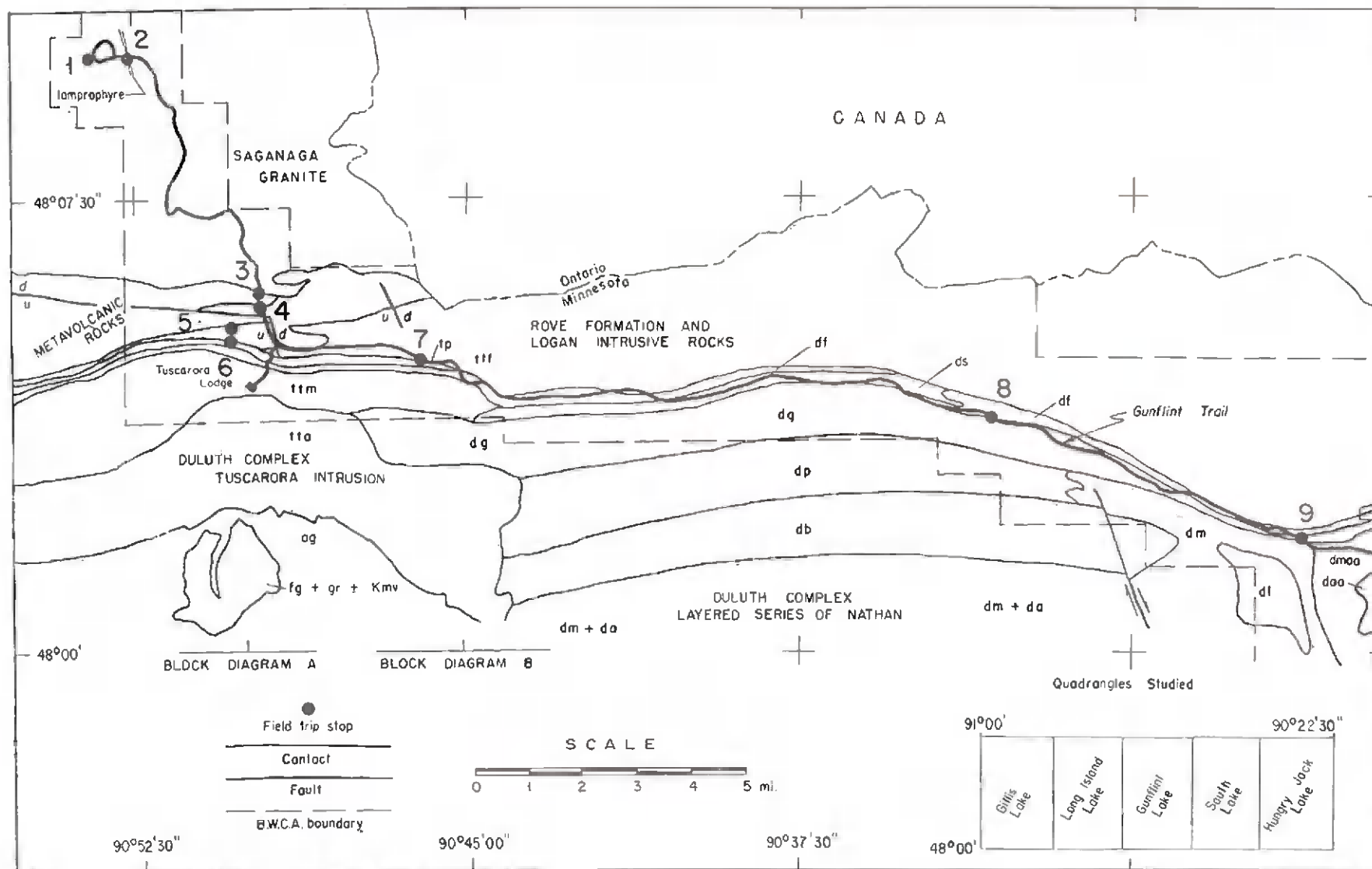


Figure 2 Generalized geologic map of part of northwestern Cook County. The Gunflint Iron-formation is stippled. Only the major units of the Layered Series of Nathan in the Duluth Complex are shown. The area designated df also includes dc, de, dk, ds, du, dy, dx, and dz; similarly ds includes dc, de, dg, dk, dt, du, dv, dw; dg includes dc, dd, dh, di, du, dv, dt, and dz; dp includes dg, dj, and dq; db includes da, dd, and dm; and dm includes da, dd, de, dn, do, and dx. (Nathan, 1969).

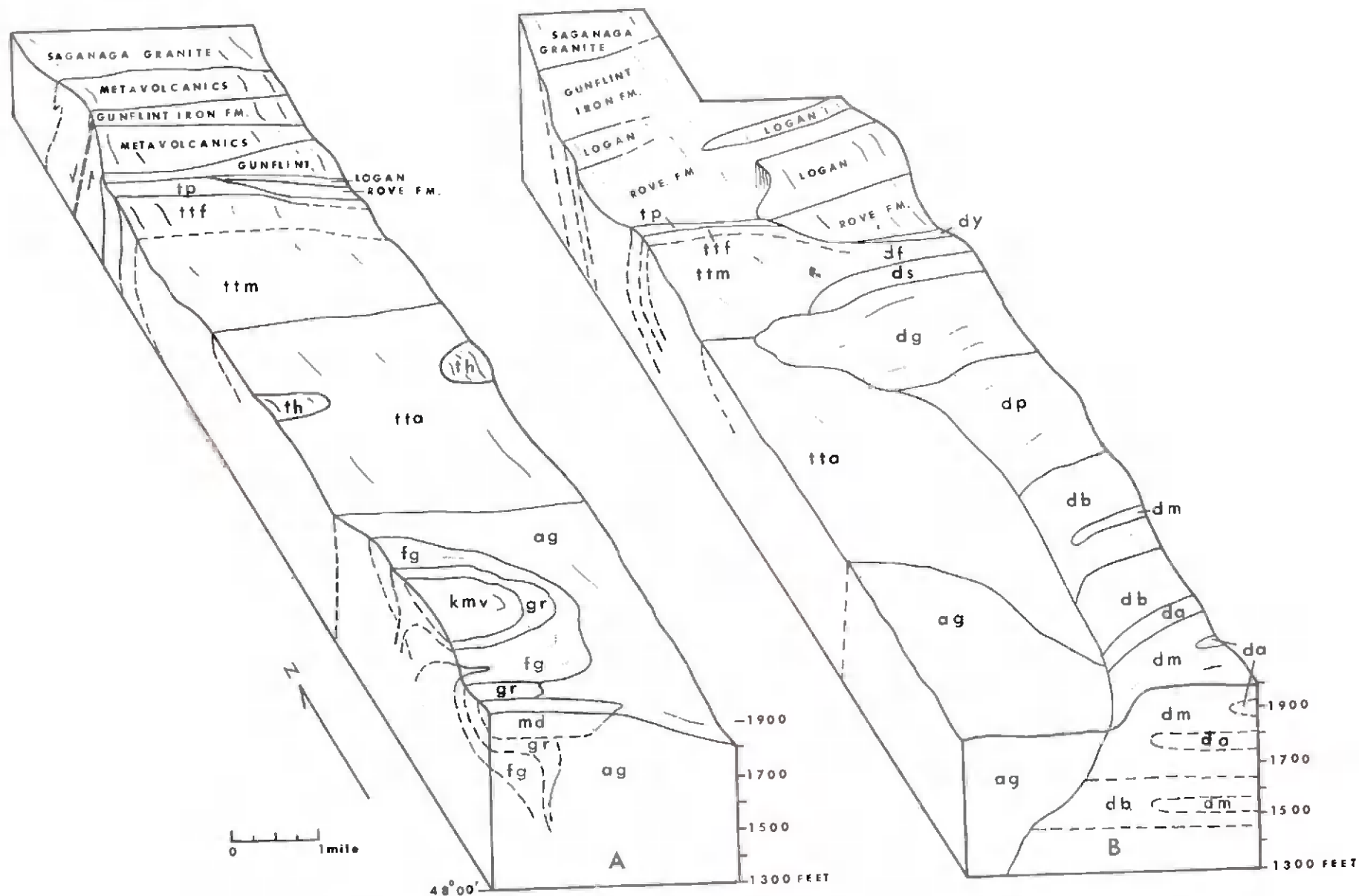


Figure 3 Block diagrams showing the inferred geologic relationships of rock units in the Long Island Lake and Gunflint Lake quadrangles (location of diagrams shown in Figure 2).

Mesabi Range Magnetite Taconite

May 8, 1971

by

R. W. Marsden
University of Minnesota, Duluth
Duluth, Minnesota

MESABI RANGE FIELD TRIP

INTRODUCTION

The Mesabi Range field trip starts at the Auburn Mine in Virginia, Minnesota and proceeds to the Erie Mine near Aurora, the Reserve Mine at Babbitt and ends at the Dunka Pit at the east end of the Mesabi Range near Birch Lake. The trip is designed to show the metamorphic changes in the Biwabik iron formation caused by the intrusion of the Duluth Complex. The trip plan is shown on the index map.

The Mesabi Range trip is made possible by the cooperation of the Minnesota Ore Operations, United States Steel Corporation, the Erie Mining Company and the Reserve Mining Company. Maps and other information were furnished by the mining companies. Leaders for each part of the trip are shown in the trip log.

Stop 1. AUBURN MINE

Leader: Wayne L. Plummer

The accompanying map, section and description of the stratigraphic sequence gives the geologic setting of the Auburn Mine. The unit numbers shown on the stratigraphic sequence are painted on the rock to aid recognition of the horizons. The upper part of the Pokegama quartzite and the Lower Cherty, Lower Slaty and 145 feet of the Upper Cherty members of the Biwabik formation are exposed. Oxidized and partly leached Biwabik formation is exposed on the west pit wall and the Upper Slaty member and leached Virginia formations are exposed in the slump structure at the north end of the pit.

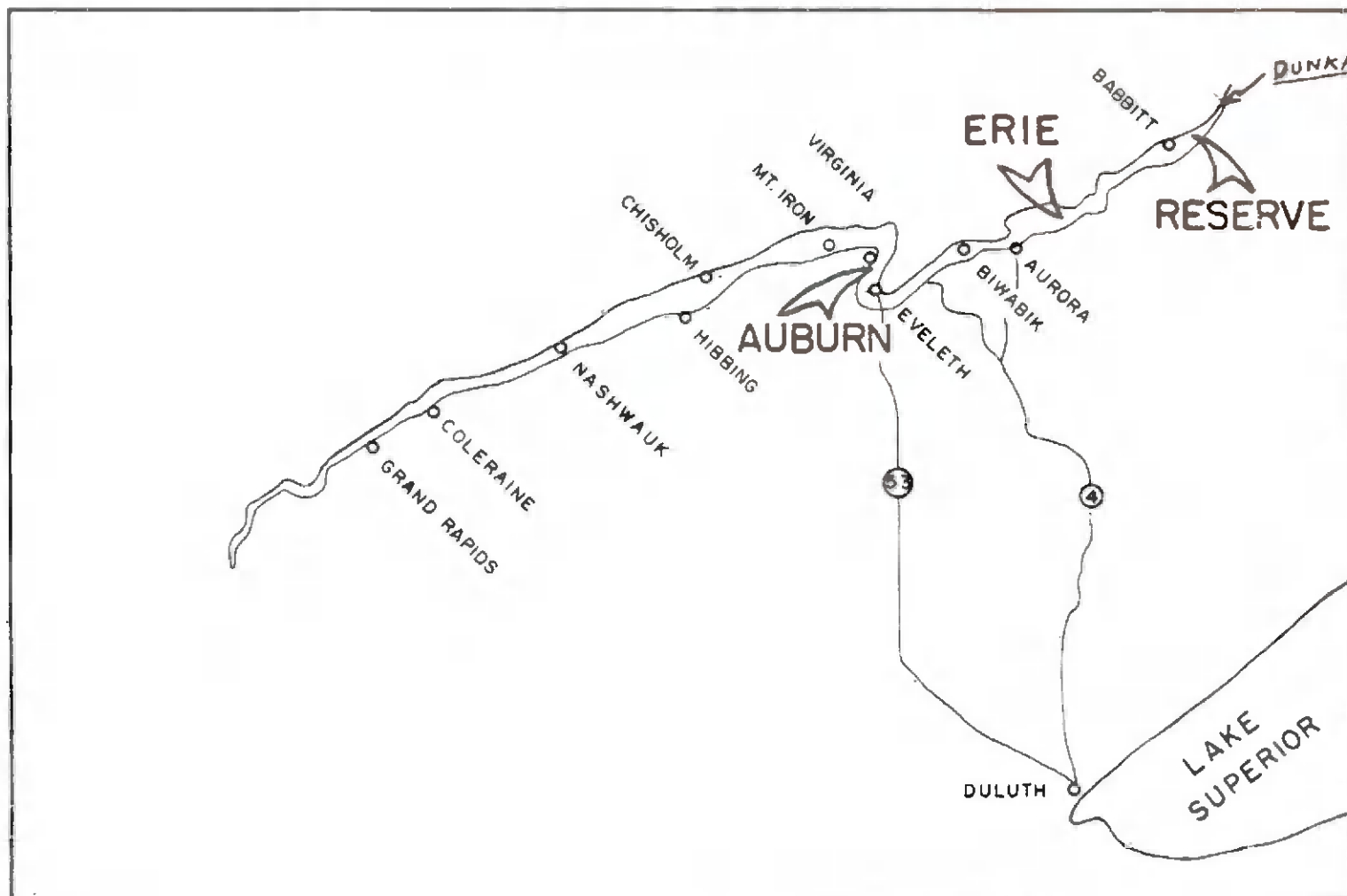
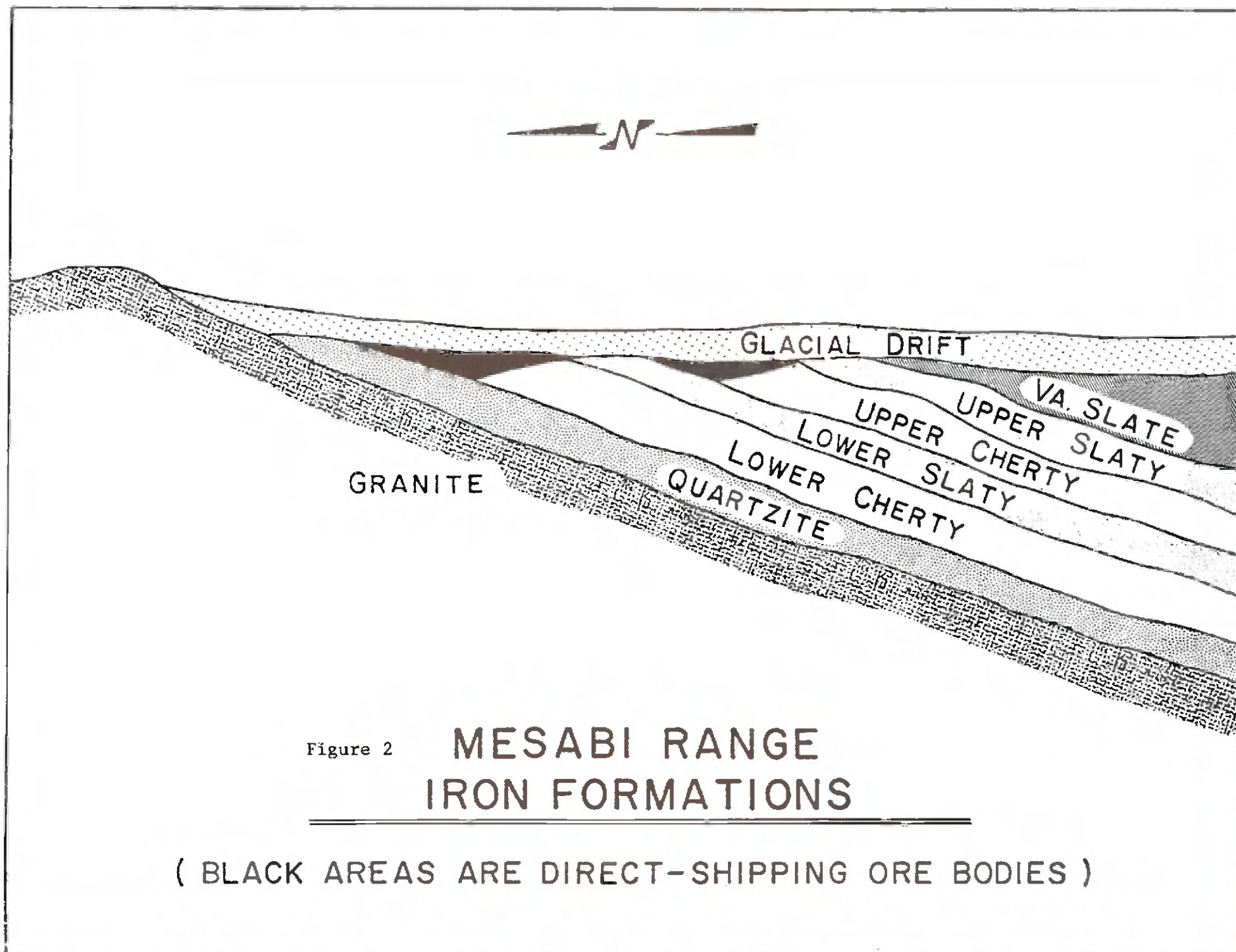


Figure 1 INDEX MAP
OF THE
MESABI DISTRICT, MINNESOTA



AUBURN MINE

The Auburn Mine is one of a group of open pits located near the city of Virginia, Minnesota. It was originally developed as an underground mine by the Minnesota Iron Company during the period from 1894-1902 and produced 2,143,000 tons of ore prior to closing in 1902 when ownership passed to the Oliver Iron Mining Company, a subsidiary of United States Steel Corporation. Reopened as an open pit by Oliver in 1951, the mine produced an additional 11,219,000 tons of ore by the end of 1969 when the mine became inactive because the remaining ore is under the approach tracks to the Virginia crushing and rescreening plant located just west of the mine. Most of the open pit ore was loaded by electric shovels into side dump cars and hauled to the plant by electric locomotives, but in the last few years, ore from the lower benches was loaded into trucks, hauled to a stockpile beside the track in the upper part of the pit and reloaded into railroad cars. The Auburn Mine and other former Oliver Iron Mining Company mines on the Mesabi Range are now operated by U. S. Steel Corporation, Minnesota Ore Operations.

The rocks exposed in the mine starting at the bottom are the Pokegama Quartzite and the lower three members of the Biwabik iron formation: Lower Cherty, Lower Slaty and part of the Upper Cherty. These dip from 5 degrees to 20 degrees to the northwest as the formation lies on the north side of the gently southwestward plunging Eveleth anticline and the center fold known as the Virginia Horn.

The Auburn ore body was formed in the Biwabik formation by removal of silica from iron bearing rock by leaching ground waters, leaving less soluble iron oxides. The ore body follows down the dip of the formation for about 3000 feet. Beginning as a small fissure scarcely 50 feet wide at the southwestern part of the mine, the ore body gradually widens toward the northwest into a larger trough with a maximum width of about 500 feet. In the vertical walled fissure at the southwestern end of the mine, the ore extends from slightly above the Quartzite (here reduced to a white sand) through 115 feet of the Lower Cherty member, whereas near the west end of the mine, the ore extends to a depth of about 260 feet from the surface to the Lower Cherty-Lower Slaty contact. Due to the leaching of silica, ore zones are commonly slumped into structures resembling synclinal folds. Where slumping occurs adjacent to taconite walls, slump faults may occur.

Glacial deposits consisting of reddish-gray-brown till containing numerous boulders of granite and greenstone covered the entire area to a depth of 10 to 35 feet.

An earth slide in the northwestern bank of the mine several years ago was stabilized with a rock fill which now covers much of previously exposed formation in this area.

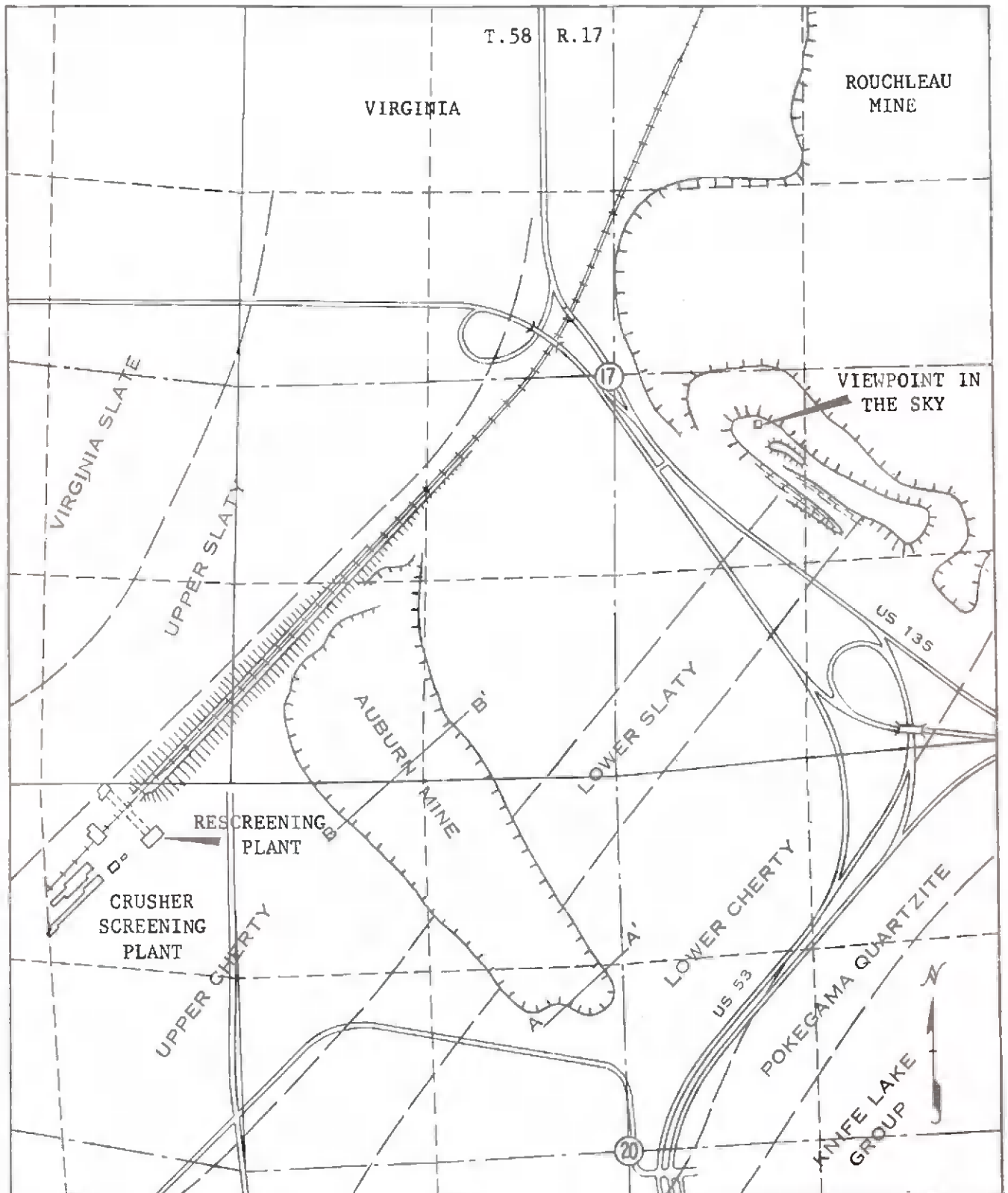


Figure 3 GEOLOGIC MAP OF AUBURN MINE AND VICINITY

Table 1

STRATIGRAPHIC SEQUENCE IN THE BIWABIK IRON FORMATION

AUBURN MINE

	Thickness in feet ¹
<u>UPPER CHERTY MEMBER</u>	
16. ² Jaspery, conglomeratic and algal chert (G and S submember I)	10 (est.)
Covered interval	10 (est.)
15. Nodular hematitic chert beds interbedded with laminated hematite-silicate-magnetite beds	48 +?
14. Laminated hematite-silicate-magnetite beds with subordinate jaspery chert beds and lenses	31
13. Jaspery, conglomeratic chert beds interbedded with subordinate laminated hematite-silicate-magnetite beds	28
12. Cherty taconite with thin irregular magnetite beds, magnetite mottles and disseminated magnetite	16
	<u>143</u>
<u>LOWER SLATY MEMBER³</u>	
11. Laminated silicate magnetite taconite with subordinate silicate chert lenses	101
10. Laminated non-magnetic silicate taconite, fissile in part. 6' of fissile "intermediate slate" at bottom (G and S submember Q)	37
	<u>138</u>
<u>LOWER CHERTY MEMBER</u>	
9. Cherty taconite with irregular magnetite beds. Upper 10' has dark-colored silicate rich beds instead of magnetite beds, making base of lower slaty somewhat indefinite	37
8. Mottled silicate-magnetite chert with chert "pebbles" and abundant coarse granules.	11
7. Cherty taconite with thick (1"±) magnetite beds and mottles	84
6. Mottled cherty taconite with thin, very irregular magnetite beds.	14
5. Thick jaspery chert beds interbedded with varying proportions of thin, regular laminated magnetite-hematite-silicate-carbonate beds.	66

<u>Lower Cherty Member (Cont'd)</u>	<u>Thickness in feet¹</u>
4. Thick hematitic chert beds with subordinate laminated zones. Some clastic sand grains near bottom. Much carbonate.	8
3. Jaspery, conglomeratic and algal chert with subordinate laminated zones. Sand grains common.	4
2. Massive chloritic (or hematitic) sandstone	8
1. Jaspery, conglomeratic and algal chert	4
	236
Total thickness exposed	517

POKEGAMA QUARTZITE

Base not exposed

* * * * *

1. Units 15 and 16 measured on bank between truck road and railroad near entrance to pit. Units 1 - 5 measured on SW bank, at SE end of pit. Remainder measured above railroad.
2. Unit numbers correspond to numbers painted on the walls of the Auburn Mine and are not intended to be a new stratigraphic system.
3. The lower slaty-upper cherty contact is not well-marked and disagreement exists as to its position.

* * * * *

The Auburn ore body is of the fissure or trough type and its location and orientation appear to be controlled by a fracture set striking about N 40° W, nearly at right angles to the strike of the iron formation. At the SE end of the mine the trough is only 50' wide and the ore extended upward from the quartzite through about 115' of the Lower Cherty member. At the northwest end the trough is 500 feet wide and ore occurs for about 260 feet from the Lower Slaty-Lower Cherty contact to the outcrop. Excellent examples of ore slump structures can be seen in the ends of the pit, especially at the northwest end.

ERIE MINE - The stops in the Erie Mine are shown on the accompanying map. The Erie geologists designate units in the Biwabik formation as follows:

A-F Upper Slaty member - av. 110'
G-O Upper Cherty member - av. 185'
P-Q Lower Slaty member - av. 105'
R-W Lower Cherty member - av. 125'

Leader: Forrest W. Bovee

Stop 2. Erie - Pit 1 West

This stop is in the upper part of the Lower Cherty member (units are designated T and S layers by Erie). The Biwabik formation is composed of fine Stilpnomelane, Minnesotaite, magnetite and cherty quartz and contains bands, mottles and blotches of pink to yellow carbonate.

Stop 3. Erie Pit 2 West

This stop is in middle to upper part of the Upper Cherty member and the lower part of the Upper Slaty member (F) with the algal layer (I) well exposed. (Units in this pit are designated F, (Upper Slaty), G, H, I, J and K by Erie). A diabase sill about 3 feet in thickness occurs near the bottom of the exposed iron formation in the K layer. Some green mottles of cummingtonite occur in the J layer and carbonate mottles in the K layer.

Stop 4. Erie Pit 3

This stop is in the western part of Pit 3 in T, S. and R layers in the middle part of the Lower Cherty member. The rock is a cherty, silicate taconite with layers of cummingtonite.

Stop 5. Erie Pit 3

This stop is in the eastern part of pit 3 in the T, S and R layers of the Lower Cherty member in about the same stratigraphic zone as stop 4. Much of the chert in the Biwabik formation has gone to form actinolite and cummingtonite. The rock is termed a magnetite-silicate taconite. Locally pyrrhotite occurs in the iron formation.

E-1835.2

ERIE MINING COMPANY
MAP OF
PLANT & MINE AREAS

LEGEND

- ① COARSE CRUSHER
- ② FINE CRUSHER
- ③ CONCENTRATOR
- ④ PELLET PLANT
- ⑤ LOADING POCKET
- ⑥ STOCKPILE
- ⑦ GENERAL SHOPS
- ⑧ ADMINISTRATION BUILDING

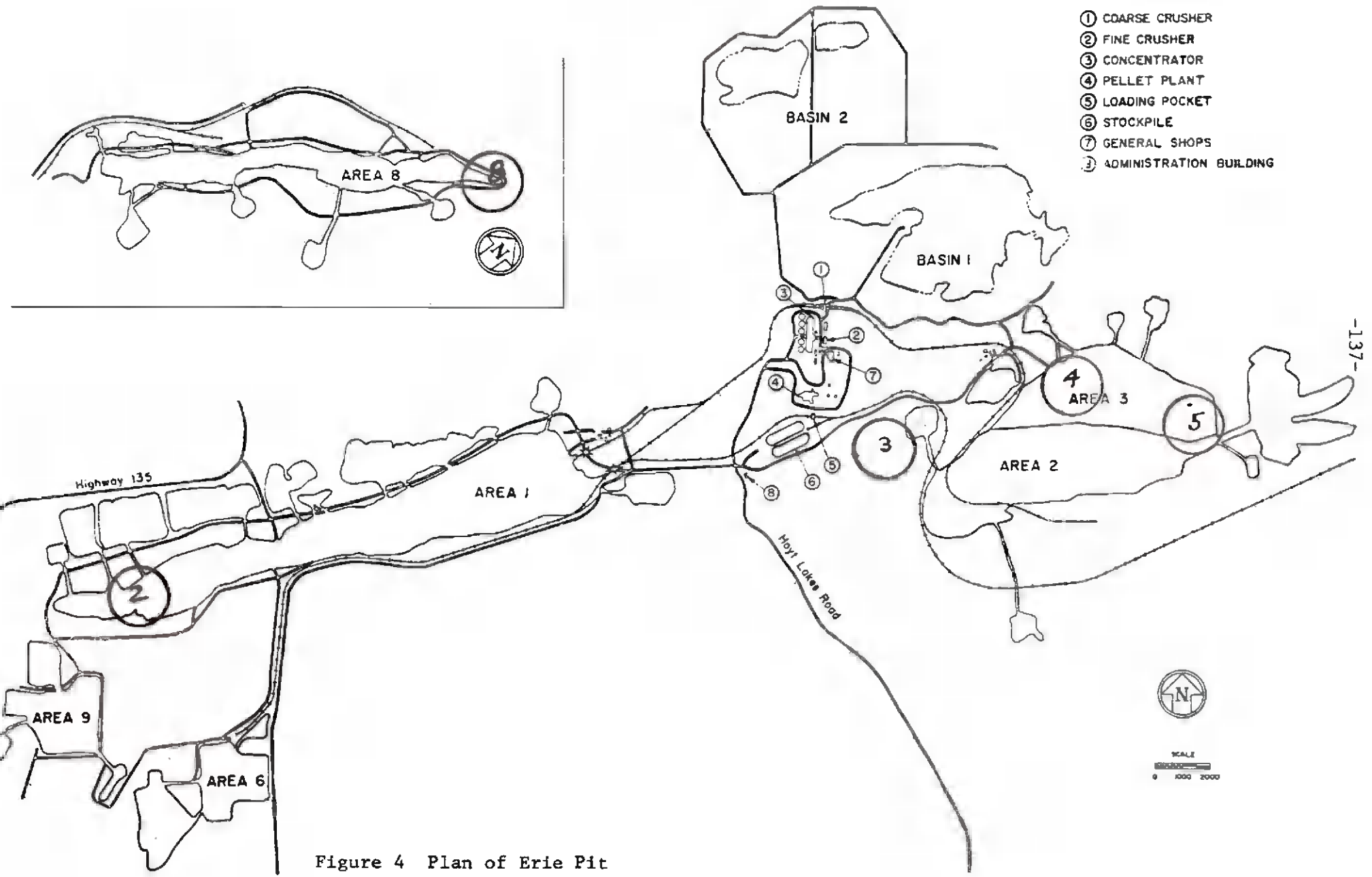


Figure 4 Plan of Erie Pit

RESERVE MINING COMPANY

The Reserve Mining Company mine is situated in a zone with a considerable range in mineralogy and texture shown by the Biwabik formation. The Reserve geologists designate units of the Biwabik formation as follows:

A-G Upper Slaty member - 100'-130' av.-120
H-O Upper Cherty member - 120-160' av.-140
P-Q Lower Slaty member - 75-120' av.-90
R-V Lower Cherty member - 30'-50' av.-30

Stop 6. Reserve Mine (Peter Mitchell Mine)

Leader: James W. Emanuelson

This stop is in the western part of the mine, northwest of Crusher No. 2 in the middle part of the Upper Cherty member in the J, K and L zones. The rock is a magnetite - silicate taconite with abundant cummingtonite.

Stop 7. Reserve Mine

This stop is in same general stratigraphic zone as stop 6. with layers from F to O exposed. The rock is a magnetite-quartz-silicate taconite with hedenbergite, ferro-hypersthene, and garnet. There are local areas of pegmatite.

Stop 8. Dunka Pit

The Dunka pit of the Erie Mining Company is situated near the eastern end of the Mesabi Range where the Biwabik formation is intruded by the Duluth Complex. This stop will show the upper part of the Upper Cherty member, the lower part of the Upper Slaty member, and gabbro of the Duluth Complex.

The taconite is composed of quartz, magnetite, hedenbergite, fayalite with andradite garnet and locally some hessingerite

The gabbro in this area contains sulphides, chalcopyrite and pyrrhotite with pentlandite.

The iron formation and gabbro will be observed in the pit and in outcrops north of the pit.

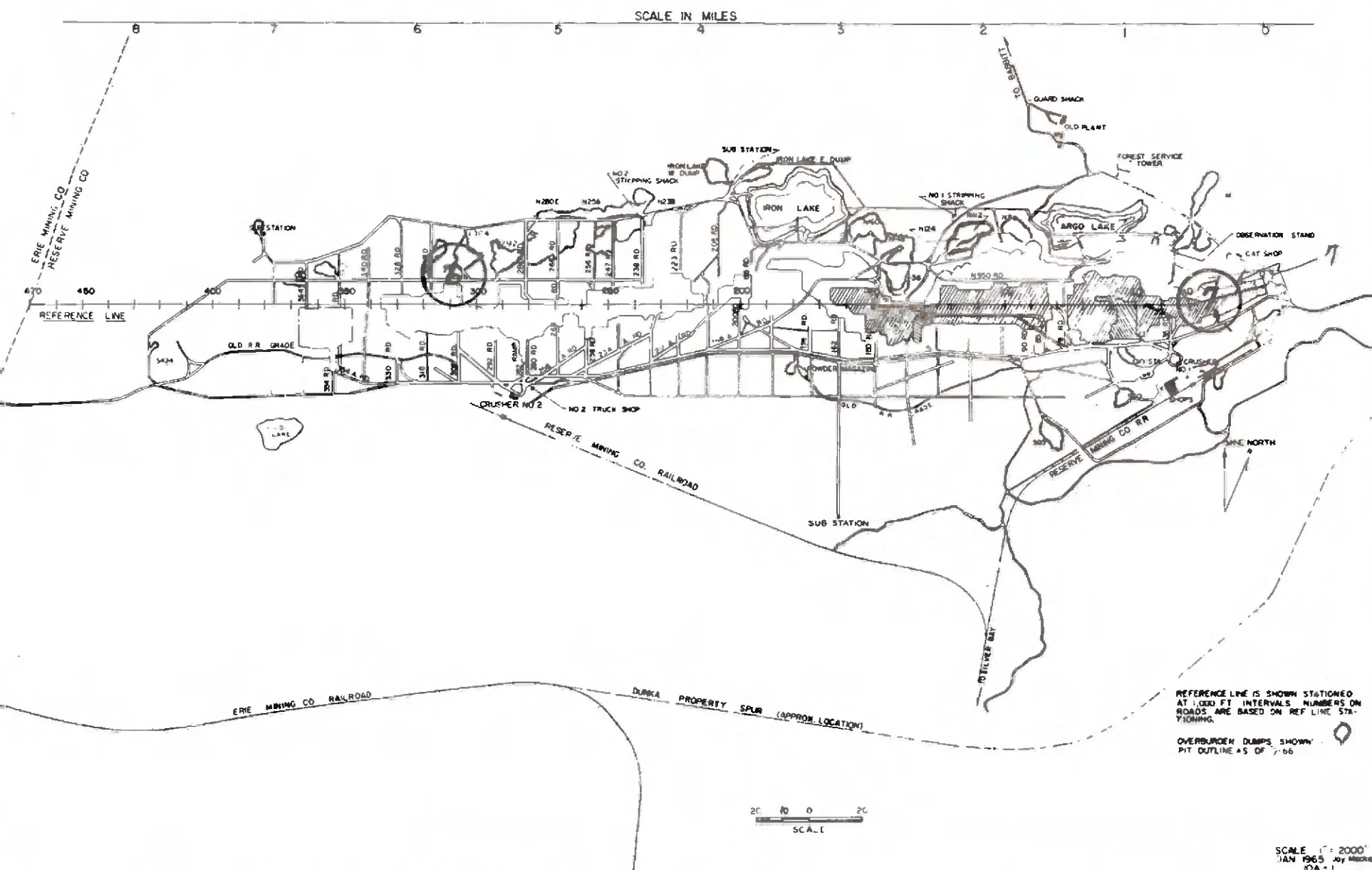
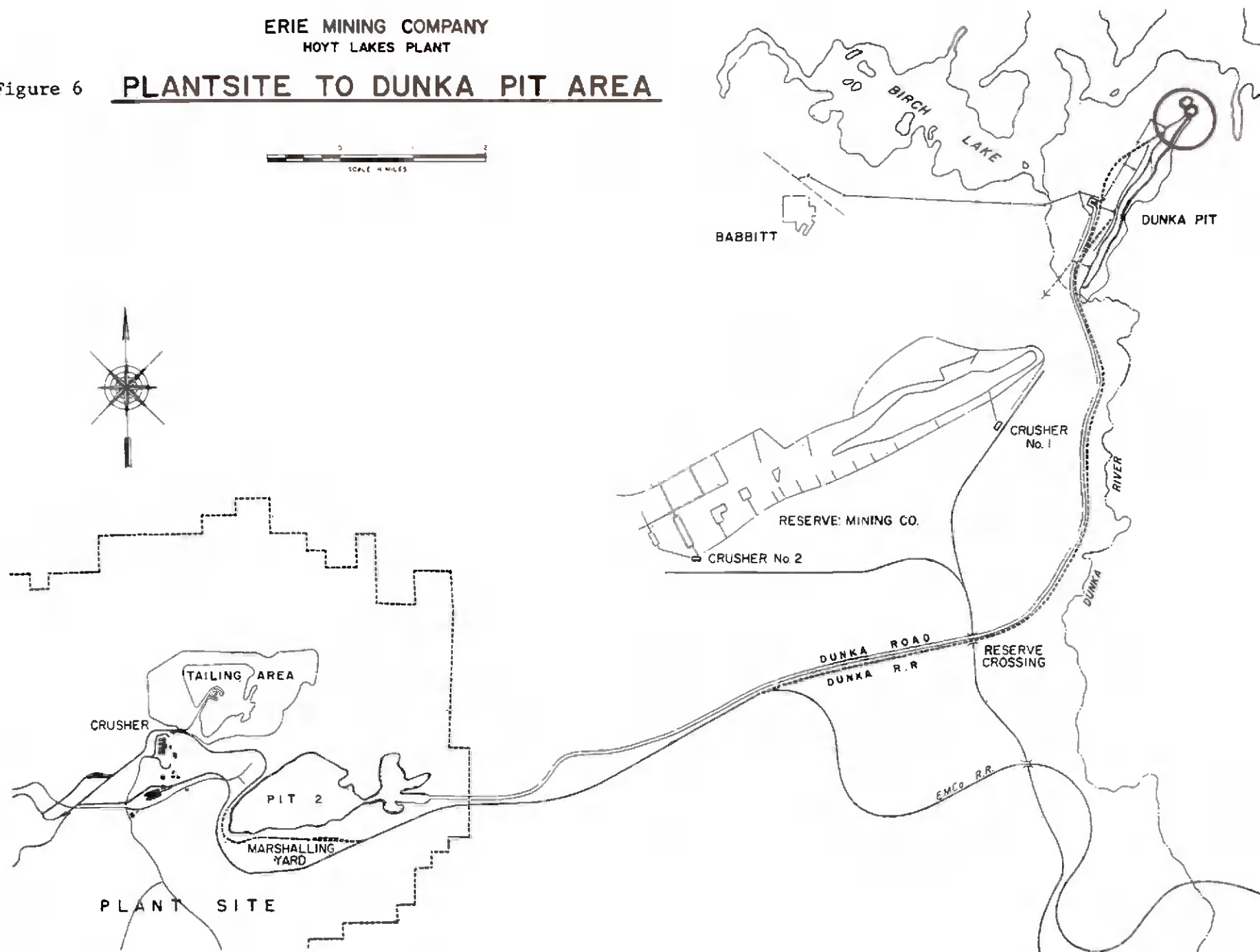


Figure 5 Plan of Reserve Mine

ERIE MINING COMPANY
HOYT LAKES PLANT

Figure 6

PLANTSITE TO DUNKA PIT AREA



Geology of the Vermilion Metavolcanic-
Metasedimentary Belt, Northeastern Minnesota

May 8, 1971

Prepared by

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Guide to the Geology of the Vermilion Metavolcanic- Metasedimentary Belt; Northeastern Minnesota

INTRODUCTION

The Vermilion district is a belt of metavolcanic-metasedimentary rocks more than 100 miles long and as much as 20 miles wide. It is bordered on the north and south by younger granitic batholiths (Fig. 1) of Algoman (Kenoran) age. The region is typical of Lower Precambrian (>2,500 m.y.) greenstone-metasediment-granite complexes of the Superior province.

The metavolcanic-metasedimentary sequence constitutes a complex volcanic pile, characterized by interfingering of lithologies and local repetitions of volcanism. Most of the metasediments are composed of volcanic detritus, and probably include volcanoclastic and epiclastic rocks. Numerous coeval and younger igneous rocks occur locally within the sequence.

The stratified sequence was metamorphosed and deformed before and during emplacement of the bordering granitic rocks of the Giants Range batholith and the Vermilion batholith. Pervasive greenschist facies assemblages were developed except adjacent to the intrusive bodies where metamorphism attained amphibolite grade. Deformation consisted of two major foldings and of later faulting on a major scale.

STRATIGRAPHY

The metavolcanic and metasedimentary rocks are assigned to five formations (Morey and others, 1970). The oldest formation, the Ely Greenstone -- composed mainly of mafic metavolcanic rocks -- is overlain stratigraphically in the west by the Lake Vermilion Formation and locally, the Soudan Iron-formation, and in the central part by the Knife Lake Group (Figs. 2 & 3). Both the Lake Vermilion Formation and the Knife Lake Group are composed mainly of intermediate-felsic pyroclastic deposits and volcanogenic sandstones. The Newton Lake Formation, a younger mafic to intermediate-felsic metavolcanic unit, overlies the Knife Lake Group in the central part of the district and interfingers with it to the east (Fig. 3). A generalized and idealized pre-deformational stratigraphic sequence for the western part of the district is shown in figure 4.

Ely Greenstone

The Ely Greenstone, as redefined (Morey and others, 1970), is an elongate body of dominantly mafic metavolcanic rocks, on the average 2-4 miles wide, that extends from the vicinity of Tower eastward to Moose Lake, a distance of about 40 miles (Figs. 2 & 3). Pillowed or massive metabasaltic lavas and metadiabase dominate the formation. Pillowed lavas of andesitic composition, intermediate-felsic pyroclastic

deposits, mafic-intermediate epiclastic deposits, chert and banded iron-formation, and siliceous carbonaceous tuff (?) comprise the remainder. Andesite and dacite porphyry are common hypabyssal intrusive rocks. The green color of most of the rocks is due to abundant secondary chlorite and green amphibole.

The maximum exposed thickness of the Ely is estimated at about 15,000 feet; the tops of separate flows are consistently to the north, as indicated by pillows.

Soudan Iron-formation

The Soudan Iron-formation, the thickest and most continuous banded iron-formation in the sequence, extends from Tower and Soudan eastward for a distance of about 16 miles (Fig. 2).

In the Tower-Soudan area it is overlain directly by intermediate-felsic volcanoclastic rocks of the Lake Vermilion Formation, whereas east of Armstrong Lake (Fig. 2) it is overlain directly by at least 7,000 feet of mafic-intermediate metavolcanic rocks with lenses of banded iron-formation, which are assigned to the Ely Greenstone. Thus, the Soudan, which represents a time-stratigraphic unit, is a useful indicator of the essential contemporaneity of intermediate-felsic volcanism in the west (Lake Vermilion Formation) and mafic volcanism in the east (Ely Greenstone).

The Soudan Iron-formation, as redefined (Morey and others, 1970), consists of several types of ferruginous cherts that are interbedded with fine-grained carbonaceous and sericitic tuffs (?) and local metabasalt; all are intruded by metadiabase and dacitic porphyries. The thickness of the formation has not been determined accurately because of complex folding, but probably is less than 1,000 feet. It should be noted that the iron-formation in the Ely trough (Reid, 1956), which has yielded large quantities of high-grade hematite iron ore, probably is not equivalent to the Soudan Iron-formation. The high-grade hematite ores that were mined in the Soudan Iron-formation at Soudan (Klinger, 1956) and in the banded iron-formation at Ely (Machamer, 1968) are considered to have been formed by hydrothermal processes (Gruner, 1926).

Lake Vermilion Formation

In the extreme western part of the district (Fig. 2), the Lake Vermilion Formation overlies either the Ely Greenstone or the Soudan Iron-formation. Until recently these strata were assigned to the Knife Lake Group. They were reassigned (Morey and others, 1970) to the Lake Vermilion Formation because they are not demonstrably continuous with strata exposed in the type area of the Knife Lake, in the eastern part of the district.

The Lake Vermilion is a heterogeneous formation which has been divided (Morey and others, 1970) into four informal members — a feldspathic quartzite member, a metagraywacke-slate member, a volcanoclastic member, and a mixed metagraywacke-felsic conglomerate member.

The feldspathic quartzite member, composed dominantly of volcanogenic minerals and rock fragments of dacitic composition, is in contact with the Ely Greenstone at the fold nose southwest of Tower (Fig. 2), and is older than the metagraywacke-slate member, as indicated by graded beds. The metagraywacke-slate member, which is areally the most extensive member, directly overlies the Ely Greenstone locally, as on the south limb of the fold at Tower, but for the most part is in contact with the older quartzite. The graywackes generally are well bedded and commonly are graded; like the feldspathic quartzite, they consist mainly of volcanogenic debris. A chloritic facies occurs on the shores of the eastern part of Lake Vermilion, but a biotitic facies, containing scattered amphibole, is dominant elsewhere. The member contains several interbedded lenses of metabasalt that are sufficiently large to be shown on figure 2.

The volcanoclastic member is of interest because it was interpreted previously to be mainly a conglomerate (Clements, 1903) related to the Laurentian orogeny. Instead, it is dominantly tuff and agglomerate of dacitic composition, with lesser dacitic lavas, banded iron-formations, and euxenic black slates. Locally, dacite porphyry intrudes the various rock types. The agglomerates, which are interbedded with tuffs, consist of sub-rounded felsite to felsite porphyry cobbles and boulders in a fine-grained matrix of similar composition. Exotic rock fragments, mainly iron-formation and greenstone, constitute only one or two percent of the rock.

The mixed metagraywacke-felsic conglomerate member, which occupies an area of about 30 square miles on the south limb of the fold south of Tower, interfingers with and is stratigraphically overlain by the metagraywacke-slate member (Fig. 2). It consists of a maximum of about 10,000 feet of felsic to mafic volcanoclastic rocks, felsite flows, several types of conglomerates and agglomerates, and metagraywacke (Griffin, 1969; Griffin and Morey, 1969).

The thickness of the Lake Vermilion Formation and its constituent members is poorly known because of complex folding and faulting and rather poor exposures. In the Tower quadrangle, the quartzite member is estimated to be 1,500-2,000 feet thick and the volcanoclastic member to be a maximum of about 4,000-5,000 feet thick. The metagraywacke-slate member is at least 3,000 feet thick and is probably much thicker.

Knife Lake Group

Rocks of the Knife Lake Group directly overlie the Ely Greenstone from the vicinity of Ely, where the Knife Lake terminates against a fault, eastward to Moose Lake (Fig. 3). The Knife Lake Group, as redefined (Morey and others, 1970), consists dominantly of graywacke, slate, and phyllite but includes substantial amounts of pyroclastic rocks, lava flows, and conglomerates. Gruner (1941, p. 1624) estimated that the Knife Lake near the eastern end of the district is about 15,000 feet thick, but this figure may be conservative.

Newton Lake Formation

The Newton Lake Formation was mapped earlier (Clements, 1903) as Ely Greenstone, but has been renamed (Morey and others, 1970; Green, 1970) because it is stratigraphically younger than the Knife Lake Group (Fig. 3). The formation is truncated on the north by the Vermilion fault and along strike to the northeast by granitic rocks of the Vermilion batholith. At its western extremity, near Wolf Lake, the formation is truncated by a fault (Fig. 2).

The western part of the Newton Lake formation is composed principally of mafic volcanics and the eastern part of intermediate-felsic volcanic members, which interfinger in the vicinity of Newton Lake. The mafic volcanic member consists dominantly of metabasalt and meta-andesite lavas, some of which are pillowed, and fine-to-coarse-grained metadiabase and tuff or tuff-breccia. Several small bodies of serpentinized peridotite are associated spatially with the metabasalt and metadiabase. Small lenses of siliceous marble and banded iron-formation occur locally in the formation. The felsic member, east of Newton Lake, is composed of felsic-intermediate volcanics, dominantly tuff-breccia deposits and lesser flows. At places, metabasalt is interbedded with the dominantly felsic volcanics.

Intrusive Rocks

Five distinct episodes of intrusive activity are recognized in the region. In order of inferred age, from oldest to youngest, these are (1) synvolcanic bodies, including hypabyssal porphyries, which have a wide range of composition, metadiabase and metagabbro, and serpentinized peridotite, (2) lamprophyres and related hornblende-bearing rocks, (3) plutonic rocks of the Giants Range and Vermilion batholiths, which are syntectonic, (4) altered diorite-gabbro which forms large dikes that are post-tectonic, and (5) basalt, which forms small, discontinuous, scattered dikes. In addition, the Saganaga Granite of Winchell (1888) at the eastern end of the district (Fig. 1) is approximately equivalent in age to the rocks of the two batholiths and intrudes the older metavolcanics (Grout, 1929; Hanson and Goldich, 1970).

The plutonic rocks of the Vermilion and Giants Range batholiths profoundly affected the volcanic-sedimentary sequence. Granitic rocks of the composite Giants Range batholith, on the south, irregularly intrude the sequence or are in fault contact with it, and have cut out an unknown amount of section at the base of the Ely Greenstone. Where the granite is not in fault contact with the lower-grade volcanic-sedimentary rocks, it has normal intrusive relationships to the older strata, with the development of amphibolite-facies assemblages adjacent to the contact. The Vermilion batholith, on the north side of the district, transects the upper stratigraphic part of the supracrustal sequence. This leucocratic biotite granite includes wide zones of abundant inclusions of biotite schist and amphibolite

STRUCTURE

The metavolcanic and metasedimentary rocks dominantly constitute a homoclinal, northward-younging sequence in the central part of the district,

whereas they are both complexly folded and faulted in the western and eastern parts. Deformation was not pervasive, and primary structures remain in most of the rocks. Graded bedding and other primary features remain in the graywacke-slate successions, and pillow structures and variolites are remarkably well preserved in the mafic metavolcanic rocks. At places, however, a penetrative deformation, mainly shearing, has obliterated the bedding.

In the western part of the area the rocks are complexly folded as a result of two distinct episodes of deformation. The younger folds and a pervasive accompanying cleavage largely obscure the older folds, although the older folds were important in determining the distribution of the rocks. Detailed studies in the Tower quadrangle and adjacent areas (Hooper and Ojakangas, 1971) indicate that the metasedimentary strata, and to a lesser degree the metavolcanic rocks, first were folded on west-northwest-trending axes. These (F_1) folds were tight to isoclinal, had steep axial planes, and probably had gentle or moderate plunges. Major fold axes, as determined by consistently facing or opposing tops of beds, were spaced from 700 to 1,500 feet apart. The younger (F_2) folds, which comprise most of the mappable ones, are strongly asymmetric and have steep axial planes that trend eastward. In most of the area the (F_2) folds are dominantly Z-folds, and the northwest-trending limbs are two or more times longer than the southwest-trending limbs; plunges are generally steep. The intersection of a pervasive, mild, axial plane cleavage with bedding is parallel to F_2 fold axes. In biotite- and higher-grade rocks, new minerals are aligned parallel to the cleavage-bedding intersection. In the Tower area, several nearly vertical structures — faults, joints, and kink bands of a third deformation displace the cleavage of the F_2 deformation.

High-angle faults of two trends, longitudinal and transverse, break the metavolcanic-metasedimentary sequence into a number of blocks or segments and separate it in part from the marginal batholithic rocks. The Vermilion fault (Sims and others, 1968), a longitudinal fault with an inferred length of 300 miles (Sims, 1970) generally separates the Vermilion batholith and associated amphibolite facies schists from lower-grade rocks of the district. The amount and direction of the horizontal component of movement is not known, but possibly is several miles. The vertical displacement is inferred to be on the order of a mile, to bring higher-temperature-facies rocks on the north against lower-temperature-facies rocks in the district. Other longitudinal faults, some of which appear to be strands from the Vermilion fault, slice the northern part of the district into separate segments. The transverse faults trend northeastward or north-northeastward and have dominantly left lateral displacements; the principal faults of this set have measureable displacements of about 3-4 miles (Griffin and Morey, 1969).

The major faults of the area are expressed commonly as narrow, linear topographic depressions. Where exposed, they are seen to consist either of wide zones of crushed and altered rock or of intensely silicified and altered rocks.

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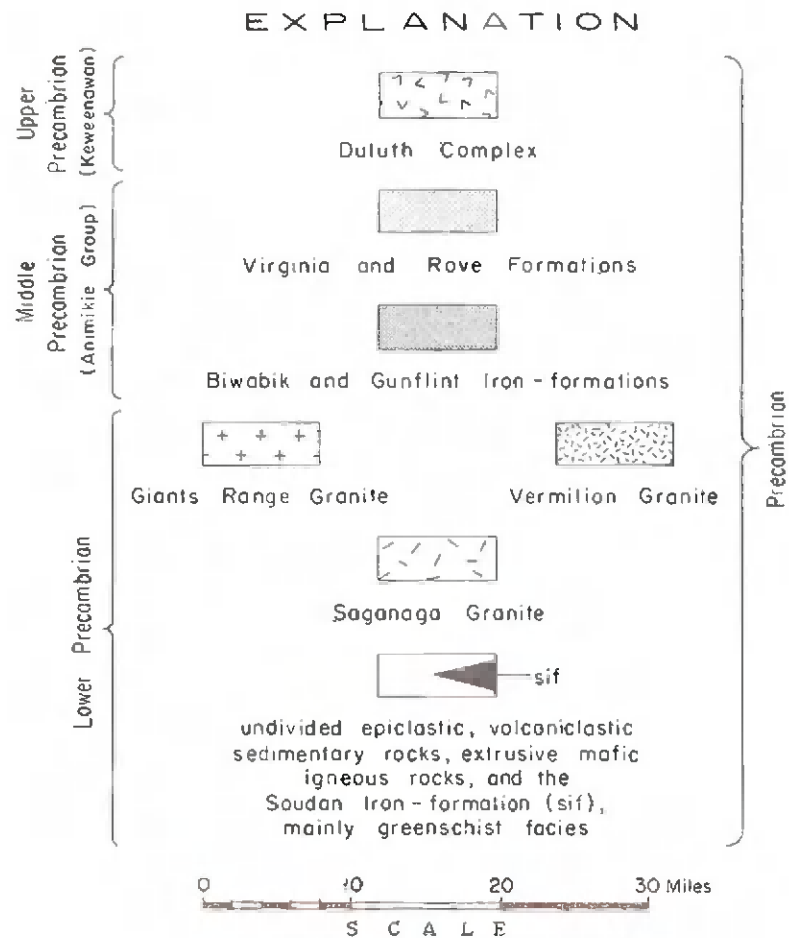
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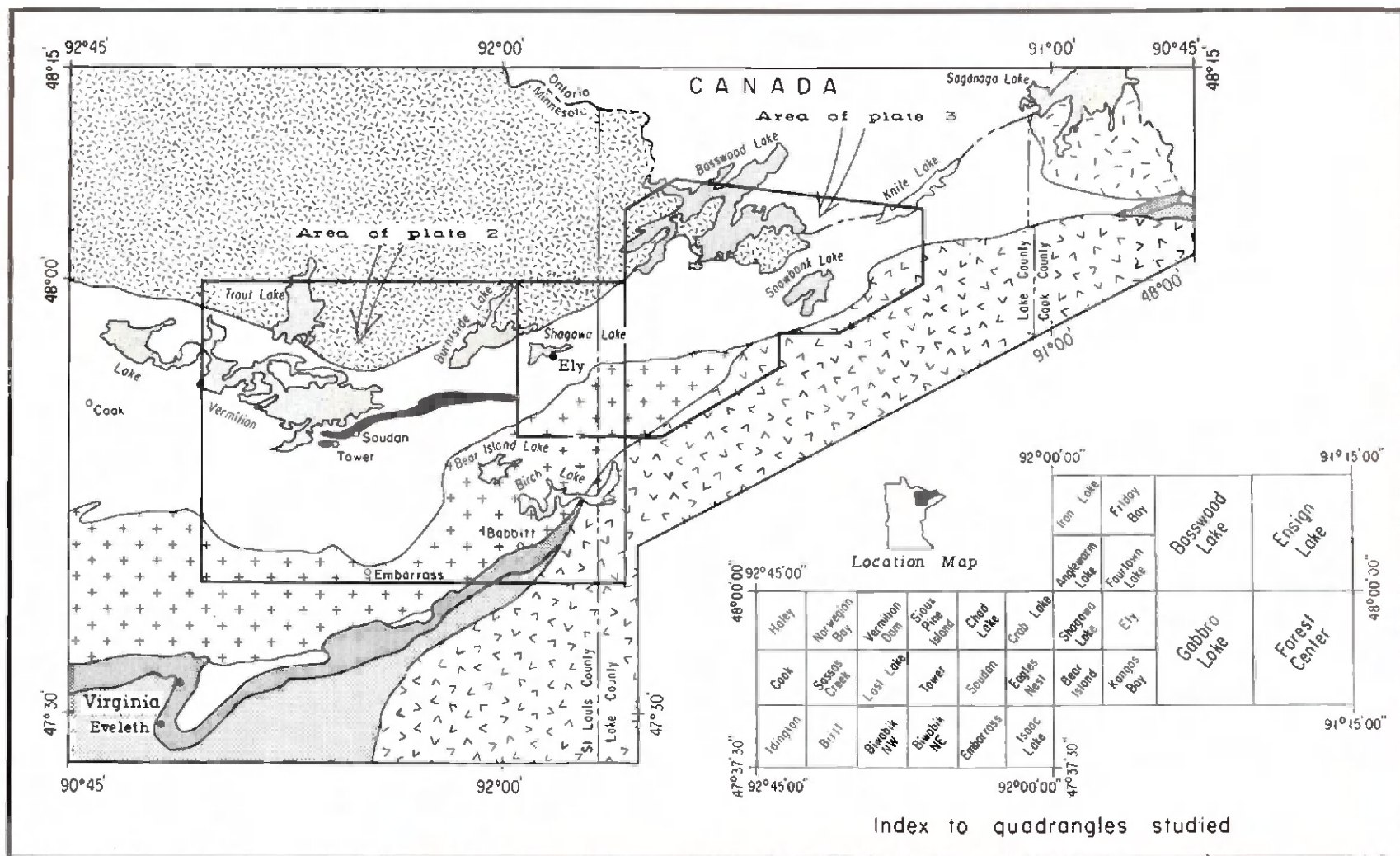
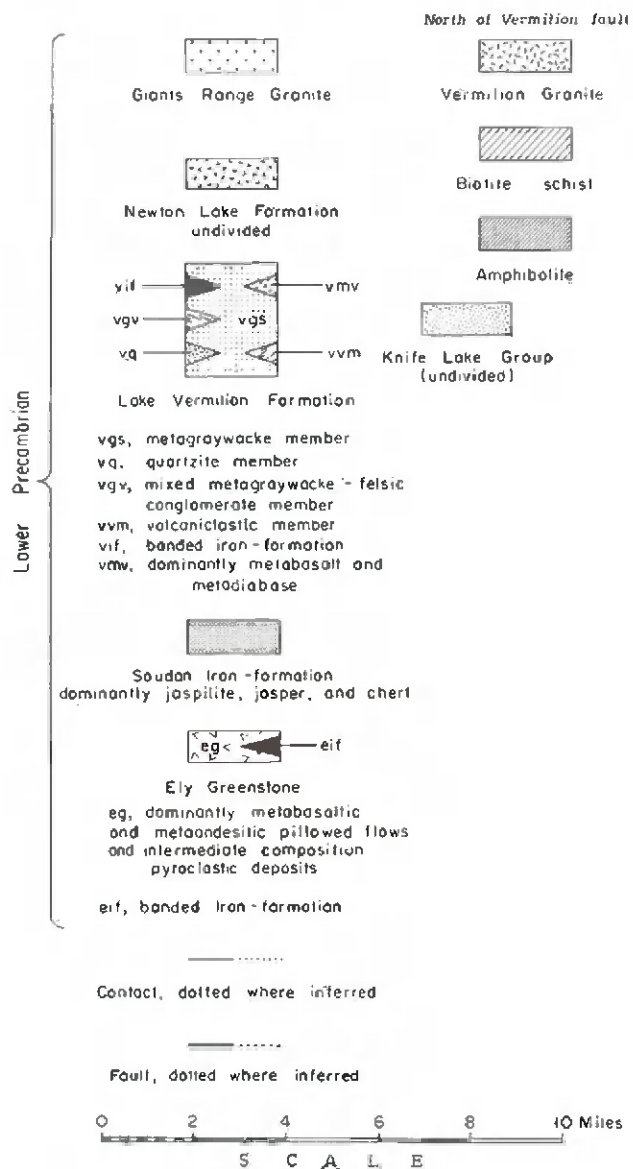


Figure 1. Generalized geologic map of the Vermilion district, Minnesota (Morey & others, 1970)

EXPLANATION



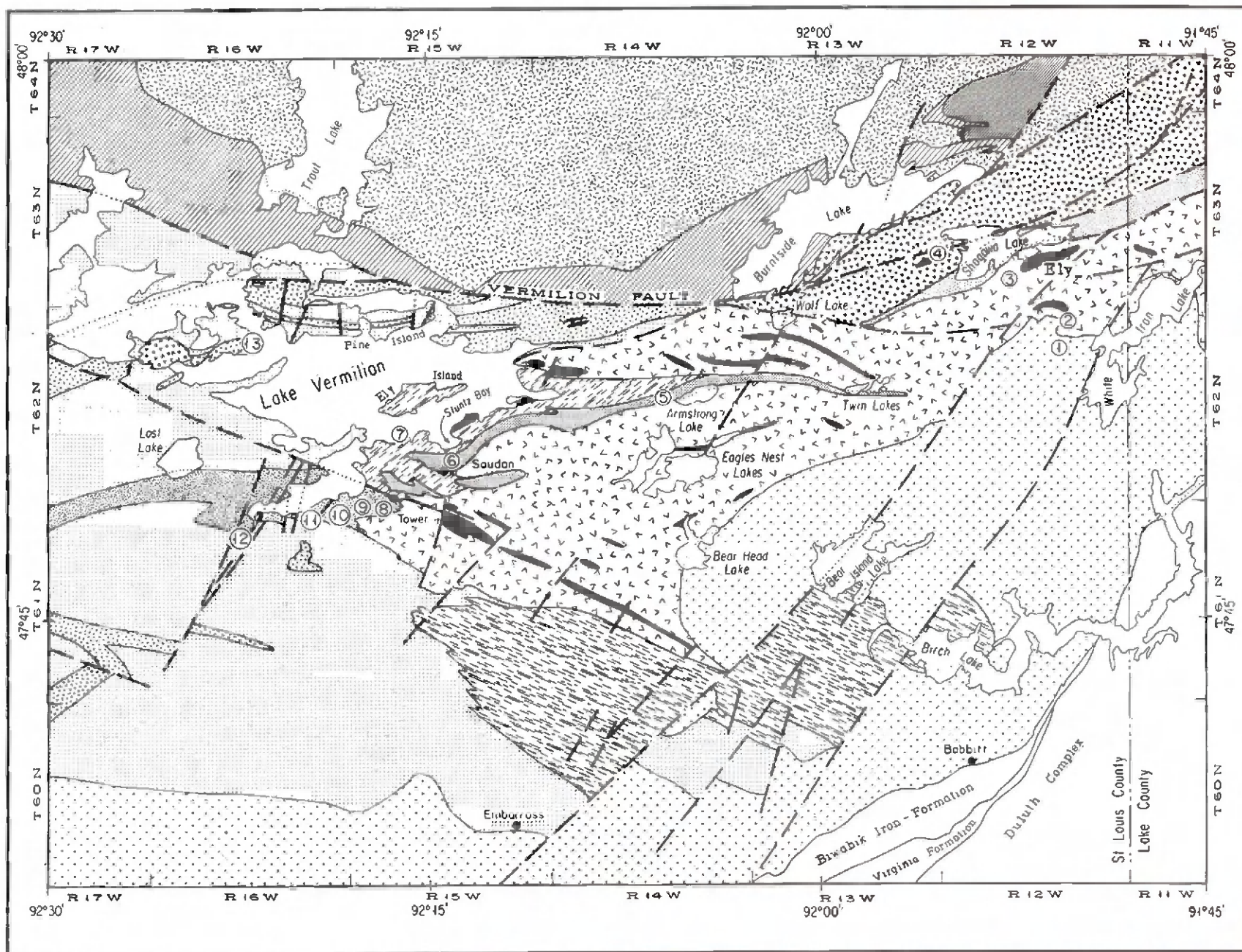
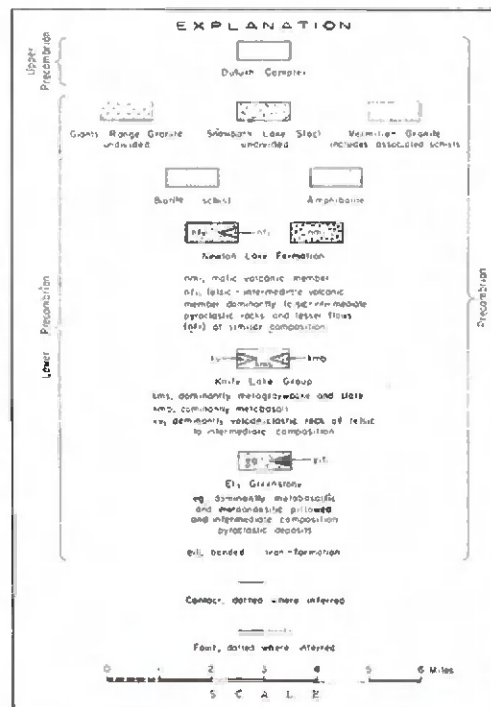


Figure 2. Geology of the western part of Vermilion district, Minnesota (Morey & others, 1970).



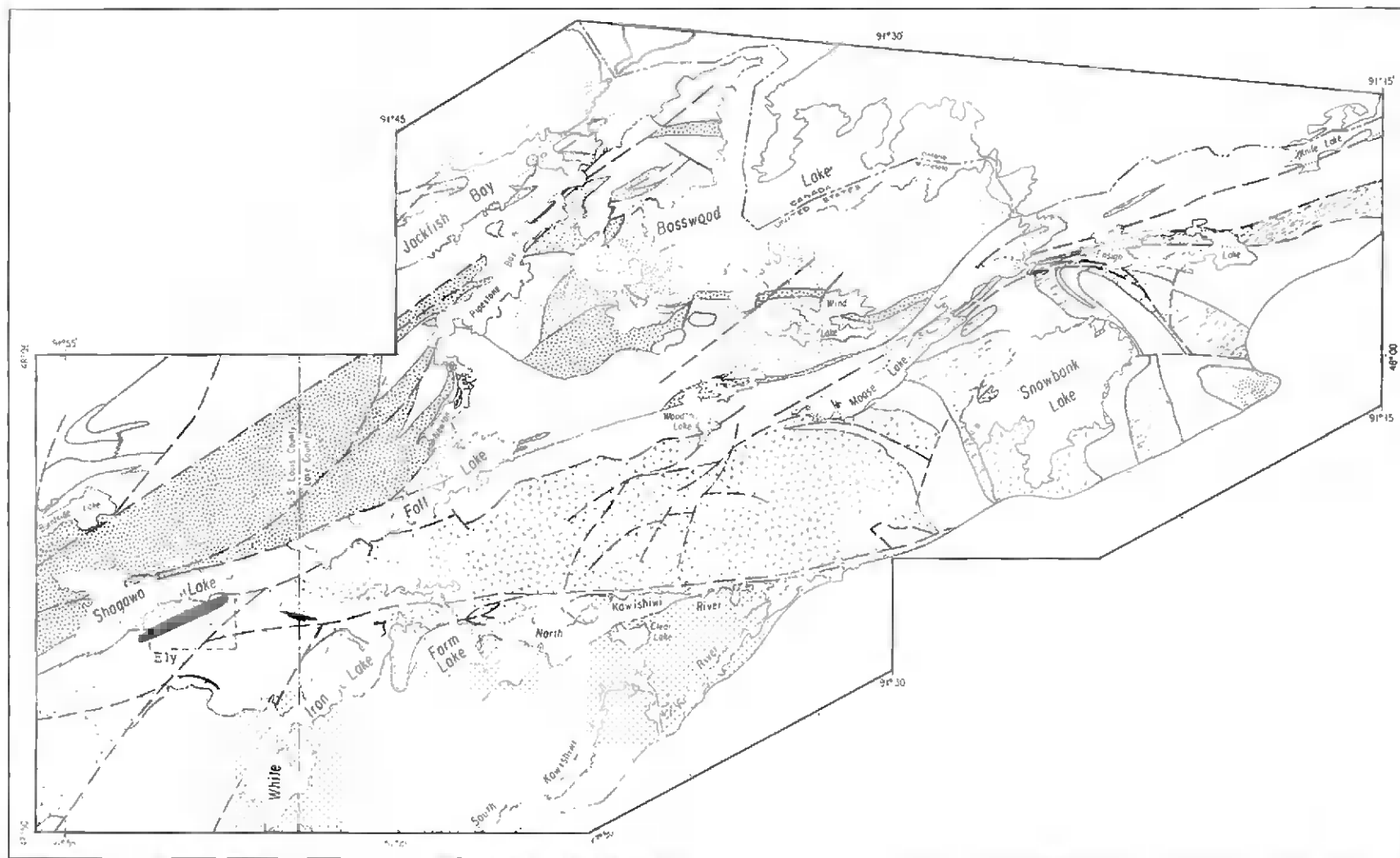


Figure 3. Geology of the central part of the Vermilion district, Minnesota (Morey & others, 1970).

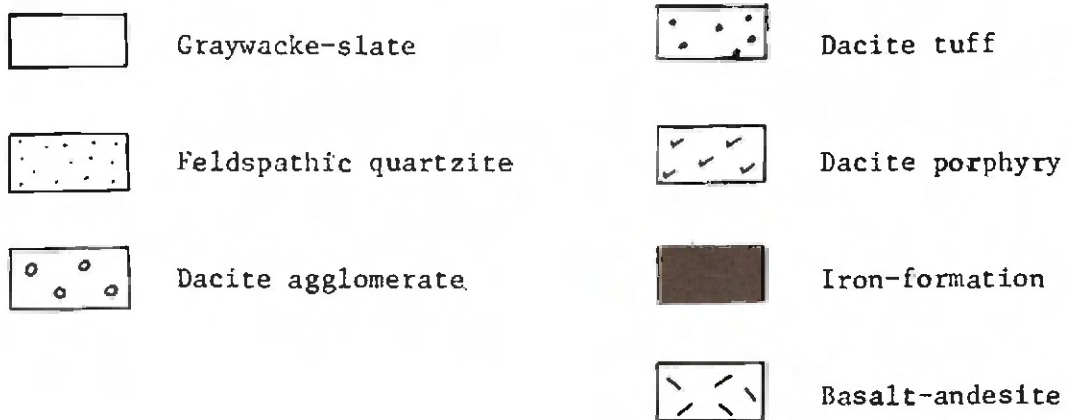
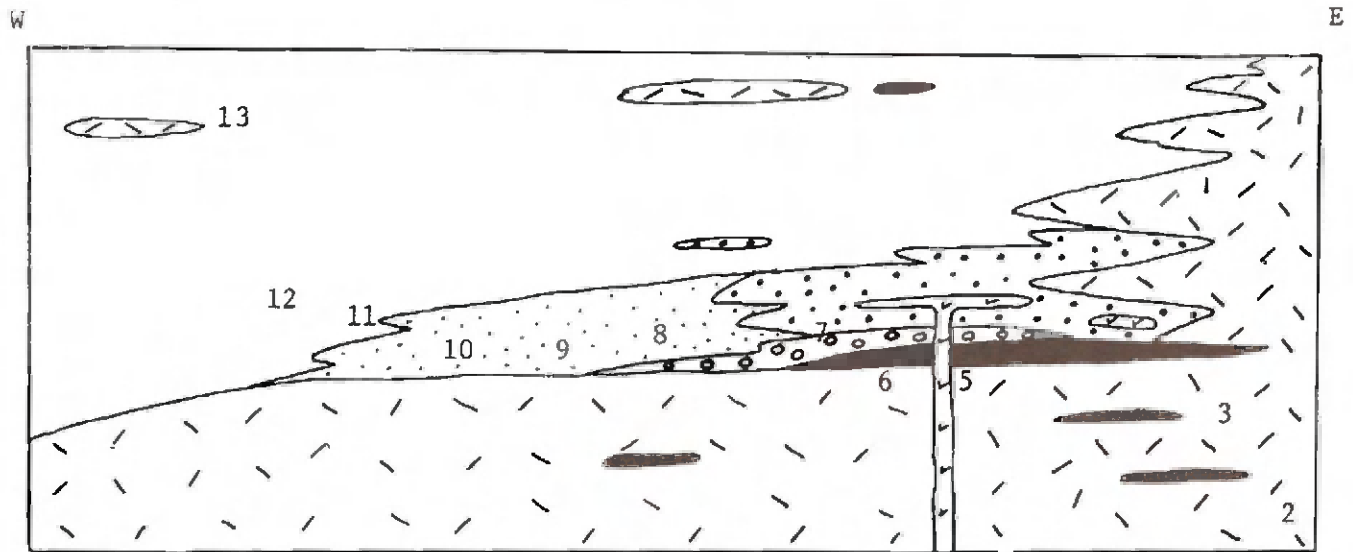


Figure 4.

GENERALIZED AND IDEALIZED PRE-DEFORMATIONAL VOLCANIC PILE,
WESTERN VERMILION DISTRICT

(Not to scale. Numbers indicate approximate stratigraphic positions
of field trip stops.)

VERMILION DISTRICT FIELD TRIP

INTRODUCTION

This field trip is designed to be a one-day trip, starting near Ely and ending a few miles west of Tower. Representative outcrops of most of the major rock types in the Vermilion district are included. Most stops are in the Lake Vermilion Formation, the Ely Greenstone, and the Soudan Iron-formation. None are in the Knife Lake Group because good exposures are not easily accessible; however, the Knife Lake rocks are similar to those in the Lake Vermilion Formation.

Stop 1 Any of several roadcuts 2-10 miles South of Ely on Hwy. 1.

Giants Range batholith

Most abundant facies in this area ("Farm Lake Facies" of Green, 1970) is medium-grained, porphyritic hornblende-biotite quartz-poor adamellite with pink K-spar phenocrysts. Hornblende and K-spar are commonly aligned in flow structure. Monzonitic, granodioritic, and dioritic phases also occur; all have been cut by shear zones locally.

Stop 2 South of Ely on Hwy 1. Outcrops under powerline on E side of Hwy 1, 1.4 mi. S of junction with Hwy 169.

Ely Greenstone

Dacitic to andesitic, pillowed lavas characteristic of a zone within the Ely Greenstone that trends E-W south of Ely. Pillow shapes show tops face north, as in most of the formation. These volcanics are cut by aplitic dikes related to the Giants Range batholith; the hidden contact lies in the slope to the southwest, and granite outcrop can be seen near the base of the slope.

Stop 3 Roadcuts on Hwy 169, at curve about 0.25 mi. W. of Ely.

Ely Greenstone

Pillowed metabasalt that is typical of the mafic lavas of the Ely Greenstone is exposed in road cut on north side of highway. The pillow structures have smoothly rounded tops, nearly flat bases, and are somewhat drawn out in vertical dimension. The chilled rinds are a fraction of an inch thick. The pillow structures strike approximately N.20° E., dip 80° SE., and face southeastward. The long dimension of the pillows is subparallel to the intersection of cleavage and bedding and plunges steeply northeastward.

The exposures are on the northwest limb of a tight syncline, the axis of which passes through the Ely trough. The Ely trough contains an iron-formation that was largely altered to hematite, and which was a substantial source of direct-shipping hematite ore.

On the south side of highway, fine-to-medium-grained metadiabase is exposed in road cut and on hill to south. The metadiabase intrudes and crosscuts the pillowed metabasalt. A contact can be seen in the southern part of the crest of the hill.

Stop 4. About 2.5 mi. W of Stop 3 on Hwy 169, turn N (right) on road to Burntside Lodge (Co. 88). Continue on road past bridge over Burntside River and past junction with Van Vac road (on left). About 1.4 miles past Van Vac road, turn left (on curve) on private road. Stop in about 0.2 miles north on private road, at curve to right.

Newton Lake Formation

Serpentinized metaperidotite and associated gabbroic rocks are exposed from base of hill northward to crest.

Serpentinized peridotite is exposed at base of hill. It is about 150 feet thick, is nearly black, and contains some poikilitic augite. Immediately north of serpentinized peridotite and apparently gradational into it is a coarse-grained hypersthene (?) gabbro, which grades in turn into a gabbro (higher on hill). The gabbro appears to have some crude compositional layering and is in part diabasic. On crest of hill, part of the gabbro (or diorite) contains coarse, radiating pyroxene crystals, as much as an inch long. There is some interstitial quartz and feldspar granophyric material in this phase of the rock. Pyrite is widely scattered through the gabbroic rocks.

The ultramafic-mafic body at this stop is near the southwestern end of an intrusive sheet that is about 3.5 miles long and 1,000 feet or more thick, and which underlies little Long Lake. The sheet appears to be a differentiated body, from peridotite at the base to gabbro at the top. North of the eastern end of Little Long Lake, a small body of serpentinized peridotite, within metadiabase, is exposed in a roadcut along the Echo Trail. The top of the body is truncated by the Vermilion fault.

Stop 5 Roadcut about 13.0 miles W of Ely and about 2.5 mi. W of Eagle's Nest Lake road (Co. 408) on Hwy 169. Other outcrops of similar rocks are also present along the highway.

Soudan Iron-formation and cross-cutting dacite.

Roadcut in Soudan Iron-formation. A quartz-feldspar (dacite) porphyry dike and Ely Greenstone are exposed at east edge of outcrop. The iron-formation is composed of interlayered red and white chert and opaque iron oxide layers; it is deformed into drag folds that plunge 50°-60° N.E. Beyond a covered interval of 0.1 miles to the east, the

iron-formation consists of thin to thick, black, red and white chert beds interlayered with black argillaceous beds that contain abundant veins, stringers, and beds of euhedral pyrite. The beds trend about N.85° and W. and dip 80°N.

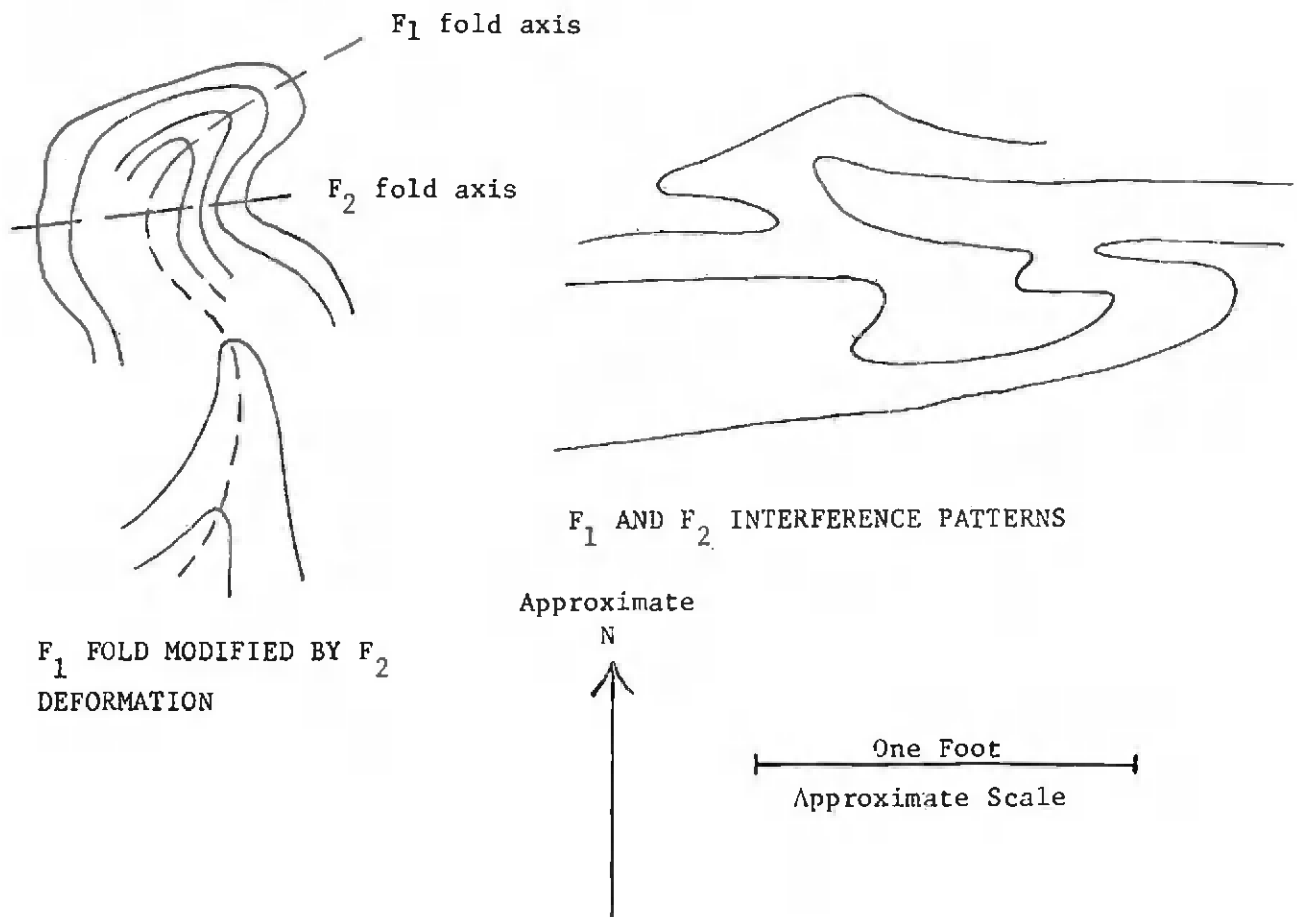
This dacite is representative of the felsic volcanic rocks which apparently provided the detritus for most of the sedimentary and tuffaceous rocks of the district.

Stop 6 Outcrop just W of Stuntz Bay road at crest of Soudan Hill, at the N. edge of village of Soudan, 1,000 ft E. of Soudan mine. Conserve this outcrop.

Soudan Iron-formation

This is a much-visited classic exposure of folded Soudan Iron-formation comprised of alternating beds of hematite and jasper. The nearby Soudan mine was opened in 1884, and operated continuously until 1962, when it was deeded to the state by U. S. Steel for the development of Tower-Soudan State Park. It was the first iron ore mine in Minnesota; 15.5 million tons of high grade ore (63-66% Fe) were shipped.

Most of the small folds are the result of the second deformation in the area, and these (F_2) folds plunge to the east at steep angles. However, evidence of an earlier set of folds is provided by structures such as these in the sketches below.



Stop 7 Several outcrops on peninsula in Lake Vermilion, east of McKinley Bay, E and W of development road.

Lake Vermilion Formation, Volcaniclastic Member

White dacitic tuff, white dacitic agglomerate, black carboniferous (?) slate and minor chloritic graywacke, all of the volcaniclastic member, are interbedded in this area. The westernmost exposures of the Soudan Iron-formation also occur here. Good exposures of the agglomerate are best reached by boat; therefore, we shall only see some large glacial erratics of this rock type which are virtually in place.

The dacitic tuff is very difficult (and commonly impossible) to distinguish from dacite flows. Study of thin sections is usually necessary to resolve the question. It is some comfort to know that Clements (1903) and numerous other workers had similar difficulties. The tuff is composed of three main components — dacitic volcanic rock fragments, plagioclase, and volcanic quartz. Recrystallization causes the volcanic rock fragments to appear as a fine-grained quartz-plagioclase matrix.

Stop 8 Large roadcuts 0.3 mi. W of Tower on Hwy 169.

Lake Vermilion Formation, Feldspathic Quartzite Member

This is a limonite-stained exposure of the conglomeratic facies of the feldspathic quartzite member. Bedding and clasts are best observed on the glaciated surface at the western end of the south roadcut. Pyrite and pyrrhotite are the major sulfides present, and appear to have replaced slaty fragments in the conglomerate. Most clasts are volcanic rocks, probably mostly dacitic. The matrix is similar to the feldspathic quartzite of Stop 10. Note the strong development of F_2 lineation which plunges easterly at about 60° .

Stop 9 Small outcrop S of Hwy 169, in and across ditch, 1.1 mi. W of Tower.
(optional)

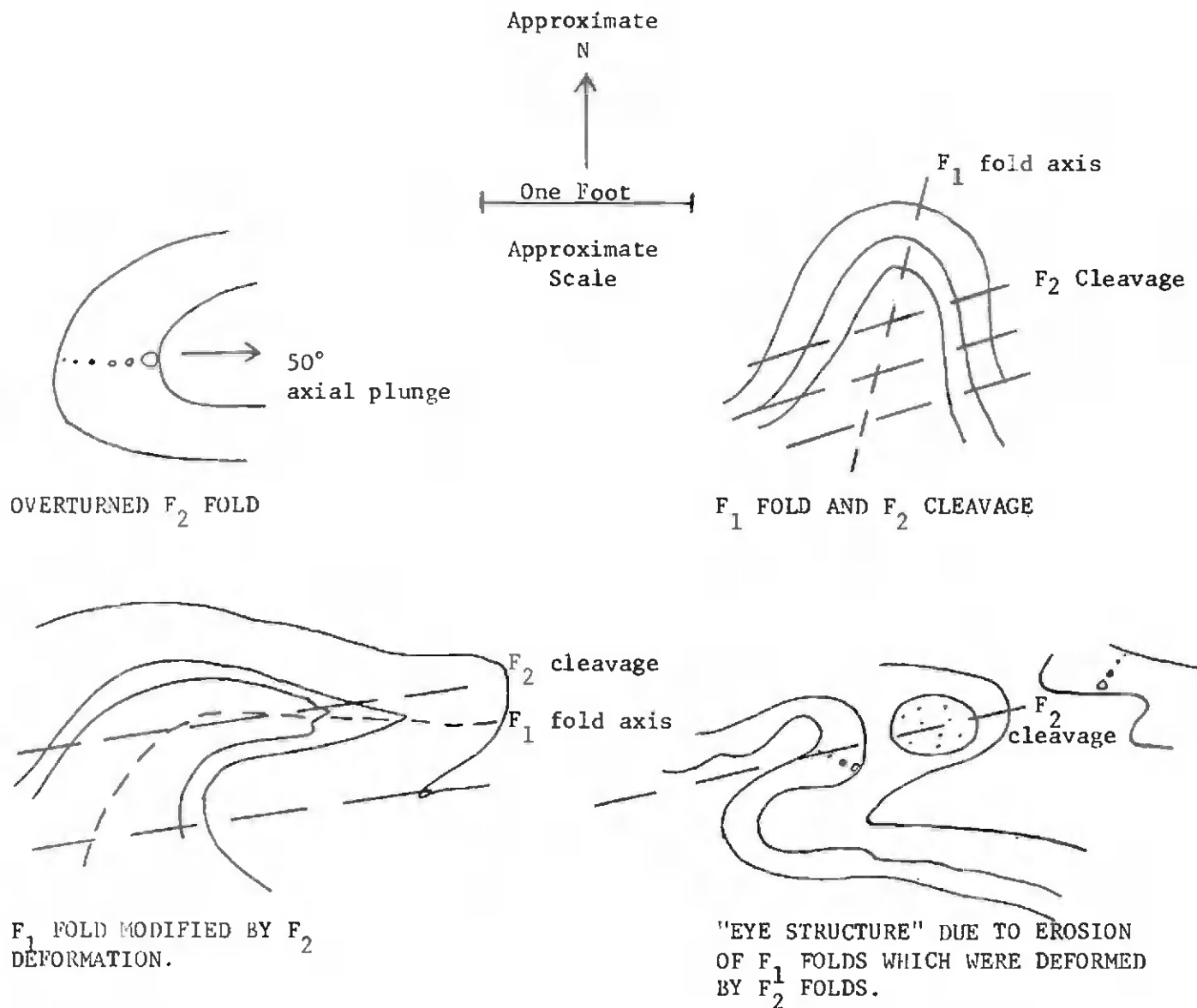
Lake Vermilion Formation, Feldspathic Quartzite Member

Lapilli tuff (?) in the basal part of the feldspathic quartzite member. This is the only exposure of this rock type in the immediate area; it appears to be transitional in texture between the dacitic tuffs and dacitic agglomerates.

Stop 11 Long roadcut S of Hwy 169, 2.5 mi. W of Tower. Conserve these folds.

Lake Vermilion Formation, Metagraywacke-Slate Member

Strongly folded biotitic metagraywacke and slate. (The composition of this rock is described at Stop 12, where the rocks are evenly bedded and relatively undeformed.) The complex folding results from two deformations, as sketched below and as described in the text accompanying this field trip log. Some geologists have speculated that the folding is soft sediment deformation, rather than tectonic. However, these structures are unique in the area, this exposure is located near a major anticlinal axis, and well-preserved sedimentary structures nearby are not chaotic. Note the excellent grading.



Stop 12 Exposure NW of bridge across Pike River on Co. 77, 0.55 mi N of Hwy 169. (Junction of Co. 77 and Hwy 169 is 2.4 miles W of Tower). Please conserve this outcrop.

Lake Vermilion Formation, Metagraywacke-Slate Member

This is an exposure of biotitic metagraywacke and slate, having excellent grading. Two-thirds of the 200 graywacke beds on this exposure are graded and nine percent of the 100 siltstone beds are graded. Beds here are thin, but graywacke beds are as much as 12 feet thick.

North-trending kink bands were formed by the latest (F_3) deformation. Small scale faults are common. A NNE-trending fault with about 1000 feet of left-lateral displacement forms the S side of the river channel at this locality, and extends for several miles to the north and south.

The biotitic graywackes contain 10-20% plagioclase; 15-25% felsic volcanic rock fragments; 30-50% fine recrystallized quartz and plagioclase which probably represents, in large part, recrystallized volcanic rock fragments, plagioclase, and quartz; 2-5% quartz, and 10-15% biotitic matrix.

Stop 13 Exposures about 10 mi N of Hwy 169 on Co. 77, at Gruben's Resort on (Optional) Arrowhead Point. Best exposures are just E of wooden bridge to Isle of Pines.

Lake Vermilion Formation, Metagraywacke-Slate Member

Exposures of chloritic graywackes and slates. Both east and west of this locality, pillowed greenstones are interbedded with the graywacke-slate. This locality is near the axis of the Arrowhead Point fold. This is an ENE-trending (F_2) anticline, the axis of which plunges steeply to the west although the beds at the fold nose are younger to the east.

The chloritic graywackes contain 40-50% plagioclase (albite-oligoclase), 20-25% felsic volcanic rock fragments, 10-20% chloritic matrix, 2-6% quartz, some of which is definitely of volcanic origin.

Stop 14 Roadcuts between lanes of Hwy 169 on "Confusion Hill" (the Continental (Optional) Divide) about 3 mi N of Virginia and about 23 miles W of Tower.

Giants Range Granite

This exposure illustrates the complexity of the south edge of the Giants Range batholith. A gray granite gneiss containing amphibolite inclusions is cut by diorite, and minor pink granites cut the above rocks.

At the top of the exposure between the two lanes of the highway are remnants of Lower Precambrian thinly bedded sediments (tuffaceous?), mafic lapilli tuffs (?), and massive amphibolites.

