GEOLOGY OF THE REGIONAL COPPER-NICKEL STUDY AREA

JUNE 1978

Level I
Typed 4/26/79
Figures are Rough

GEOLOGY OF THE REGIONAL COPPER-NICKEL STUDY AREA

Minnesota Environmental Quality Board
Regional Copper-Nickel Study
Author: Roger W. Cooper
June 1978

TABLE OF CONTENTS

TABLE OF CONTENTS (contd.)

INTRODUCTION TO THE REGIONAL COPPER-NICKEL STUDY

The Regional Copper-Nickel Environmental Impact Study is a comprehensive examination of the potential cumulative environmental, social, and economic impacts of copper-nickel mineral development in northeastern Minnesota. This study is being conducted for the Minnesota Legislature and state Executive Branch agencies, under the direction of the Minnesota Environmental Quality Board (MEQB) and with the funding, review, and concurrence of the Legislative Commission on Minnesota Resources.

A region along the surface contact of the Duluth Complex in St. Louis and Lake counties in northeastern Minnesota contains a major domestic resource of copper-nickel sulfide mineralization. This region has been explored by several mineral resource development companies for more than twenty years, and recently two firms, AMAX and International Nickel Company, have considered commercial operations. These exploration and mine planning activities indicate the potential establishment of a new mining and processing industry in Minnesota. In addition, these activities indicate the need for a comprehensive environmental, social, and economic analysis by the state in order to consider the cumulative regional implications of this new industry and to provide adequate information for future state policy review and development. In January, 1976, the MEQB organized and initiated the Regional Copper-Nickel Study.

The major objectives of the Regional Copper-Nickel Study are: 1) to characterize the region in its pre-copper-nickel development state; 2) to identify and describe the probable technologies which may be used to exploit the mineral resource and to convert it into salable commodities; 3) to identify and assess the impacts of primary copper-nickel development and secondary regional growth; 4) to conceptualize alternative degrees of regional copper-nickel development; and 5) to assess the cumulative environmental, social, and economic impacts of such hypothetical developments. The Regional Study is a scientific information gathering and analysis effort and will not present subjective social judgements on whether, where, when, or how copper-nickel development should or should not proceed. In addition, the Study will not make or propose state policy pertaining to copper-nickel development.

The Minnesota Environmental Quality Board is a state agency responsible for the implementation of the Minnesota Environmental Policy Act and promotes cooperation between state agencies on environmental matters. The Regional Copper-Nickel Study is an ad hoc effort of the MEQB and future regulatory and site specific environmental impact studies will most likely be the responsibility of the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency.

GEOLOGY OF THE REGIONAL COPPER-NICKEL STUDY AREA

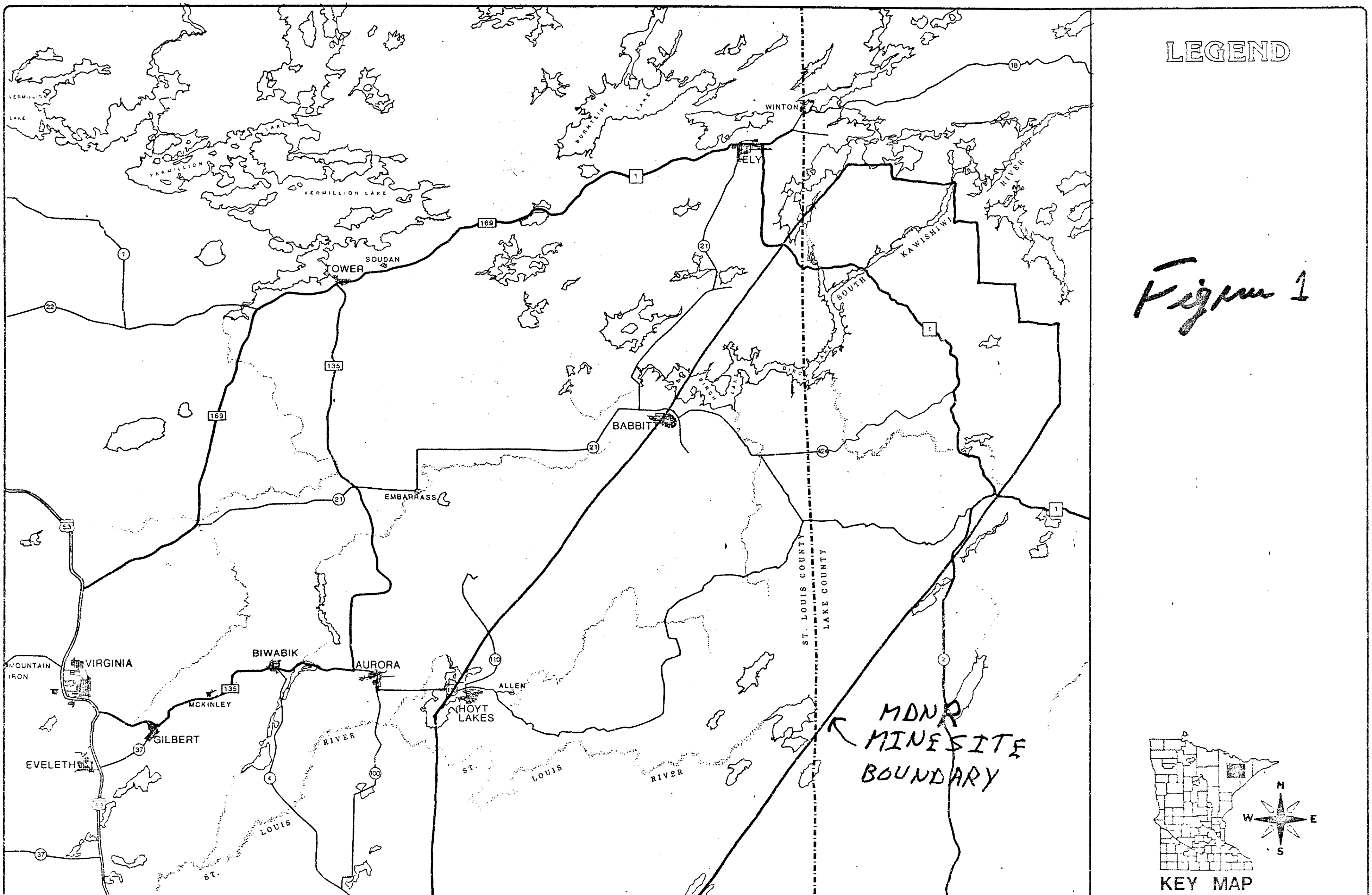
I. INTRODUCTION

A) General Statement

This report is designed to summarize and synthesize material concerning the bedrock geology and sulfide mineralization of the Regional Copper-Nickel Study Area (Study Area); specifically, the MDNR Minesite Area compiled by numerous people in recent years. The reports range from Master's thesis to published articles to various reports done by state agencies specifically for the MEQB Regional Copper-Nickel Study. The major geologic work including field work, petrographic analyses, and mineral composition in recent years have been done by various personnel of the Minnesota Geological Survey and Department of Geology and Geophysics at the University of Minnesota. A resource estimate of the nature and amount of copper-nickel sulfide mineralization has been completed by the Minnesota Department of Natural Resources. Numerous other people and agen-cies have been involved in various aspects of the regional impact of mining on northeastern Minnesota.

B) Location of Area and Scope of Study

The MDNR Cu-Ni Minesite Area is part of the Regional Cu-Ni Study Area in northeastern Minnesota (Figure 1), covering over 1,300 sq km (approximately 500 sq mi) and including most of the known copper-nickel mineralization that occurs at or near the basal contact of the Duluth Complex. The bedrock geology consists of Lower Precambrian metavolcanic, metasedimentary, and granitic rocks of the western Vermilion district, Middle Precambrian metase-dimentary rocks, and various mafic intrusive rocks assigned to the Upper Precambrian Duluth Complex



MEQC REGIONAL COPPER-NICKEL STUDY

(Figure 2). In general the MDNR Minesite Area is extensively forested by a variety of coniferous trees such as pine and spruce as well as birch, aspen, and various other deciduous trees. The topography can be described as gently rolling with numerous northeast-southwest trending ridges separated by low swampy area. Numerous lakes are found throughout the area.

This report attempts to summarize and synthesize geologic data and information concerning the bedrock geology. Necessarily it will not cover in extensive detail all of the detailed knowledge in an effort to provide an overall understanding of the geology, and all the geologic units described in the area, at the present time relate to one another and the general nature of the Cu-Ni sulfide mineralization. Since the Minesite Area, as designated by the MDNR, contains most of the known Cu-Ni sulfide mineralization the more detailed portions of this report are confined to that area. The more technical words used in this report are defined in the glossary located near the end of the report. However, many of the names used in this report, such as Puckwunge and Kawishiwi, are merely names assigned on the basis of a nearby geographic feature (i.e. the Puckwunge Formation was named for Puckwunge Creek and Kawishiwi is derived from the South Kawishiwi River).

C) Major Industries in the Area

The major industries in the Study Area are taconite mining, logging, and tourism. Taconite mining, the major heavy industry, involves the processing of low grade iron ore (approximately 20-30% Fe) into pellets (approximately 60-65% Fe) for use in steel making. Logging is also a major industry in the area pro-ducing several types of wood for various lumber products. The third major industry in the area is tourism with a wide range of both summer and winter activities. The Boundary

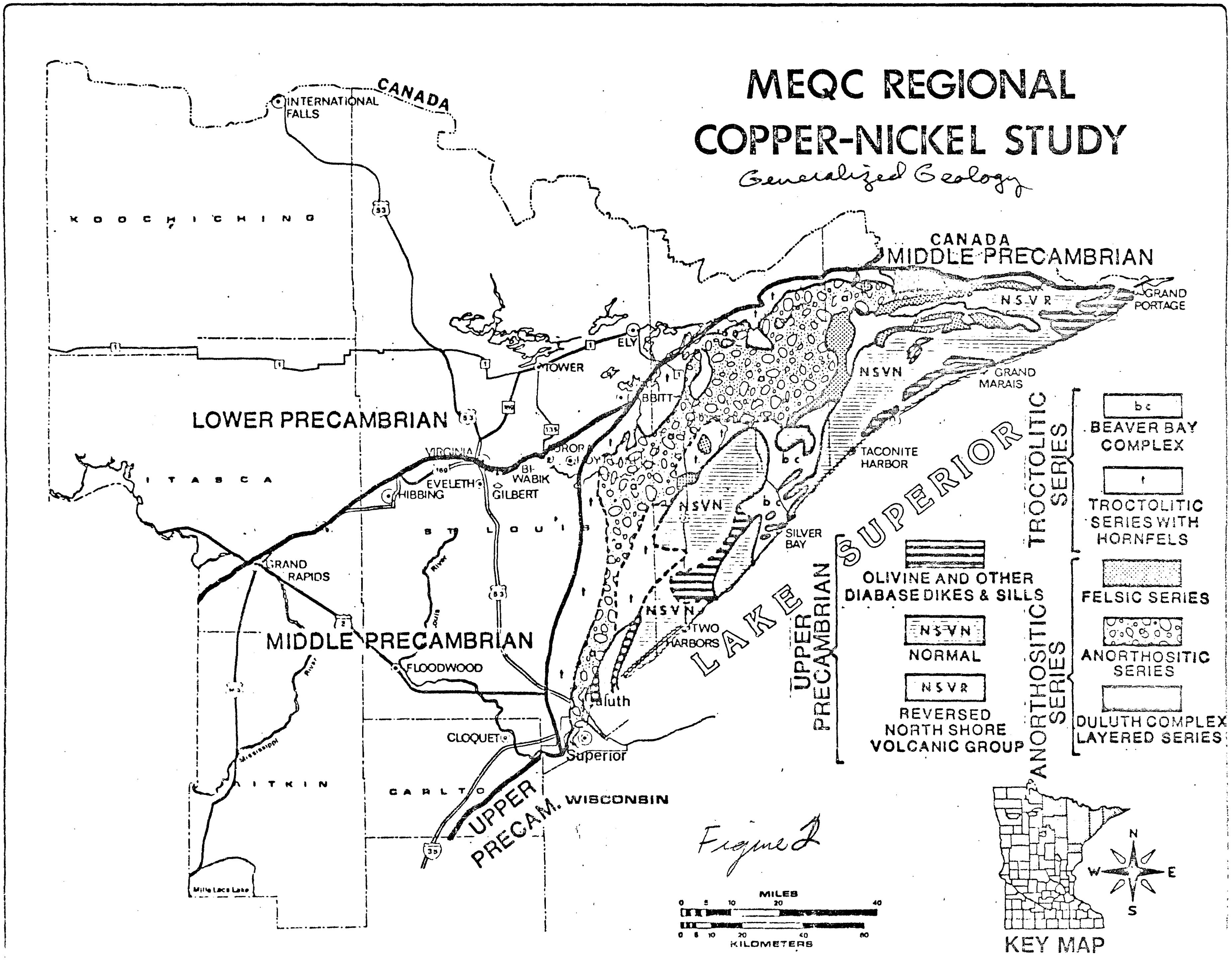

MEQC REGIONAL
COPPER-NICKEL STUDY
Generalized Geology
CANADA
INTERNATIONAL FALLS
KOOCHICHING
ITASCA
ST. LOUIS
AITKIN
CARLTON
LOWER PRECAMBRIAN
MIDDLE PRECAMBRIAN
CANADA
MIDDLE PRECAMBRIAN
UPPER PRECAM.
WISCONSIN
ELY
TOWER
VIRGINIA
EVELETH
HIBBING
BIWABIK
GILBERT
GRAND RAPIDS
FLOODWOOD
CLOQUET
Duluth
Superior
GRAND PORTAGE
GRAND MARAIS
TACONITE HARBOR
SILVER BAY
TWO HARBORS
NSVR
NSVN
bc
LAKE SUPERIOR
UPPER PRECAMBRIAN
OLIVINE AND OTHER DIABASE DIKES & SILLS
NSVN
NORMAL
NSVR
REVERSED NORTH SHORE VOLCANIC GROUP
TROCTOLITIC SERIES
bc
BEAVER BAY COMPLEX
t
TROCTOLITIC SERIES WITH HORNFELS
ANORTHOSITIC SERIES
FELSIC SERIES
ANORTHOSITIC SERIES
DULUTH COMPLEX LAYERED SERIES
MILES
0 5 10 20 40
0 5 10 20 40 60
KILOMETERS
N
W
E
S
KEY MAP
Mille Lacs Lake

Figure 2

Waters Canoe Area (BWCA) located, in part, in the northern and eastern parts of the Study Area is a wilderness area preserved for canoeing, hiking, and other nonmotorized related activities.

The presence of extensive Cu-Ni sulfide mineralization at the base of the Duluth Complex creates the potential for another major industry in the area if mining of the sulfides is economically feasible and permitted by the State of Minnesota. Although the mineralization is extensive, it is very disseminated, which results in a marginally economic to subeconomic deposit at the present time. As technology develops for concentrating and extracting the metals and/or demand increases the mineralization may become economic to mine.

II. REGIONAL GEOLOGY

A) General Statement

A fairly detailed summary of the Precambrian geology of northeastern Minnesota is presented in this report. A thorough understanding of the regional geology is needed to evaluate the geology of any single area. The Pleistocene geology of the MDNR Minesite Area is also presented. Glaciation has significantly affected the region and influenced the development of many present day landforms.

The generalized stratigraphy and structure of the Lower Precambrian rocks of northeastern Minnesota has been described by Goldich and others (1961), Morey and others (1970), and Sims (1976a and b). The Middle Precambrian rocks have been described by White (1954) and Morey (1965, 1969, 1973a and b). General descriptions of the Late Precambrian rocks have been compiled by Halls (1966), Craddock (1972c), Green (1972), and Weiblen and Morey (1975). The Pleistocene history of the area has been studied by Wright (1972), Stark (1977), and Olcott and Siegel (1978) for the Regional Copper-Nickel Study group. The general chronologic and stratrigraphic sequence of Precambrian rocks in northeastern Minnesota is summarized in Table 1, and a generalized map of the geology of northeastern Minnesota is presented in Figure 2. Of these, the Lower and Middle Precambrian rocks were deformed and metamorphosed to varying degrees by several episodes of faulting and intrusion. The majority of the faults trend northeast while a few trend in an east-west direction.

B) Early Precambrian Rocks

1) Metavolcanic and Metasedimentary Rocks

Metavolcanic and metasedimentary rocks occur extensively as a linear belt extending from west of Tower, Minnesota, to Saganaga Lake on the International Boundary and then on eastwad into Ontario. The belt is termed the Warwa belt in Canada while in Minnesota it is part of the Vermilion district (Sims 1972a). The stratigraphic sequence of the Vermilion district consists of four formations as defined by Morey and others (1970) and Sims (1976b). The oldest formation is the Ely Greenstone which consists dominantly of mafic volcanic rocks of basaltic and basaltic andesite affinity. It comprises a complex accumulation of mainly subaqueous volcanic lava flows and forms a volcanic pile that has been severely distorted by polyphase deformation, metamorphism, and faulting (Hooper and Ojakangas 1971, Sims 1972a). Included as part of the Ely Greenstone is the Soudan Iron Formation. It is composed of several varieties of fine-grained ferruginous chert which are intergradational (Sims 1972b). It is intercolated with the Lake Vermilion Formation Knife Lake group described below.

The Ely Greenstone is overlain by the Lake Vermilion Formation and the Knife Lake Group. The Lake Vermilion Formation is found in the western part of the

Table 1.

ERA	PERIOD-SYSTEM	MAJOR SEQUENCE	FORMATION	OROJENY	INTRUSIVE ROCKS
0.9 B.y. -----	----- -----	----- -----	----- ----- -----	----- -----	----- ----- ---- ---
			Hinckley sandstone		
			Fond du Lac sandstone	Bayfield Group	
		Oronto Group	Freda Sandstone		
			Novesuck shale		
			Copper Harbor		sills at Duluth
Late			Conglomerate		Beaver Bay Complex
Precambrian	Keewenawan				-Duluth Complex-Melle
					Logan Intrusives
		North Shore			
		Volcanic Group	undivided		
			Puckwunge Fm.		
1.7 B.y. -----	----- -----	----- -----	unconformity ----	--- Penokean	
			Virginia Fm=Rove Fm=Thomson Fm		
Middle		Animikie	Biwabik Fe-Fm=Gunflint		
Precambrian	Huronion	Group	Pokegama Qtzite=		
					Snowbank ?
2.5 B.y. -----	----- -----	----- -----	uncomformity ----	--- Algoman	Giants Range batholith
					Vermilion massif
	Timiskemian		Newton Lake Fm.		
		Knife Lake Group	Knife Lake Group		
(? B.y.) -----	----- -----	----- -----	----- ----- -----	--- Laurentian	Saganaga tonalite
			Lake Vermilion Fm.		
Early			Soudan Iron-Formation		
Precambrian	Ontarian	Keewatin Group	Ely Greenstone		

must be corrected for typos, etc

Table I

Era	Period - System	Major Sequence	Formation	Orogeny	Intrusive Rocks.
0.9 B.y.					
			Hinckley sandstone, Fond du Lac sandstone } = Bayfield Group.		
Late Precambrian	Keweenawan	Oronto Group	Freda Sandstone Nonesuch shale Copper Harbor Conglomerate		
		North Shore Volcanic Group	undivided		Sills at Duluth Beaver Bay Complex - Duluth Complex - Mel Logan Intrusives
			Puckwunge Fm.		
1.7 B.y.			unconformity	Penokean	
Middle Precambrian	Huronian	Animikie Group	Virginia Fm = Rove Fm = Thomson Fm Biwabik Fe-Fm = Gunflint Pokegama Qtzite =		Snowbank pluton Giants Range batholith
2.5 B.y			unconformity	Algoman	Vermillion massif
	Timiskamian		Newton Lake Fm.		
(? B.y)		Knife Lake Group	Knife Lake Group Lake Vermilion Fm.	Laurentian	Saganaga tonalite.
Early Precambrian	Ontarian	Keewatin Group.	Soudan Iron-Formation. Ely Greenstone.		

Vermilion district while the Knife Lake Group predominates in the eastern part (Figure 2). Both units are characterized, in general, by a sequence of felsic and intermediate volcaniclastic rocks at the base grading upward into volcanogenic graywacke, graywacke, and slate (Morey and others 1970, Sims 1972c, Ojakangas 1972). The Lake Vermilion Formation and Knife Lake Group are con-sidered, in part, to be stratigraphically equivalent. They have been given different names because of the inability to trace the Knife Lake Group from the type locality near Knife Lake to the Lake Vermilion area (Morey and others 1970).

Overlying the Knife Lake Grup in the vicinity of Ely is the Newton Lake Formation which consists of subaqueou mafic and felsic volcanic rocks ranging from kmatiites to dacites. Also present are interformational sediments, volcaniclastic sediments, and various types of pyroclastic deposits (Sims 1972c, Schulz 1977).

All of the volcanic and sedimentary rocks of the Vermilion district have been metamorphosed in varying degrees from greenschist facies to upper amphibolite facies. The majority of the rocks are greenschist facies with amphibolite facies becoming dominent near the "granitic" intrusives in the area (Sims 1976a and b), which will be discussed in the next section. The rocks, especially the Ely Greenstone and Newton Lake Formation, are intruded by metadiabase (Sims 1972). The Vermilion district in general has been subjected to polyphase deformation and at least three periods of faulting.

2) Vermilion Massif, Giants Range Batholith, Related Rocks

Following deposition of the volcanic and sedimentary rocks large intrusions of granitic material were emplaced during the Algoman orogeny from 2.75 to 2.5 b.y. (Prince and Hanson 1972). The earliest of these intrusions was the Saganaga tonalite which cut the Ely Greenstone and part of the Knife Lake Group. It provided clastic debris which was incorporated into the uppermost part of the Knife Lake Group (Sims 1972c). Almost contemporaneous with but slightly later than the Saganaga tonalite, the Vermilion massif and Giants Range batholith were emplaced. These intrusions form the borders of the Vermilion district on the north and south, respectively.

The Vermilion massif consists largely of a sequence of granitic rocks with associated migmatites. The major rock types are quartz diorite, diorite, grandodiorite, granite, and amphibolitic and biotitic migmatites (Southwick 1972). The Giants Range batholith has been divided into two major rock groups by Sims (1976b). The western part consists of older granitic and tonalitic plutons that in general trend N.55^{o}E. The younger eastern part is comprised of monzonite and quartz monzonite. Other major intrusive bodies in the region include the Snowbank pluton which consists of monzonie and quartz monzonite similar to the eastern part of the Giants Range batholith (Sims 1976a and b).

C) Middle Preçambrian

1) General Statement

Middle Precambrian rocks in the region are represented by a sequence of sedimentary rocks. In northeastern Minnesota these rocks form the Mesabi Range while in extreme northeastern Minnesota and Ontario they form the Gunflint Range (Figure 2).

2) Mesabi Range

The Mesabi Range, comprised of the Pokegoma Quartzite, Biwabik Iron Formation, and the Virginia Formation, extends from southwest of Grand Rapids east-northeast to Birch Lake near Babbitt. The general attitude of the rocks is N.55°-65°strike E.5°-20°S.E. dip. Over much of its extent it is underlain by the Giants Range batholith although locally it is underlain by various types of Lower Precambrian metasedimentary and metavolcanic rocks of uncertain stratigraphic position (Sims et al. 1970).

The Pokegama Quartzite forms a thin basal unit of feldspathic quartzite and graywacke along with some quartzose argillite (Morey 1972). It is discontinuously exposed in the area and therefore is not shown on Figure 2.

The Biwabik Iron Formation is the best known of the Middle Precambrian units because of the extensive open-pit mining of taconite, a low grade iron ore containing 25 to 30 percent iron which is used for making steel. The iron formation has been divided into four members which are: 1) lower cherty; 2) lower slaty; 3) upper cherty; and 4) upper slaty (White 1954). The general attitude of the iron formation is the same as that mentioned above for the entire Mesabi Range although it is modified locally by the preence of folds and faults as discussed below. The Biwabik Iron Formation has been extensively studied by a number of people (Wolff 1917, Gruner 1946, White 1954, French 1968, Bonnichsen 1969a and 1975) and the reader is referred to these studies for more detailed descriptions.

The Virginia Formation conformably overlies the Biwabik Iron Formation and has the same general attitude. It extends over the same area but is inferred to extend much further south under the glacial drift and is thought to be equivalent to the Thomson Formation in east-central Minnesota (Morey 1973 a and b). It is dominated by argillite, graywacke, and siltstone with subordinate amounts of carbonaceous rocks such as limestone, dolomite, and carbonaceous graywacke and argillite (Morey 1972).

The Mesabi Range in general consists of a homocline that strikes east-northeast and dips 5° to 20° southeast as noted above. Developed within this framework are a number of structural features. Most notable are a number of southwestward plunging synclines and anticlines. These include the Virginia syncline and Eveleth Anticline which make up the Virginia horn (Morey 1972). The trends of minor folds, however, is at right angles to the regional strike although a few are nearly parallel to the strike (White 1954). Also present are a number of faults trending N.75°W. strike and N.20°W. dip and northeast which are more prominent where the Mesabi range is underlain by Lower Precambrian metasedimentary and metavolcanic rocks (Morey 1972). In general, the folding and faulting is not significant where the rocks are underlain by the Giants Range batholith (White 1954). The major jointing directions in the Animikean rocks are N.10°E. strike, N.45°W. dip, and N.80°W. strike with N.75°E. dip being a minor joint direction. The joints dip from 70° to vertical (White 1954).

The extreme eastern part of the Mesabi Range (Figure 2) has been metamorphosed by the intrusion of the Duluth Complex which upgraded the iron formation from lower greenschist facies to pyroxene hornfels facies (Bonnichsen 1969a). Presumably the Virginia Formation has undergone equivalent metamorphism but the effects of metamorphism are less well known because the Duluth Complex-Virginia Formation contact cannot always be defined accurately. In addition to the meta-morphism the area appears to have undergone some kind of structural complica-tions as the strike abruptly changes from the regional value of N.55°-65°E to N.30°-40°E. and the dip increases from 5°-20°S.E. to 20°-70°S.E. Further northeast, the Duluth Complex has effectively cut out all Animikean rocks although inclusions of hornfels and Biwabik-type iron formation are found locally.

3) Gunflint Range

The Gunflint Range consists of the Kakabeka Quartzite, Gunflint Iron Formation and the Rove Formation in ascending stratigraphic order. These units have been correlated with those present in the Mesabi Range described above and in general the stratigraphy and structure are the same. The major exception is the presence of numerous dikes and sills in the Rove Formation. These are referred to as the Logan Intrusions and are Middle to Late Precambrian in age (Weiblen and others 1972b, Hanson and Malhotra 1971, Hanson 1975). Goodwin (1956) and Morey (1967, 1969) have described the nature of the Gunflint Iron Formation and Rove Formation in detail.

D) Late Precambrian (Keweenawan)

1) General Statement

Late Precambrian (Keweenawan) rocks are exposed over much of northeastern Minnesota (Figure 2) and consist of sediments, subaerial volcanic flows, intraflow sediments, and mafic intrusive rocks assigned to the Duluth Complex. The Keweenawan rocks in northeastern Minnesota have been divided into three units which are: 1) the Puckwunge Formation; 2) the North Shore Volcanic Group; and 3) the Duluth Complex.

2) Puckwunge Formation

The Puckwunge Formation forms a thin (approximately 100 ft) basal unit of Keweenawan Series. It is exposed north of Hovland (Figure 2) and consists of cross-bedded sandstone with a local occurrence of basal conglomerate. It strikes east-west and dips gently southward (Craddock 1972c). The Puckwunge Formation disconformably overlies the Rove Formation and in turn is unconformably overlain by the North Shore Volcanic Group (Mattis 1972). West of Duluth in a similar stratigraphic juxtaposition, approximately 25 feet of quartzite and pebble conglomerate are found underlying the lowermost exposed Keweenawan lava flow and overlying the Middle Precambrian Thomson Formation. However, these sediments are believed to represent interflow sediments on basis of a nearby well log (Mattis 1972).

3) North Shore Volcanic Group

The North Shore Volcanic Group is exposed in an arcuate pattern from Duluth to Grand Portage, a distance of 240 km. It generally consists of subaerial lava flows and interflow sedimentary rocks reaching a thickness of 7.5 to 9 km (White 1966, Green 1972). The flows have been dated at 1.1-1.2 b.y. by Rb-Sr dating (Faure and others 1969). The lava flows are underlain by the Middle Precambrian Thomson and Rove Formations near Duluth and Grand Portage, respectively. The North Shore Volcanic Group overlies the Duluth Complex and related intrusive rocks, some of which intrude the lava flows.

The volcanic rocks have been divided into two groups on the basis of paleomagnetic character. The lower unit is made up of flows with reversed paleomagnetism while the majority of the lava flows are assigned to the upper, normally magnetized group (Green 1972). The structural attitude of the volcanic rocks changes from near north-south strike with gentle (15°) easterly dip near Duluth to near east-west strike with a 15° south dip near Grand Portage. The recogni-tion of subtle changes in the attitudes of the flows has defined two large basins of lava accumulation. A southern basin extending from Duluth to northeast of Tofte and a northern basin from near Lutsen to Grand Portage (Figure 2). Although the flows now dip toward Lake Superior the original direc-tion of lava movement was away from the lake (Green 1972).

The North Shore Volcanic Group resembles plateau lava sequences such as the Columbia River Plateau, Deccan Traps of India, and the Tertiary flows of eastern Iceland in occurrence and/or chemistry. The lava flows consist mainly of several varieties of olivine basalt, quartz tholeiite, andesite, trachyandesite, and various felsites. Although individual flows have been traced for up to 32 km along strike, the lateral continuity of many flows cannot be established due to poor exposure (Green 1972).

4) Duluth Complex

a) General Statement

The Duluth Complex is a long arcuate mafic intrusion of Keweenawan age. It has been dated at approximately 1.1 to 1.2 b.y. (Silver and Green 1963, Faure and others 1969). The Duluth Complex extends from Duluth on the south, north-northeast toward Ely and then east-northeast to a point near Hovland (Figure 2). It presents a gross dish shape with a gentle dip of 10^{o}-30^{o} to the east, southeast, and south as one progresses from Duluth to Ely to Hovland. The Duluth Complex has been subdivided into three gross units on the basis of mineralogy and textue by nearly all who have worked in the area (Grout 1918a through e, Taylor 1964, Green and others 1966, Phinney 1969, Nathan 1969, Weiblen and others 1972a, Bonnichsen 1972a and b, Davidson 1972). The three units are the anorthositic series, the troctolitic series, and the felsic series or granophyres (Weiblen and Morey 1975).

b) Anorthositic Series

The anorthositic series consists of rocks which have greater than 80 percent plagioclase with olivine, augite, and various oxide minerals occurring interstitially to the tabular plagioclase crystals (Phinney 1969, Davidson 1969, Weiblen and Morey 1975). Plagioclase is usually the only cumulate mineral wih the interstitial minerals being intercumulus (forming from melt trapped in the plagioclase framework (Jackson 1967, 1971). The anorthositic rocks occupy the central portion of the Duluth Complex bounded on the west and north by rocks of the troctolitic series and on the east and south by the troctolitic series, felsic series, and locally the North Shore Volcanic Group (Figure 2). The strongest evidence for the anorthositic series rocks being a separate, early event is found in the Duluth area where Taylor (1964) described several exposures which exhibited anorthositic series rocks crosscut by rocks of the troctolitic series. In the same area are several exposures of the North Shore Volcanic Group crosscut by the anorthositic series. When plotted on the mafic rock diagram (Figure 3) of Phinney (1972a) most of the anorthositic series rocks plot as anorthositic gabbro, gabbroic anorthosite or anorthosite.

Nathan (1969) described a sequence of layered rocks consisting primarily of troctolite, gabbro, oxide gabbro, and norite. On the basis of crosscutting relationships, mineralogy, bulk chemistry, and reversed polarity these rocks have been correlated with the reversed flows of the North Shore Volcanic Group and are therefore thought to predate the rest of the anorthositic series which is normally magnetized (Weiblen and Morey 1975).

c) <u>Troctolitic Series</u>

As described above, the troctolitic series bounds the anorthositic series on all sides except for a few places where anorthositic rocks are in contact with felsic rocks, the North Shore Volcanic Group or Early Precambrian rocks. The troctolitic rocks are made up of plagioclase, olivine, pyroxenes, and oxide

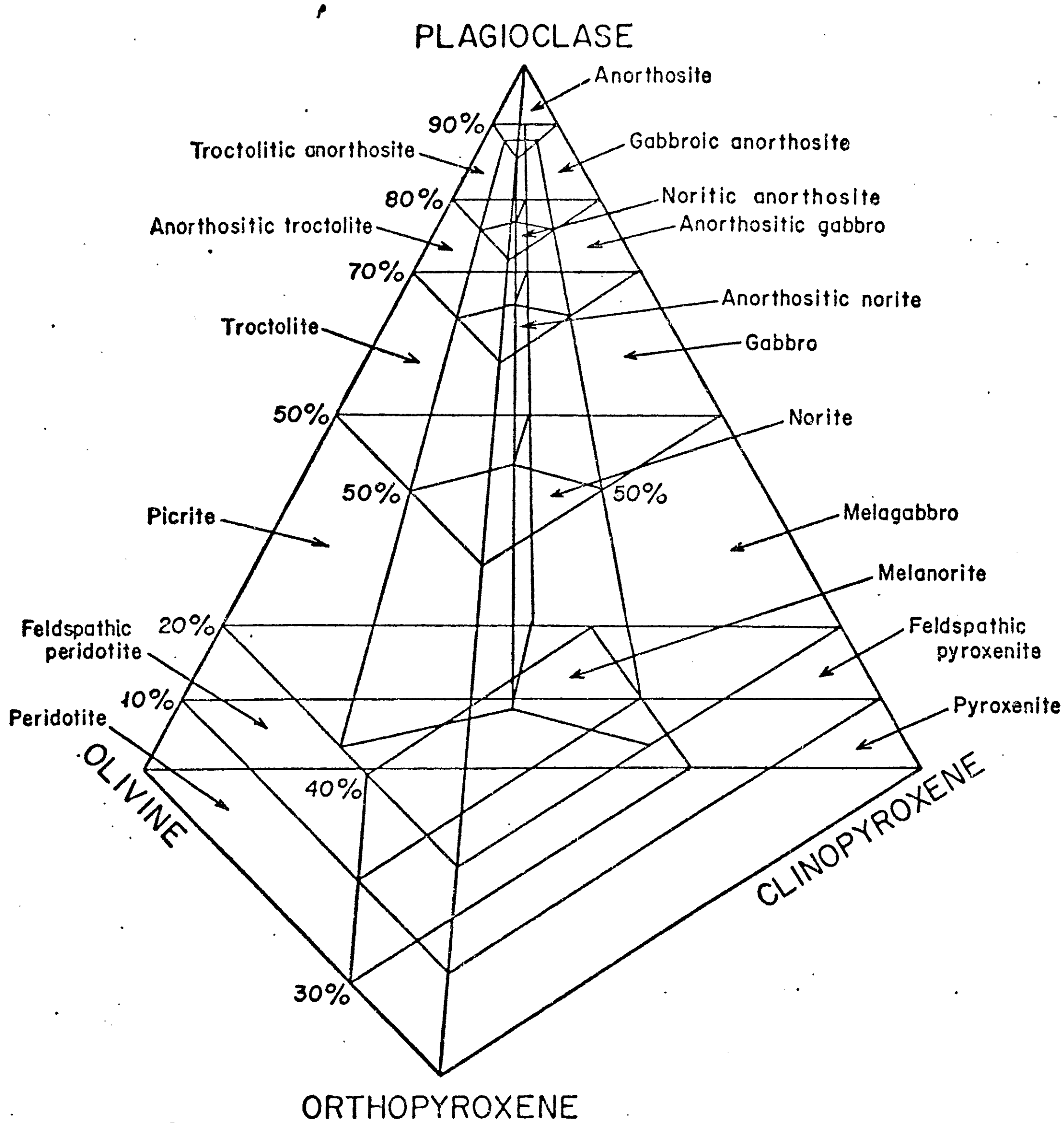


Figure 3. Mafic rock classification scheme for the Duluth Complex (after Phinney, 1972a).

minerals. Plagioclase is the predominant mineral making up 50-80 percent of the rocks with olivine the second most abundant mineral making up 10-40 percent. Locally the percentage of olivine increases or decreases so that the rock is a pacite or anorthosite, respectively. Using the rock classification diagram (Figure 3) suggested by Phinney (1972a) most of the troctolitic rocks plot as troctolitic anorthosite, anorthositic troctolite or troctolite. Olivine is commonly cogenetic to slightly later than the plagioclase while pyroxene (clino-and ortho-) and oxide minerals are usually intercumulus (Bonnichsen 1969b and 1972a, Davidson 1969 and 1972, Weiblen and Morey 1975).

Gabbroic rocks (Figure 3) are not prominent in the Duluth Complex and occur in restricted areas. One major occurrence of gabbroic rocks is in the Bald Eagle Intrusion which is a funnel shaped intrusion with a core of gabbro and an outer rim of troctolite (Weiblen 1965)(Figure 2). Olivine gabbro and gabbro have been reported by Davidson (1969, 1972) as underlying parts of the eastern Duluth Complex (Figure 2).

d) Felsic Series

Felsic rocks are scattered throughout the eastern part of the Duluth Complex (Figure 2). They include granodiorite, ferrogranodiorite, adamellite, syenodiorite, granite, and granophyre (Taylor 1964, Davidson 1969). These rocks have gradational to sharp contacts with rocks of the anorthositic and troctolitic series. They vary from being clearly intrusive into the older rocks to having an ambiguous relationship to other units of the Duluth Complex (Taylor 1964, Davidson 1972, Weiblen and Morey 1975). Weiblen and Morey (1975) interpret all of the felsic rocks as being genetically related to the anorthositic series and the result of differentiation of a single low-alumina magma while the troctolitic series is accounted for by a second high-alumina magma that was tapped periodically.

e) General Structure of the Duluth Complex

The overall structure of the Duluth Complex is that of a dish-shaped structure that dips gently to the east and south. This uncomplicated picture persisted from the early work by Elftman (1898) and Grout (1918) until the past few years. Sims (1973) noticed several apparent offsets of the basal contact of the Duluth Complex near Ely and inferred that faults may be present. Nathan (1969) mapped one northwest trending fault on the basis of offset units and suggested that several others may be present. Davidson (1969) noted the presence of several strong topographic lineaments and suggested that they might be caused by fracture zones. Stevenson (1974) mapped several north-northeast trending faults in a small olivine gabbro intrusion (Sonju Lake Intrusion) near Finland, Minnesota, that forms part of the Beaver Bay Complex. Beyond these scattered occurrences there has been no substantial documentation of extensive faulting in the Duluth Complex.

Weiblen and Morey (1975) suggest that faulting may be much more extensive than previous mapping indicates and proposed a model for the intrusion of the Duluth Complex based on extensive faulting associated with a rifting environment. They also stressed the multiple intrusive nature of the Duluth Complex. Beyond this no data on the structural nature of the Duluth Complex has been collected except for foliation and modal layering data collected in the field and even this data has not been analyzed in detail for possible structural implications.

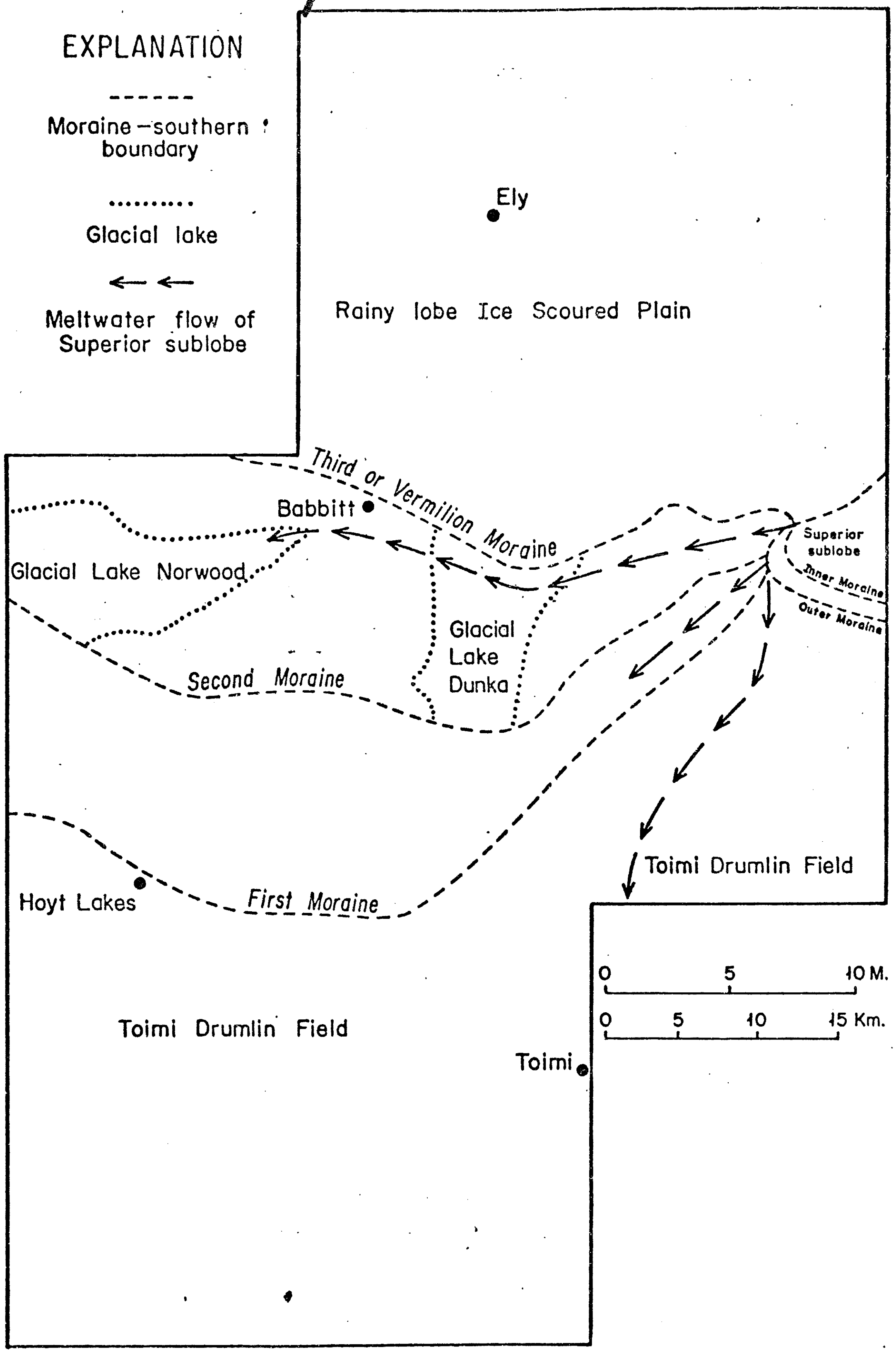
E) Pleistocene Geology

The following summary of the Pleistocene geology is confined mainly to part of the MDNR Minesite area (Figure 4) and is taken largely from Stark (1977) and in part from Wright (1972). The earliest evidence of glaciation in the area is a dark brown, calcareous till identified by Stark (1977) in the Dunka pit of Erie Mining Company. It lies directly atop the Biwabik Iron Formation and is overlain by glaciofluvial sediments and bouldery till associated with later glaciation. Stark (1977) suggests that this till may be correlative with a basal till identified by Winter and others (1973) further west and have an age of more than 35,000 years B.P. They suggest a northwesterly source for the till.

The first major glaciation in the area is represented by the St. Croix phase of the Rainy and Superior lobes during Wisconsin time (20,000 years B.P.). This major advance deposited a thick mantle of glacial materials and produced the Toimi drumlin field which dominates the southern part of the area (Figure 4). The overall trend of glacial movement is S.45°W. as determined from the long axes of the drumlines (Wright 1972). The St. Croix phase reached its terminus in central and east-central Minnesota with the deposition of the St. Croix moraine (Stark 1977). A sample of the till from near Toimi, Minnesota is described by Stark (1977) as being red and sandy with pebbles indicative of a source to the northeast in the Lake Superior basin.

Following wastage of the St. Croix phase glaciation the Rainy and Superior lobes again advanced into the Hoyt Lakes-Kawishiwi area producing the final glacial deposits. This advance has been termed the Automba phase by Wright (1972). The Rainy lobe advanced from the north-northeast as determined from glacial striations and "rock drumline" trends and formed a series of three moraines (Stark 1977). At its terminus the Rainy lobe was intercepted by a sublobe of the Superior lobe advancing out of the Lake Superior basin (Figure 4). The Superior

Figure 4 ~~Source~~ Pleistocene Geology and Glacial Evidence in Minesite Area



sublobe appears to have advanced into the area slightly before the Rainy lobe based on the contortion of the two southernmost moraines of the Rainy lobe around the Superior sublobe moraines (Stark 1977)(Figure 4).

The Rainy lobe deposited a basal bouldery till with the majority of the pebbles being derived from the Duluth Complex, and Giants Range batholith and related granitic rocks. Minor amounts of volcanoclastic, metasedimentary, iron-formation and greenstone pebbles are also present. A red, sandy till is associated with the Superior sublobe in the area. It is identified mainly by the red color and pebbles of the North Shore Volcanic Group and the Duluth Complex along with minor amounts of red sandstone, diabase, metasedimentary, greenstone, and granite pebbles (Stark 1977).

As the Rainy lobe wasted to its second moraine glacial outwash from the Superior sublobe was deposited on the first moraine. With continued wastage the Rainy lobe retreated to the third moraine or as it is more commonly known, the Vermilion moraine. During and following this wastage outwash from the Superior sublobe moved westward along the front of the Vermilion moraine and formed glacial lakes Dunka and Norwood which were filled with glaciofluvial sands and gravels. North of the Vermilion moraine, the Rainy lobe produced an ice scoured plain characterized by thin drift and elongate bedrock ridges in areas underlain by the Duluth Complex (Stark 1977).

In summary, the area can be divided into three areas (Figure 4) based on the surficial geology. A northern area which is an ice scoured plain and is characterized by a thin and discontinuous mantle of till. This is also the area in which almost all of the outcrops of the Duluth Complex are found. A second central area extending from Hoyt Lakes east-northeast across the entire region and characterized by extensive moraines and glaciofluvial sediments. The third area comprises the southern part of the area and is dominated by the Toimi drumlin field, associated glacial deposits, and a thick mantle of glacial materials. In the last two areas only rare and isolated exposures of the Duluth Complex have been found.

III. GEOLOGY OF THE STUDY AREA

A) Giants Range Batholith

The Giants Range batholith underlies much of the northwestern part of the Study Area. It is composed mainly of monzonite and quartz monzonite (a rock similar to granite but with roughly equal proportions of plagioclase and potassium feldspar). Hornblende is the major mafic mineral present while biotite is present in minor amounts. The Duluth Complex overlies the Giants Range batholith in the northeastern part of the Study Area, while in the southwestern part of the area sedimentary rocks of the Mesabi Range overlie the batholith. The Giants Range is unmineralized except locally near the contact with the Duluth Complex. This mineralization will be discussed in conjunction with the Duluth Complex in a later section.

B) Middle Precambrian Metasedimentary Rocks

The Middle Precambrian rocks consist mainly of the Biwabik Iron Formation and Virginia Formation. In the Study Area they comprise the extreme eastern end of the Mesabi Range.

The Biwabik Iron Formation has been divided into four members by White (1954). These include: 1) lower cherty; 2) lower slaty; 3) upper cherty; and 4) upper slaty. The unit has been and is extensively mined for taconite by several mining companies. The Biwabik Iron Formation is underlain by the Pokegama Quartzite, a thin basal clastic unit, which is present sporadically in the eastern Mesabi Range. The iron formation has been metamorphosed to pyroxene hornfels facies by the Duluth Complex (Bonnichsen 1975). The degree of meta-morphism decreases away from the contact until it is essentially unaltered at a distance of ten miles (French 1968). Figure 5 (after French 1968) shows the mineralogy and zones of degreasing metamorphism as a function of distance from the contact.

The iron formation in general consists of fine grained, finely laminated taconite (slaty members) and massive granular ferruginous chert (cherty members). Mineralogically, the unmetamorphosed parts of the iron formation consist mainly of quartz, magnetite, hematite, iron carbonates, and iron silicates (French 1968, Bonnichsen 1975). Closer to the contact with the Duluth Complex the mineralogy of the iron formation was changed due to the intrusion of the Duluth Complex. The increased temperatures caused by intrusion of the Duluth Complex produced alteration of the primary minerals to new minerals which were more stable at the higher temperatures. These new minerals include olivine, ortho-pyroxene, clinopyroxene, amphibole, as well as other less abundant minerals.

The environment of deposition for the iron formation was a shallow sea which was present in the area during the Middle Precambrian. The sediments were chemically deposited in conditions that ranged from a very quiet water to an aitated, well-aerated environment (Bonnichsen 1975). The deposition of these iron-rich sediments was terminated by the onset of clastic sedimentation which resulted in the Virginia Formation described below.

The Biwabik Iron Formation is extensively mined for taconite. The term "taconite" refers to rocks, usually iron formations, which contain 20 to 30 per-

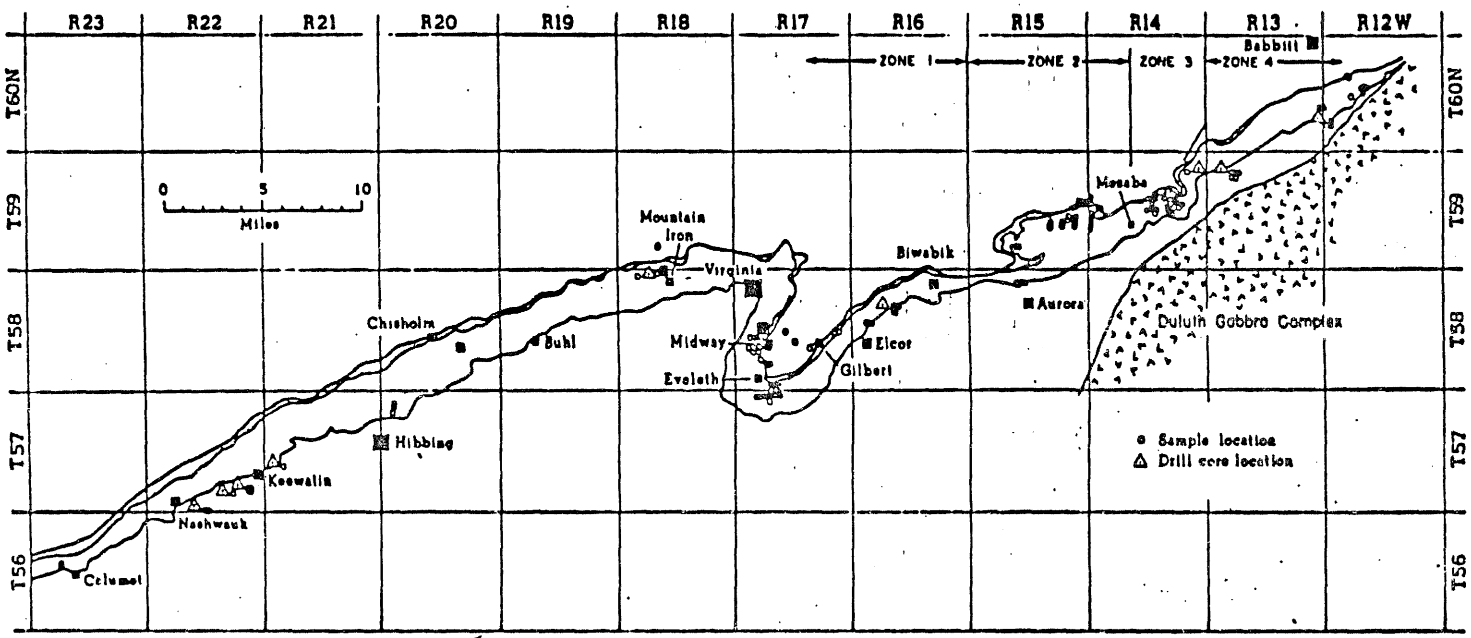


Figure 5. Generalized geologic map of the Mesabi Range, showing location of samples and boundaries of the four metamorphic zones ~~distinguished in this study~~. (After French, 1968)

cent iron. The taconite is mined by several mining companies on the Mesabi Range. The major companies in the Study Area are Reserve Mining and Erie Mining Company. ..e iron formation has been cut out by the intrusion of the Duluth Complex to the southeast and east.

The Virginia Formation comformably overlies the Biwabik Iron Formation and consists of interlayered argillite, siltstone, graywacke, quart sandstone, and carbonate rocks (White 1954, Morey 1972). It represents a period of clastic sedimentation in a deepwater, reducing environment which followed the chemical sedimentation of the Biwabik Iron Formation. Mineralogically the unmetamorphosed Virginia Formation is made up of quartz plagioclase, and microcline with chlorite, muscouite, quartz, and plagioclase and opaque minerals making up the finer-grained fraction (Morey 1972). The unit appears to thin from west to east across the area until it is cut out by the intrusion of the Duluth Complex.

The Virginia Formation has been metamorphosed by the Duluth Complex to a hornfels with cordierite, biotite, and feldspar. Pyrrhotite, graphite, and orthopyoxene are minor constituents with ilmenite, chalcopyrite, quartz, and other metamorphic minerals occurring locally (Bonnichsen 1975).

C) Duluth Complex

The Duluth Complex can be divided into two major rock series. These are an older anorthositic and felsic series and a younger troctolitic-gabbroic series (Weiblen and Morey 1975). Also included with the discussion of the Duluth Complex are inclusions which are found along and near the basal contact.

1) Inclusions

Metamorphosed inclusions found in the Duluth Complex are considered here to be of Late Precambrian age regardless of the original age of the rock. Metamorphosed inclusions are found along the entire basal contact of the Duluth Complex area in the south to the area of the North Kawishiwi River in the BWCA on the north. They consist of metvolcanic and metasedimentary rocks. For the purposes of the geologic map (Figure 6) these rocks were collectively designated as hornfels undivided (h) because it is difficult to determine the original parentage of these rocks in the field. The Biwabik-type iron formation inclu-sions were easily identified because their very distinctive quartz-magnetite-iron silicate mineralogy and their characteristic bedding have been preserved. Because of their small size they are not designated on the accompanying map (Figure 6). The size of the metavolcanic and metasedimentary inclusions varies from a few centimeters in diameter to bodies nearly 1000 meters across.

Metavolcanic hornfels in general consist, in decreasing abundance, of pla-gioclase, augite, olivine, inverted pigeonite, hyperstne, and opaque oxides. They are generally fine-grained and display a granoblastic texture. Based on their mineralogy and relict flow textures, Tyson (1976) concluded that the four occurrences of hornfels bodies in the Babbitt-Hoyt Lakes area that he examined were metamorphosed basalts originally part of the North Shore Volcanic Group. Metasedimentary inclusions are usually characterized by an assemblage of 60 to 80 percent plagioclase with varying amounts of hyperstene, cordierite, augite, biotite, and/or chlorite (Renner 1969, Fukui 1976).

The bulk of the hornfels inclusions mapped along the basal contact of the Duluth Complex in the Hoyt Lakes-Kawishiwi area are probably of metasedimentary origin. They most likely represent inclusions of Viginia Formation that forms the foot-wall in the Babbitt-Hoyt Lakes area. They are characterized by locally recogni-

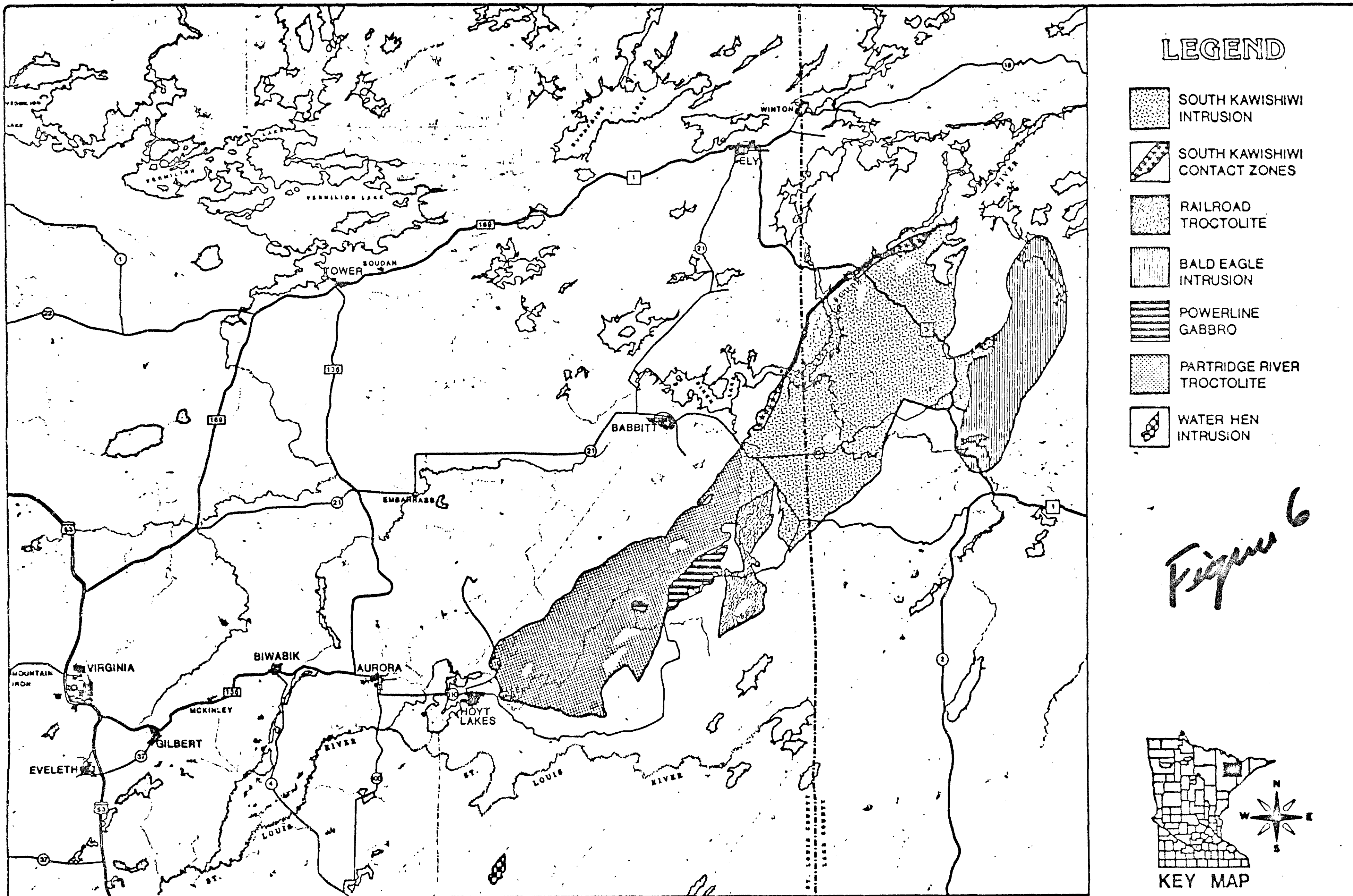


Figure 6

MEQB REGIONAL COPPER-NICKEL STUDY

BEDROCK GEOLOGY OF MAPPED TROCTOLITIC INTRUSIONS zable bedding which is reflected by a planar distribution of plagioclase and mafic minerals. The metamorphic grade varies from lower greenschist to pyroxene hornfels facies containing cordierite (Renner 1969, Bonnichsen 1972a). Some of the hornfels found near the South Kawishiwi River are similar to the measedimentary variety found in the Babbitt-Hoyt Lakes area although no footwall of Virginia Formation is present. These inclusions may represent a thin unit of Virginia Formation that has been completely disrupted and caught up in the Duluth Complex. In the Kawishiwi area a unit informally referred to as the Spruce breccia (Wager et al. 1969) contains greater than 30 percent hornfels inclusions. Most of these represent metasedimentary rocks. The Spruce breccia has been found in the cntact zone from Birch Lake to Filson Creek in Sec. 19, T.62N., R.10W. and has been encountered extensively in drill core.

Biwabik-type iron-formation inclusions are found throughout the Hoyt Lakes-Kawishiwi area in the contact zone. The inclusions vary in size from less than a meter in diameter to one hundred or more meters across. They have retained the characteristic bedding of iron-formation. Quartz and magnetite are recognizable in hand specimens, but characterization of the iron-silicate mineralogy has not been made. The largest inclusions occur some distance from the contact zone in Sec. 30, T.62N., R.10W. near Omaday Lake where a large (700 X 100 meters) inclusion of metairon-formation is bounded on the south and east by a larger body of hornfels of uncertain origin.

Some hornfelsic rocks of the contact zone in the Kawishiwi area appear to be recrystallized fine-grained troctolite or gabbro based on preliminary petrographic examination. This is particularly true of part of the large hornfels body located in Secs. 29 and 30, T.62N., R.10W. between Omaday and Nickel lakes. Hornfels in units of this type could represent chilled marginal rocks of early troctolitic-gabbroic intrusions which have been included in later intrusions.

Small meter-sized hornfels inclusions have been found at scattered localities throughout the entire area, some as far as 0.6 km from the basal contact. The origin of these inclusions is not known.

Granitic inclusions probably derived from the Giants Range batholith have been described from drill core (Bonnichsen 1974) but none have been found at the present erosional surface.

2) Anorthositic Series Rocks

In this report, peridotite and felsic rocks have been included in the anorthositic rock series following the petrogenetic and stratigraphic interpretation of Weiblen and Morey (1975).

a) Peridotitic and Noritic Rocks

Peridotite and noritic rocks are found locally in the Hoyt Lakes-Kawishiwi area. The best expoures of norite are those on Gabbro Lake in Secs. 9 and 16, T.62N., R.10W. They consist of approximately 65 percent plagioclase (An_{35-46}) and 24 percent hyperstene with augite, opaques, and biotite present in minor amounts (Phinney 1969). The norite at these localities cuts other rocks of the anorthositic series. Norites have also been described from drill core in the basal contact zone of the troctolitic series rocks, but these are probably related to the troctolitic-gabbroic rather than to the anorthositic series.

Small meter-sized masses of pyroxene-oxide-olivine peridotite have been found locally in the Study Area in the troctolitic series rocks (Weiblen and Cooper

1977). The exact relationship (intrusive or included) of these occurrences of peridotite and the norite described above to the troctolitic-gabbroic series or anorthositic series rocks is not clear from the exposures.

Larger volumes of peridotite have been intersected in drill core south of Hoyt Lakes near the basal contact of the Duluth Complex. This occurrence has been referred to as the Water Hen Intrusion (Bonnichsen 1972a; Mainwaring 1975; Mainwaring and Naldrett 1977). It consists mainly of a layered sequence of dunite, peridotite and troctolite. The relationship of the Water Hen Intrusion to the troctolitic-gabbroic or anorthositic series is obscure although P.W. Weiblen has suggested that it may be a larger example of the minor peridoite exposed at Bardons Peak south of Duluth and postulated to be genetically related to the anorthositic series rocks by an original low-alumina magma composition (Weiblen and Morey 1975).

b) Gabbroic Anorthosite and Anorthositic Gabbro (aga, ago, agu)

Anorthositic rocks are the most common rock type in the anorthositic rock series in the region. They have been divided into three units on the basis of texture and composition.

Gabbroic anorthosite (aga) was defined by Phinney (1969) and contains an average of 87 percent plagioclase (An_{58-70}), 6 percent hypersthene, and 3 percent augite as the principal minerals. The only exposures of the unit are near and northeast of Gabbro Lake. It has not been identified elsewhere in the region.

Anorthositic gabbro (ago) is characterized by clusters of oikocrysts of olivine, pyroxene, and/or oxide minerals and has been identified in the Gabbro Lake and Omaday Lake areas. Clusters of dark mafic minerals in grey plagioclase give this rock a distinctive texture which is esily recognized in the field. The petrologic origin of the clusters is not well understood, but may be due to the crystallization of trapped interstitial magma after plagioclase had already crystallized. The clusters, or oikocrysts, vary in diameter from 5 to 50 mm, but most are 5 to 20 mm in diameter. The groups of single mafic mineral grains are referred to as clusters, and optically continuous crystals are called oikocrysts. Unfortunately, it is commonly very difficult or impossible to determine in the field whether the groups of mafic minerals are clusters or oikocrysts. In field descriptions, the term cluster has been used in ambiguous cases (Beltrame 1975).

The age relationship of gabbroic anorthosite to anorthositic gabbro (aga, ago) is unknown, although Phinney (1969) suggested that the former may be older on the basis of an antiformal feature he mapped north of Gabbro Lake.

Anorthositic gabbro undivided (agu) forms the majority of the anorthositic series rocks exposed in the Hoyt Lakes-Kawishiwi area. The average range in composition is 75 to 88 percent plagioclase (An_{55-85}), 3 to 8 percent olivine (Fo_{54-65}), and 4 to 23 percent clino- and orthopyroxene. Oxide minerals and biotite are minor constituents (Phinney 1969, Beltrame 1975). Plagioclase is usually the only cumulus mineral with all other minerals being interstitial.

Reconnaissance (1:1000) mapping of an area in the middle of a large area of this unit disclosed that the area could be further subdivided with detailed mapping. The anorthositic troctolite present in this area is very similar to some of the troctolitic series rocks present further to the west in the South Kawishiwi intrusion described below. This indicates that the agu body may, in fact, be broken in places by troctolitic series rocks. It also indicates the need for further mapping in this area as other instances of troctolitic-appearing rocks in this area have been noted (Weiblen and Cooper 1977, Beltrame 1974). In the Babbitt S.E. quadrangle, south of the southern limit of exposures, anorthositic gabbro undivided (agu) has been inferred on the basis of aeromagnetic data to overlie troctolitic-gabbroic rocks (Bath et al. 1965, USGS 1969).

c) Felsic Series

Granophyre associated with the anorthositic series rocks is rare in the Hoyt Lakes-Kawishiwi area. Granophyre has ben found as dikes such as granophyric dike 15 to 20 cm wide which cuts anorthositic gabbro (agu). This occurrence is close (less than 100 meters) to a contact between anorthositic gabbro (agu) and troctolitic-gabbroic series rocks (tpg). Some small granophyric dikes have also been found that are associated with a hornfels inclusion exposed along the Erie Mining Company railroad (Bonnichsen 1970). These occurrences of granophyre consist of both fine-grained massive red rock and coarser-grained quartz-feldspar rocks which appear white to yellow in outcrop. These occurrences of granophyric rocks are now shown (Figure 6) because of their small (less than 1 meter) size.

3) Troctolitic-Gabbroic Series Rocks

a) Mixed Troctolite and Anorthositic Rocks of Uncertain Origin

In several places in the Hoyt Lakes-Kawishiwi area isolated exposures of mixed troctolitic and anorthositic rocks are found. In the Kangas Bay quadrangle several elongate bodies have been found. They consist of a variable mixture of troctolite and the anorthositic gabbro unit (ago) described above (Phinney 1967). Other exposures of these rocks define a 0.5 sq km plug-shaped body. These rocks have irregular layering and variable textural relations similar to both the anorthositic series rocks and the troctolitic rocks described below (Phinney

1969). The origin of these mixed zones is not known, although Phinney (1969) suggested that they might represent an intrusive contact zone of the troctolitic rocks in anorthositic rocks.

Southwest of August Lake isolated exposures of flow-textured troctolite are surrounded by isolated exposures of anorthositic rocks. These were interpreted by Phinney (1969) to represent possible dike or sill-like extensions of the Bald Eagle intrusion into anorthositic rocks. On the accompanying map (Figure 6) these exposures have been interpreted to represent a northeast trending contact between troctolitic (tt) and anorthositic (agu) rocks.

b) Troctolitic and/or Gabbroic Rocks Undivided

A line has been drawn on the accompanying map (Figure 6) to separate the area of extensive exposures of the Duluth Complex from the area in the southern part of the map where exposures are rare due to a thick mantle of Pleistocene glacial material. All of the known troctolitic exposures in this area have been designated with the notation (tu), and no attempt was made to relate any of the exposures to the units mapped further north. On the basis of interpretations of aeromagnetic maps (Bath et al. 1965, Meuschke et al. 1963, USGS 1969) troctolitic rocks are inferred to underlie part of this largely covered area.

c) South Kawishiwi Intrusion

The South Kawishiwi intrusion was informally named by Green, Phinney, and Weiblen (1966) to designate troctolitic-gabbroic rock exposed in the Gabbro Lake quadrangle. The areal extent of this intrusion has been considerably expanded here. It has been subdivided into five units: 1) a contact zone of troctolite with sulfide mineralization (tcz); 2) a contact zone of gabbro with sparse sulfide mineralization (tg); 3) troctolite (tt); 4) anorthosite (ta); and 5) troctolite with less than five percent augite (tap).

The contact zone of troctolitic rocks (tcz) in the Kawishiwi area is 0.5 to 1 km wide and extends from the north side of Birch Lake on the southwest to a point near the BWCA boundary on the northeast where it appears to end due to faulting. It is characterized by sulfide mineralization and extreme heterogeneity of rock types. The various rock types include dunite, picrite, troctolite, anorthositic troctolite, troctolitic anorthosite, norite, gabbro pegmatite, and gabbro. The various rock types range in grain size from fine-grained to pegmatite with many of the fine-grained rock types appearing to be recrystallized. Various types of hornfels and Biwabik-type iron formation commonly occur as inclusions in this unit. These inclusions were described in earlier section. Also present as inclusions in and near the contact zone are small (one meter to tens of meters) bodies of anorthositic series rocks. Mineralogic layering and foliation is extremely irregular in the contact zone with no systematic distribution apparent at the surface.

Gosan is fairly common in the contact zone and is indicative of sulfide mineralization. The sulfide minerals most commonly present are pyhrrhotite, chalcopyrite, cubanite, and pentlandite. Minor sulfide phases include bornite, sphalerite and pyrite as well as other sulfide minerals present in only trace amounts. For a more complete discussion of the nature of sulfide mineralization the reader is referred to Bonnichsen (1972b) and Weiblen and Morey (1976). The mineralization will also be discussed in more detail in a later section.

Based on the results of all mapping in the contact zone, the mineralization is apparently not restricted to any single rock type or to specific localities. It has been found sporadically along the entire area of the exposed part of the contact zone, and the surface expression is usually brown-stained, pitted rock (gossan). The stained and pitted appearance of the gossan is a result of oxidation and solution of sulfide minerals.

Bonnichsen (1970) has mapped a unit of gabbro (tg) along the base of the Duluth Complex south of Birch Lake. It consists of fine- to medium-grained gabbro, norite and troctolite, with variable quantitis of olivine and oxide minerals. Hornfels inclusions are common throughout the unit and are especially abundant in the subsurface (Bonnichsen 1972a and 1974). The unit contains sparse sulfide mineralization, but its exact relationship to the tcz unit is unknown. The southwest extension of the tg unit is unknown because of a paucity of exposures.

Troctolite (tt) is the most extensively exposed unit of the South Kawishiwi intrusion. It is bounded on the east and northest by the anorthositic rock series and the Bald Eagle intrusion. On the southwest it is inferred to be in fault contact with the Partridge River troctolite. The southern boundary is unknown because of lack of exposures but is inferred to be in part rocks of the anorthositic series on the basis of aeromagnetic interpretation. The troctolite is a rather uniform unit in terms of rock types and texture although both vary with distance from and along the stratigraphic contact with the contact units (tg and tcz). Parallel to the contact zone a band of troctolite 4 to 5 km wide can be distinguished from the troctolite found further to the southeast. Near the contact, inclusions of the anorthositic series rocks (agu) and hornfels (h) are relatively abundant in the troctolite. Whether the anorthositic bodies represent a single sheet(s) or are just isolated remnants of the anorthositic series ocks caught up in troctolitic magma is not clear from the present evi-dence. The troctolite host rock has an average compositional range of 65 to 85 percent plagioclase (An_{57-60}), 8 to 30 percent olivine (Fo_{50-55}), and minor amounts of pyroxene (1 to 6 percent), oxides (1 to 8 percent), and 1 to 3 per-cent biotite (Phinney 1969, Beltrame 1974). The troctolite is very homogeneous in appearance with plagioclase and olivine the only primary or cumulus minerals. All other minerals are interstitial with clinopyroxene commonly poikolitic. Orthopyroxene is commonly present but only in minor to trace amounts. It usually forms a reaction rim around olivine crystals, but rare interstitial grains are also found. Apatite has also been found locally in trace amounts in some of the rocks. Plagioclase commonly has a foliation which in general stri-kes northeast and dips 10 to 30^{o} southeast. Modal layering of olivine and plagioclase is occasionally found in this area. It almost always parallels the trend of the foliation. The modal layering is usually on the scale of a single outcrop and cannot be traced from one outcrop to another.

Gabbro to olivine gabbro has also been noted at a few localities in the troc-tolite. These occurrences are confined to single outcrops which are surrounded by troctolitic rocks. Their genetic relationship to the surrounding troctolite could not be determined in the field and they have not yet been studied in detail.

Southeast of the 4 to 5 km wide zone described above, the troctolite changes slightly in texture and mineralogy. Instead of being homogeneous with in general an even distribution of minerals, it has a marked layered appearance. The layering is shown by an accumulation of olivine crystals at the base of each layer that either abruptly or gradually gives way to a more plagioclase rich rock at the top of the layer. The top of the layer commonly contains only minor amounts of olivine. Pyroxene, oxides, and biotite are commonly present only in trace amounts throughout an individual layer. An individual layer may be a few centimeters to a meter or more in thickness and usually can be traced in few meters laterally (where the exposures are good) before it pinches out. This indicates that the lateral continuity of single layers is limited. The average range in composition of the layered troctolite is 65 to 85 percent plagioclase (An_{57-67}), 10 to 35 percent olivine (Fo_{55-62}), and minor amounts of pyroxene (0 to 2 percent), oxides (0 to 4 percent), and zero to trace amounts of biotite (Phinney 1969, Beltrame 1974). The compositional range for these rocks is very similar to that noted for the troctolite closer to the basal contact. The main differences are the pronounced layering of these rocks and the decrease in the minor phases pyroxene, oxides, and biotite. Locally pyroxene content exceeds the range (0 to 2 percent) noted above, but this is rare in the exposures that have been examined prior to the present work.

Troctolite with less than five percent augite (tap) was mapped by Bonnichsen (1970, 1971) in the Babbitt N.E. quadrangle. This unit may be correlative with the layered troctolites exposed to the northeast in the Harris Lake area.

Exposures of anorthosite (ta) are scattered throughout the troctolitic rocks in the Gabbro Lake quadrangle and the surrounding area. In general, they all have more than 90 percent plagioclase and are presumed to represent plagioclase rich segregations within troctolite (Phinney 1969).

The Railroad troctolite (tr) was informally named by Bonnichsen (1974) for the somewhat unique troctolite exposures along the Reserve Mining and Erie Mining Companies railroad tracks in T.59N., R.12W. Here the troctolite is characterized by complex textures and consists mainly of medium-grained augite troctolite, augite oxide troctolite, and oxide troctolite. Foliation is extremely variable throughout the unit. A variety of inclusions are found in the unit and include metasedimentary and volcanic hornfels, troctolites, and anorthositic series rocks. It appears to merge with the troctolitic rocks of the South Kawishiwi intrusion to the north, but limited exposure prevents recognition of the true relationship between the two units. The southern limit of the Railroad troctolite is unknown, but on the basis of interpretation of aeromagnetic maps anorthositic series rocks are inferred to be present a few miles south of the last known exposures of troctolite. It is in fault contact with rocks of the Partridge River troctolite on the west.

The Bald Eagle intrusion of Weiblen (1965) is an intrusion of foliated troctolite (tbt) and gabbro (tbg) located in the S.E. quarter of the Gabbro Lake and N.E. quarter of the Greenwood Lake quadrangle. On the accompanying map the overall length of the intrusion has been extended to the south from that originally mapped by Weiblen (1965). This southern addition is covered by glacial deposits and rock types have been inferred on the basis of a similarity of aeromagnetic anomalies with those associated with the exposed part of the Bald Eagle intrusion to the north. The intrusion does not have a chilled margin. Medium to coarse-grained foliated troctolite is either in direct contact with or separated by 1 to 10 meter wide covered areas from anorthositic series rocks along the western, northern, and eastern sides of the intrusion. Based on the mineralogic data and the dip of foliation near the contacts the intrusion is believed to be funnel-shaped at depth with steep dips on the east and somewhat shallower dips (45 to 75^{o}) on the west (Weiblen 1965). The exposed troctolite is distinctly flow layered with parallel alignment of plagioclase laths and elongate olivine crystals. Olivine and plagioclase are the main cumulus minerals present. Modal layering and foliation are common throughout the troctolite and in general are parallel to the contacts of the intrusion. The foliation of the troctolite dips steeply (75 to 90°) on the north and east sides of 15° and 75° on the west toward the center of the intrusion. The average composition is 57 percent plagiocl--- (An_{62-81}) and 34 percent olivine (Fo_{71-74}) with clinopyroxene and opaques present in minor amounts (Weiblen 1965, Phinney 1969).

The gabbro (tbg) in the northern part of the intrusion is completely surrounded by troctolite. The average composition is 42 percent plagioclase (An_{57-67}), 46 percent clinopyroxene, and 10 percent olivine (Fo_{61-61}). Orthopyroxene, oxides, and biotite are present in trace amounts (Phinney 1969). The plagioclase laths and elongate olivine and clinopyroxene crystals are aligned and form a prominent foliation. Modal layering is also common and parallels the foliation. The trend of the foliation and modal layering is in general parallel to that observed in the troctolite with dips varying from 10 to 80° towards the center of the intrusion (Weiblen 1965, Phinney 1969). Plagioclase-rich segregations are common throughout the exposed portion of the Bald Eagle intrusion. These may have resulted from flow differentiation during the intrusion of the magma.

On the basis of the interpretations of the lineament studies, it has been inferred that the intrusion is largely bounded by faults on both sides and that the intrusion itself is also cut by several faults. These faults are also consistent with the aeromagnetic anomalies associated with the intrusion. Geologic evidence that faults cut the intrusion consists of offsets of contacts and rather abrupt changes in the trend of foliation.

Between Gabbro and Omaday lakes a dike-like body has been mapped by W.C. Phinney (Green et al. 1966). The dike consists of two units, an outer unit of flow layered troctolite and medium-grained gabbro (tf) and an inner unit of pegmatite (tp). Also present in the dike are inclusions of Biwabik-type iron formation, hornfels and undivided anorthositic gabbro which have been discussed in an earlier ion. The dike is almost totally surrounded by rocks of the anorthositic series.

The outer part of the dike is very heterogeneous in nature. Flow-layered troctolite is present along the southern boundary of the BWCA near an entry gate at the end of Spruce Road. The layering is due mainly to variable proportions of olivine and plagioclase and is commonly contorted. This leads to the conclusion that the dike was emplaced as a flowing mass with plagioclase and olivine adhering to the walls (flow layering) forming modal layers that were then crumpled and distorted as magma continued to flow through the center. However, near Omaday Lake, medium- to coarse-grained oxide gabbro, olivine gabbro, and gabbro are found adjacent to the northern boundary of the dike. Whether this is an inclusion or actually part of the dike could not be determined in the field. The marked difference between the gabbro and the rest of the dike, however, suggests that the gabbro may be an inclusion. The troctolite just north of the western part of Omaday Lake and immediately east and south of the western part of the lake is a layered troctolite similar to the layered troctolite in the vicinity of Harris and Heart lakes. The trend of the layering is diverse and shallow dips are common. For this reason these rocks were included as part of the (tt) unit of the South Kawishiwi intrusion described above. In general, the outer part of the dike can be characterized as a troctolite with 55 to 65 percent plagioclase (An_{58-72}), 15 to 30 percent olivine (Fo_{55-63}), and 5 to 10 percent pyroxene. Oxide minerals and biotite are present in minor and trace amounts, respectively (Phinney 1969).

The central portion of the dike is made up of gabbro to olivine gabbro pegmatite high in oxide minerals. The pegmatite appears to pinch out near Omaday Lake on the southwest and Gabbro Lake in the northeast. The flow layered outer portion (tf) appears to break up into several parts near Gabbro Lake. Its genetic relationship to the troctolite (tt) of the South Kawishiwi intrusion or the Bald Eagle intrusion is unknown.

Partridge River troctolite of Bonnichsen (1974): The name Partridge River troctolite (tpt) was informally used by Bonnichsen (1974) to designate troctolitic rocks near Hoyt Lakes and south of the Reserve Mining Company. Augite troctolite and troctolite are the main rock types present. The Partridge River troctolite is bounded on the southeast by anorthositic series rocks which are inferred to be present from aeromagnetic data. On the east side it is in fault contact with the Railroad troctolite (tr) and part of the South Kawishiwi intrusion (tt). The southwest extension of the Partridge River troctolite is unknown because of a paucity of exposures although troctolite is the major rock type present in known outcrops.

The basal contact zone is much more homogeneous in nature than the contact zone of the South Kawishiwi intrusion although zones of inclusions are found (Bonnichsen 1974). The contact zone is also characterized by sulfide mineralization similar to that found in the tcz unit of the South Kawishiwi intrusion, but the mineralization appears to be present over a wider stratigraphic interval. The exact extent of mineralization and whether there is a genetic relationship of the mineralization with that in the tcz unit is not known.

The Powerline gabbro (tpg) of Bonnichsen (1974) is located in the northwest part of T.59N., R.12W. and adjacent townships south of Reserve Mining Company. It is bordered by the Partridge River troctolite on the west and northwest. The rest of the body is surrounded by rocks of the anorthositic series (agu). It is a coarse-g· ·ed olivine gabbro containing abundant apatite. The magnetite content is relatively high and the augite is characterized by abundant opaque inclusions. Bonnichsen (1974) suggested that the unit may be a ferrogabbro and represent a late stage differentiate of the troctolite-gabbroic rock series.

Cross-cutting diabasic rocks (d) are found widely scattered throughout the Duluth Complex in the Hoyt Lakes-Kawishiwi area. They consist mainly of basalt or diabase dikes. The dikes vary in width from less than 30 cm to a meter and appear to be vertical. They cut both the troctolitic-gabbroic and the anorthositic rock series. Their origin and relationship to the Duluth Complex is unknown.

D) Lineament Analysis

Cooper (1977, 1978) presented an analysis of topographic lineaments in an area that covers all of the MDNR Minesite area plus areas to the south and north. The following discussion is a brief summary of the lineament study taken from Cooper (1977).

A lineament is a mappable linear feature on a surface, whose parts are aligned in a rectilinear or curvilinear pattern distinct from adjacent patterns and it may reflect a subsurface feature (O'Leary, Friedman, and Pohn 1976). A lineament may represent the physiographic expression of isolated or continuous landforms. This includes the boundaries of morphologically distinct areas, stream courses and alignment of topographic features such as hills or lakes. Lineaments may represent positive features such as hills or ridges or negative features such as stream courses, valleys, or lakes. General definitions of lineaments (O'Leary, Friedman, and Pohn 1976) are broad enough to include alignment of aeromagnetic features. Aeromagnetic lineaments were used to aid in compiling the bedrock geology.

All lineaments depicted on the Lineament Map (Cooper 1976) of the Hoyt Lakes-Kawishiwi area are topographic features. Since the map represents a preliminary analysis to test the use of lineaments as an aid to geologic interpretation, no other type of lineament was mapped. The main reason for initiating a lineament study in this area is the fact that extensive glacial cover obscures much of the bedrock geology. The major use of lineaments is to define subsurface structures that may have no or only a subtlt expression as seen on the ground. The subsurface structures may be any of a number of geologic features such as faults, domes, basins, anticlines, synclines, etc. A lineament analysis of an area also helps in extending known geologic relationships into areas where bedrock exposures are sparse or nonexistent. For the present study 1:2400 high altitude blue line air photographs were used. These air photographs were done by Mark Hurd Aerial Surveys, Inc. and are available from the Minnesota Highway Department.

Three categories of lineaments (as seen on the photographs) were distinguished in this study: 1) pronounced lineaments--those easily identified after only a cursory examination; 2) less pronounced lineaments--those identified after a short examination of the photograph; and 3) vague lineaments--subtle or interpreted linear features which are identified only after the photograph has been examined in detail.

The map was then divided into cells three miles square. The size of the cell was completely arbitrary. This size was picked mainly to give enough lineaments in an individual cell so that if a preferred lineament orientation(s) was pre-sent it would be expressed in a linear histogram of frequency vs. orientation. A computer program was written to compile the data for each individual cell and plot the data in a linear histogram form. Lineament trends were divided into class intervals of six degrees to average out errors in measurement of the lineaments. This procedure also produced histograms that could be visually examined for dominant lineament trends. The length of each individual lineament was also characterized. The following arbitrary intervals were selected: class of 0-1 mile (0-1.6 km); 1-2 miles (1.6-3.2 km); 2-3 miles (3.6-4.8 km); greater than 3 miles (4.8 km); and much greater than 3 miles. Although this data has not been analyzed, future research efforts will be directed toward this end.

One area in the Duluth Complex was chosen to be analyzed in detail for the correspondence of lineament trends with known geology. The area is located along Spruce Road and includes all or portions of Sections 23, 24, 25, 26, 35, and 36, T.62N., R.11W. and Sections 19, 30, and 31, T.62N., R.10W. It includes International Nickel Company's (INCO) proposed open pit mine and much of the MDNR Minesite area. The area was chosen because it has a thin and discontinuous mantle of drift providing good exposure, several prominent lineaments, and the area has economic potential in the form of copper-nickel sulfide mineralization. The area was mapped by Cooper and Churchill (1975) at a scale of 1:400 (Figure 7).

In general, there is a good correlation beween mapped faults and lineaments in the INCO area. Most of the lineaments that correspond with mapped faults are pronounced lineaments (Figures 7 and 8) with a few being less pronounced. A frequency vs. orientation histogram of all lineaments in the area shows a pronounced peak at N.15°E. with subsidiary peaks at N.33°E. and N.45°E.

(Figure 9). The mapped faults are in two groups. One with an orientation of N.20-26°E. and the other at N.31-35°E. (Figure 10). The fault orientations of N.31-35°E. compare favorably wih the N.33°E. peak seen on the lineament histogram. The other fault peaks correlate with the flank of the dominant N.15°E. peak on the lineament diagram.

Most of the faults are contained in or border units of the troctolitic series (tcz, tt, and ta). The lineament histogram for these three units displays a broad dominant peak at N.12-24°E. with subsidiary flanking peaks at N.3°E. and N.33°E. (Figure 11). The fault directions again fall within the prominent peak or a secondary peak. The histogram for the anorthositic series rocks (ago and agu) shows a strong N.15°E. direction with a secondary peak also present at N.15°W. (Figure 12). The other peaks present in the histogram are not considered significant because of the few observations.

In summary, there appears to be a good correlation between lineament and inferred fault orientation in the INCO area. The predominance of the N.15°E. direction is probably due to the influence of glacial activity which trended north-northeast in the entire Hoyt Lakes-Kawishiwi area (Wright 1972, Stark 1974). This must be taken into consideration when analyzing lineament data because it may obscure other lineament trends more closely related to bedrock control. Although the direction of glacial activity may have been in part controlled by the preglacial northeast trending bedrock structure.

For a general lineament analysis the Duluth Complex was divided into two areas. A northern area where drift is discontinuous and relatively thin (0-6 m) and a southern area in which extensive (3-13 m) drift is present (Stark 1974). The northern area is a 7 to 14 km wide band along the base of the complex from Hoyt

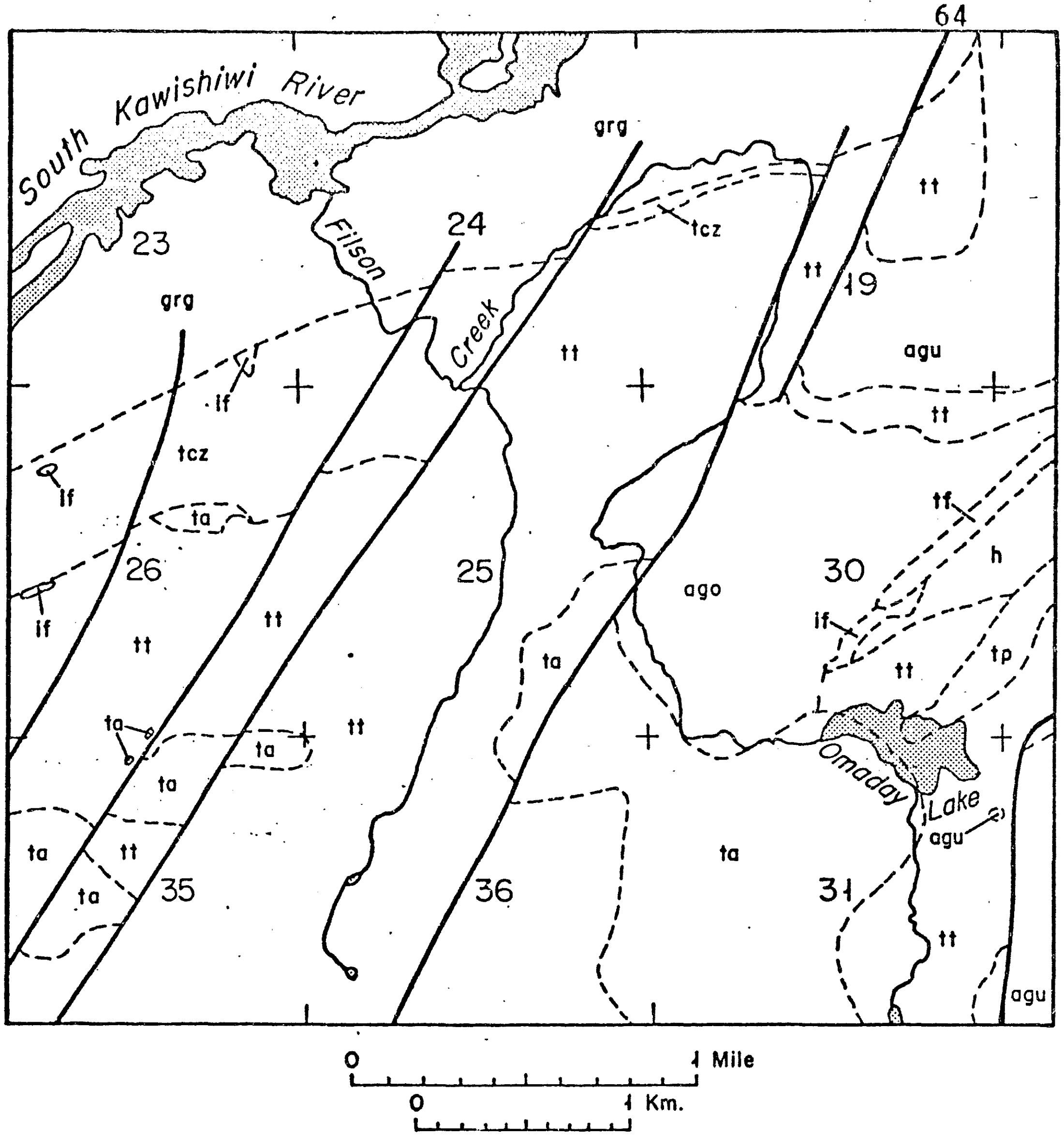
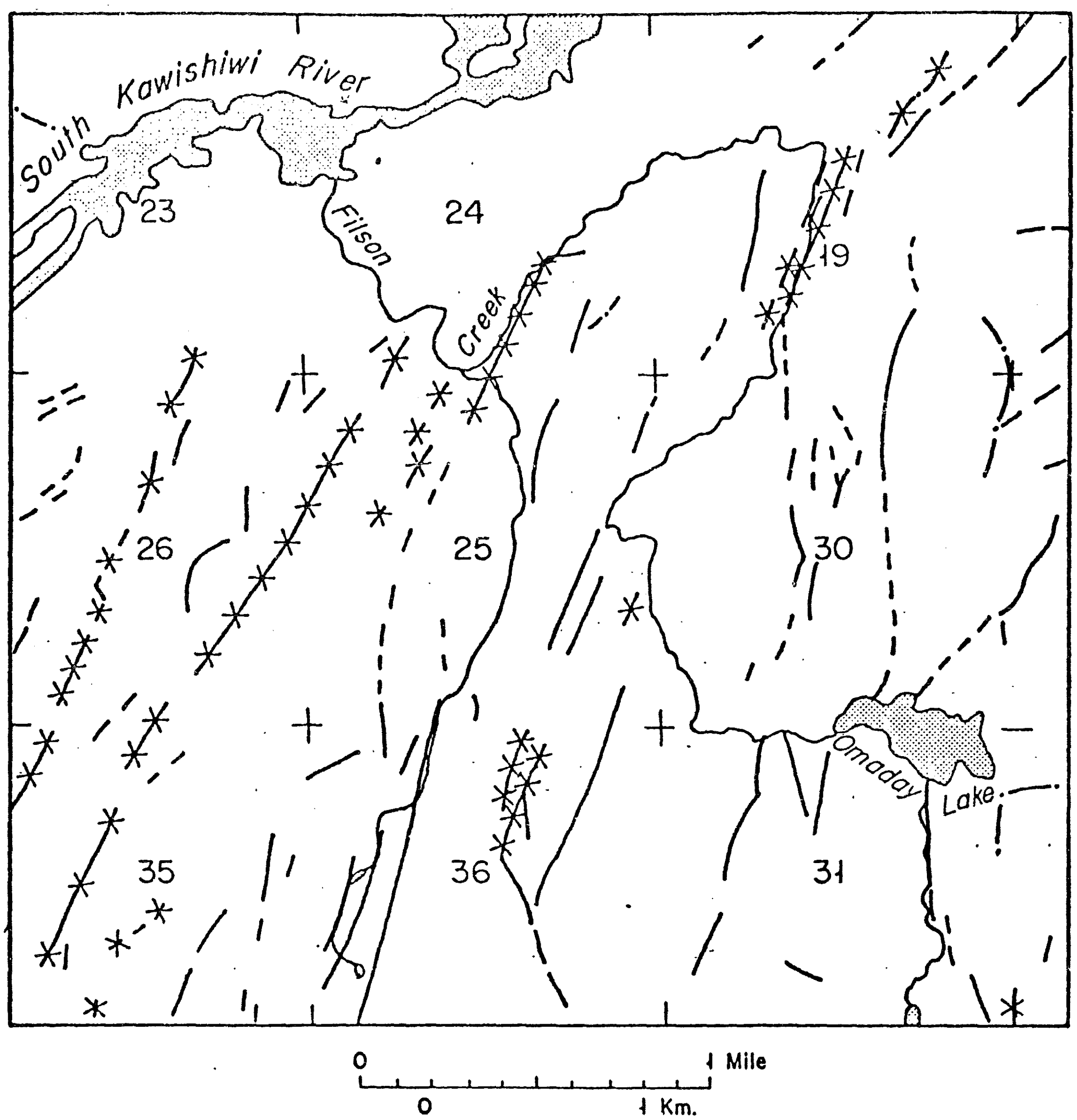


Figure 7. Bedrock geology of the INCO minesite (see Figure 5, text, and Appendix A for description of designated units).



EXPLANATION

Pronounced Lineament

Less Pronounced Lineament

Vague Lineament (subtle or interpreted)

Lineaments which correspond to mapped fault

Figure ~~28~~ 8. Topographic lineament map of the INCO minesite (after Cooper, 1976). See Figure 13 for bedrock geology.

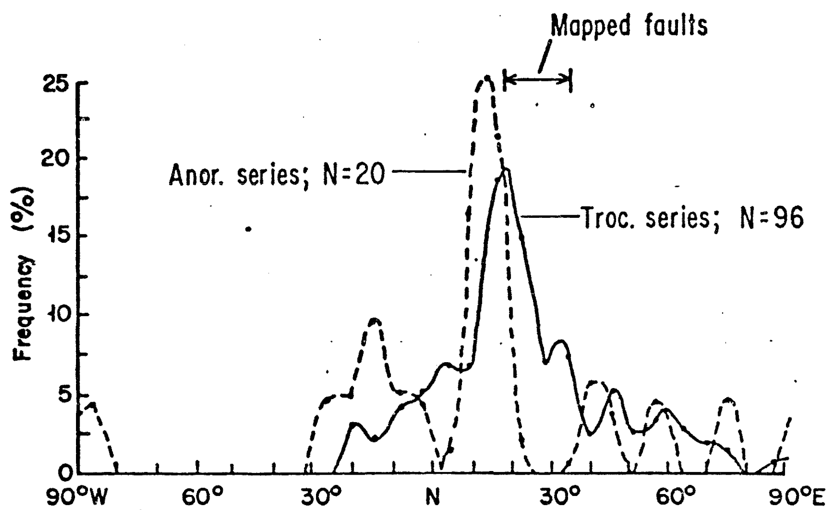


Figure 9. Histogram of topographic lineaments (with mapped faults) in the INCO minesite.

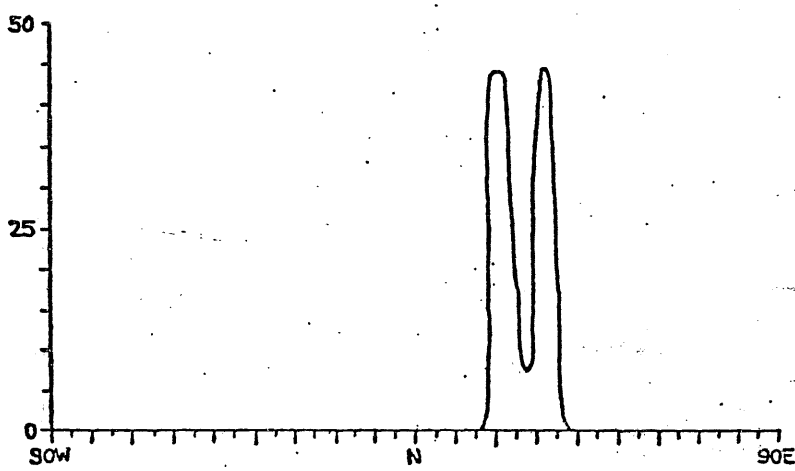


Figure 10 - Mapped fault frequency vs. orientation diagram
[redacted]

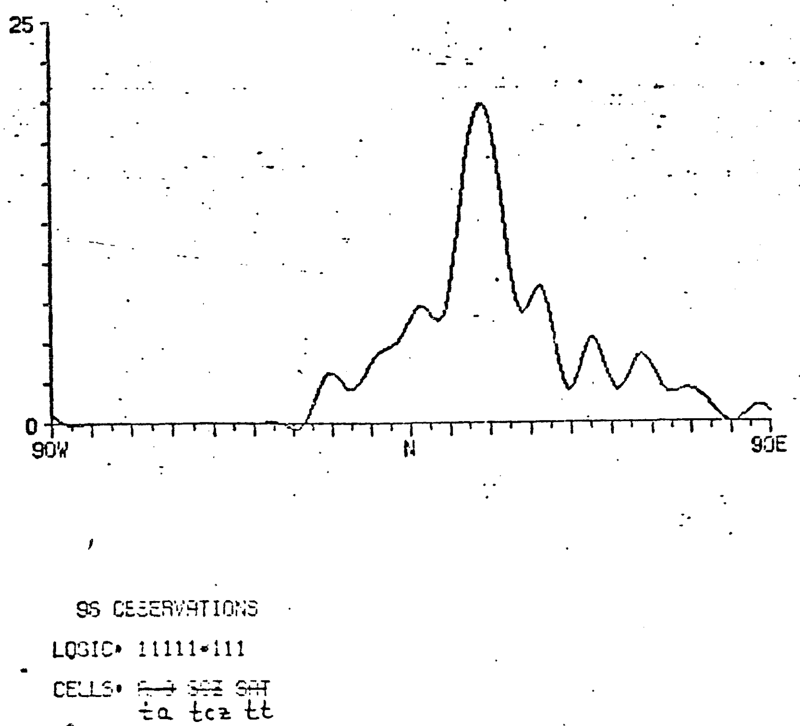
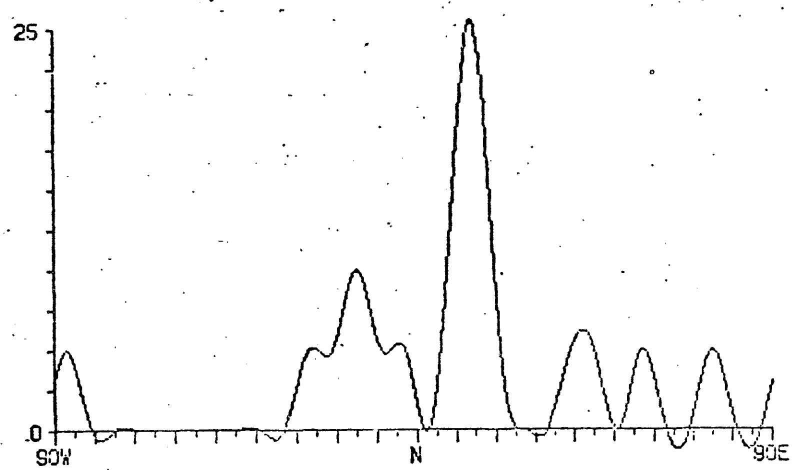


Figure 11 - Lineament frequency vs. orientation diagram of troctolitic series rocks



20 OBSERVATIONS

LOGIC: 11111*111

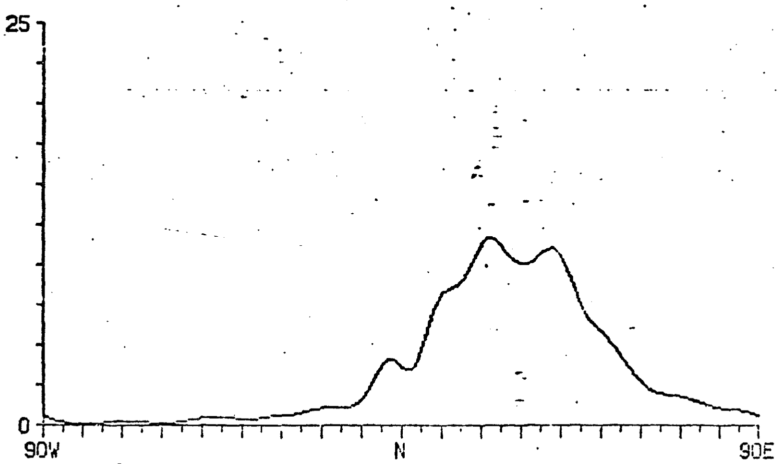
CELLS: 480 480

Figure 12 - Lineament frequency vs. orientation diagram of anorthositic series rocks,

Lakes to the eastern edge of the Gabbro Lake quadrangle. It also include most of the known outcrops in the Hoyt Lakes-Kawishiwi area (Cooper 1976). The southern area contains only scattered exposures and includes the rest of the area inferred to be underlain by the Duluth Complex.

The histogram for the northern area (Figure 13) displays a broad double peak from N.18°E. to N.42°E. One peak is at N.21°E. and the other at N.39°E. These peaks correspond well with inferred faults in this part of the Duluth Complex. There is a minor peak at N.3° which does not correlate with any of the known geologic features in the area. The histogram for the southern or drift covered area (Figure 14) exhibits a prominent peak from N.33°E. to N.45°E. with a flanking peak at N.21°E. The dominant peak probably repre-sents the trend of Quaternary glaciation as expressed by the Toimi drumlin field. This is a slightly more northeasterly trend than that indicated from glacial striations on bedrock exposures in the northern area (Stark 1974).

Comparing the trends in the southern and northern area shows some overlap of the prominent peaks. The flanking N.21°E. peak in the southern area probably reflects bedrock faulting in that it matches well with the N.21°E. peak in the northern area and the mapped faults in the INCO area. It does, however, indicate that faulting in this general direction (N.30-40°E.) may be present throughout the area. The correspondence of inferred faulting with northeast lineament trends in the northern area indicates that the northeast trend in the southern area is the result of two controlling factors. The northeast trending faults in the area produced a northeast trending structural grain prior to glaciation and the NE-SW trend of glaciation greatly enhanced this northeast grain. The Toimi drumlin field present in the southern part of the map may have been in part controlled by the structure in the underlying bedrock.



1631 OBSERVATIONS

LOGIC: 11111*111

CELLS: C11 C12 D11 D12 E 9 E10 E11 E12 F 8 F 9 F10 F11 F12
G 7 G 8 G 9 G10 H 7 H 8 I 5 I 6 I 7 J 4 J 5 J 6 K 3

Northern Duluth Complex - exposed

Figure ~~8~~ 13 - Lineament frequency vs. orientation diagram of the ~~northern Duluth Complex including most of the known~~ outcrops. The southern limit of this area is approximated by the limit of extensive exposure on the map of the bedrock geology.

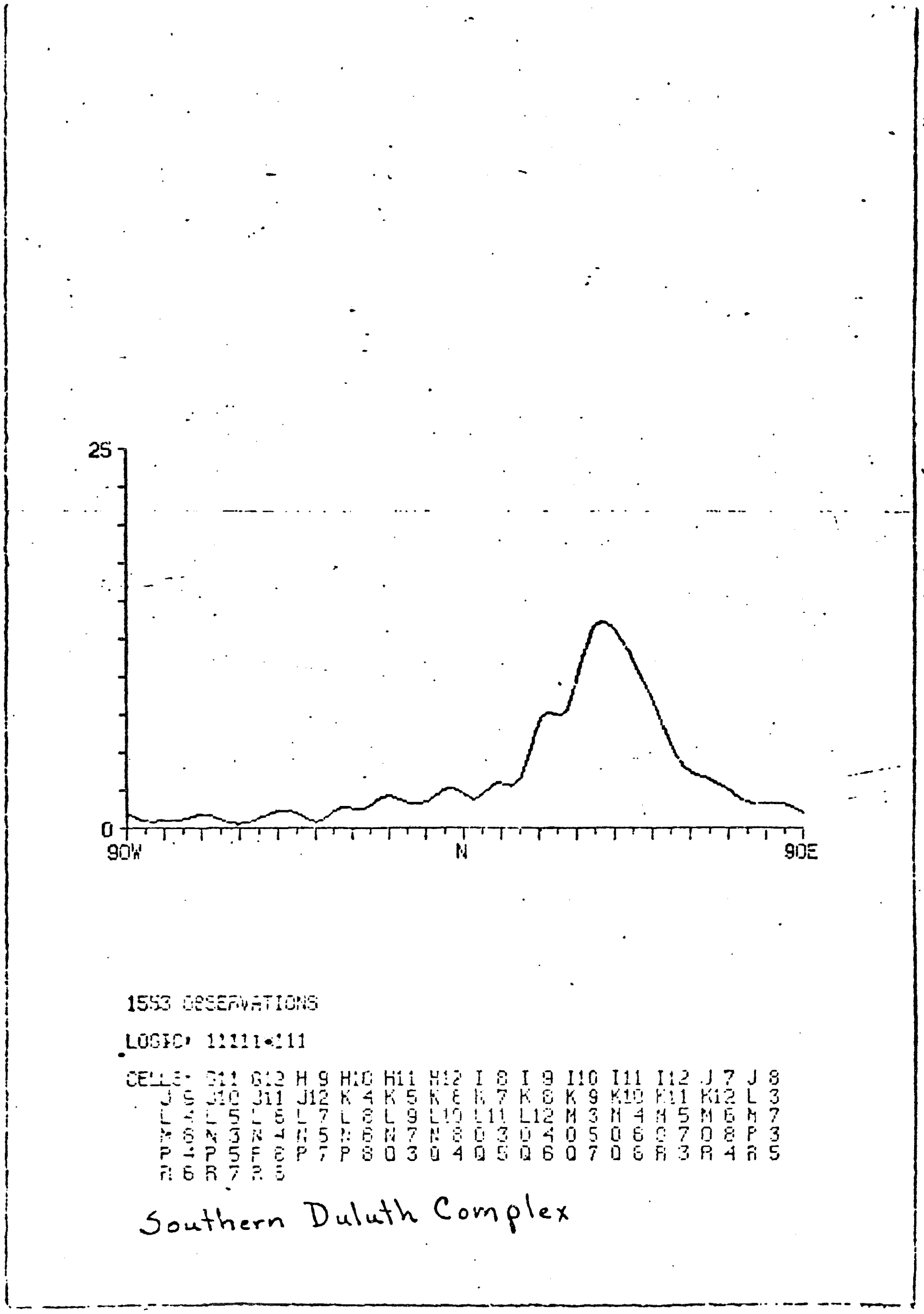


Figure 14 - Lineament frequency vs. orientation diagram of the southern Duluth Complex in the Hoyt Lakes-Kawishiwi area.

There are some northwest trending structures in the southern area as evidenced by faults, known only on the basis of subsurface information, along the western margin c̄ 'ie Duluth Complex. This is further substantiated by northwest trends exhibited by the aeromagnetic maps of the area (Meuschke et al. 1963, Bath, Schwartz, and Gilbert 1965, USGS 1969). The absence of these trends on the lineament map can possible be explained by the northeast trend of Quarternary glaciation which probably enhanced all northeast trending structures and may have all but eliminated any surface expression of the northwest trending structures.

To further substantiate the idea that lineament trends in the Duluth Complex reflect faults, a lineament analysis was undertaken in the Lower Precambrian rocks exposed in the area. These rocks are exposed north and west of the Duluth Complex and form the footwall for the Duluth Complex over much of the exposed contact. The glacial cover is thin and exposures are numerous. For convenience, the Lower Precambrian rocks are divided into two large units. The "granitic" rocks of the Giants Range batholith and Vermilion massif make up one unit. The metavolcanic and metasedimentary rocks of the Ely Greenstone, Knife Lake Group, Lake Vermilion formation, and Newton Lake formation comprise the second group.

The lineament histogram of the "granitic" rocks (Figure 15) has a broad peak from N.20°E. to N.40°E. This corresponds almost exactly with the predomi-nance of mapped fault directions (Figure 16) in these rocks as determined from the maps of this area by Sims (1973) and Morey and Cooper (1977).

The metavolcanic and metasedimentary rocks have several prominent lineament trends oriented at N.24°E., N.39°E., N.57°E., and N.85°E. (Figure 17). The most pronounced of these is the N.57°E. trend. The histogram of mapped

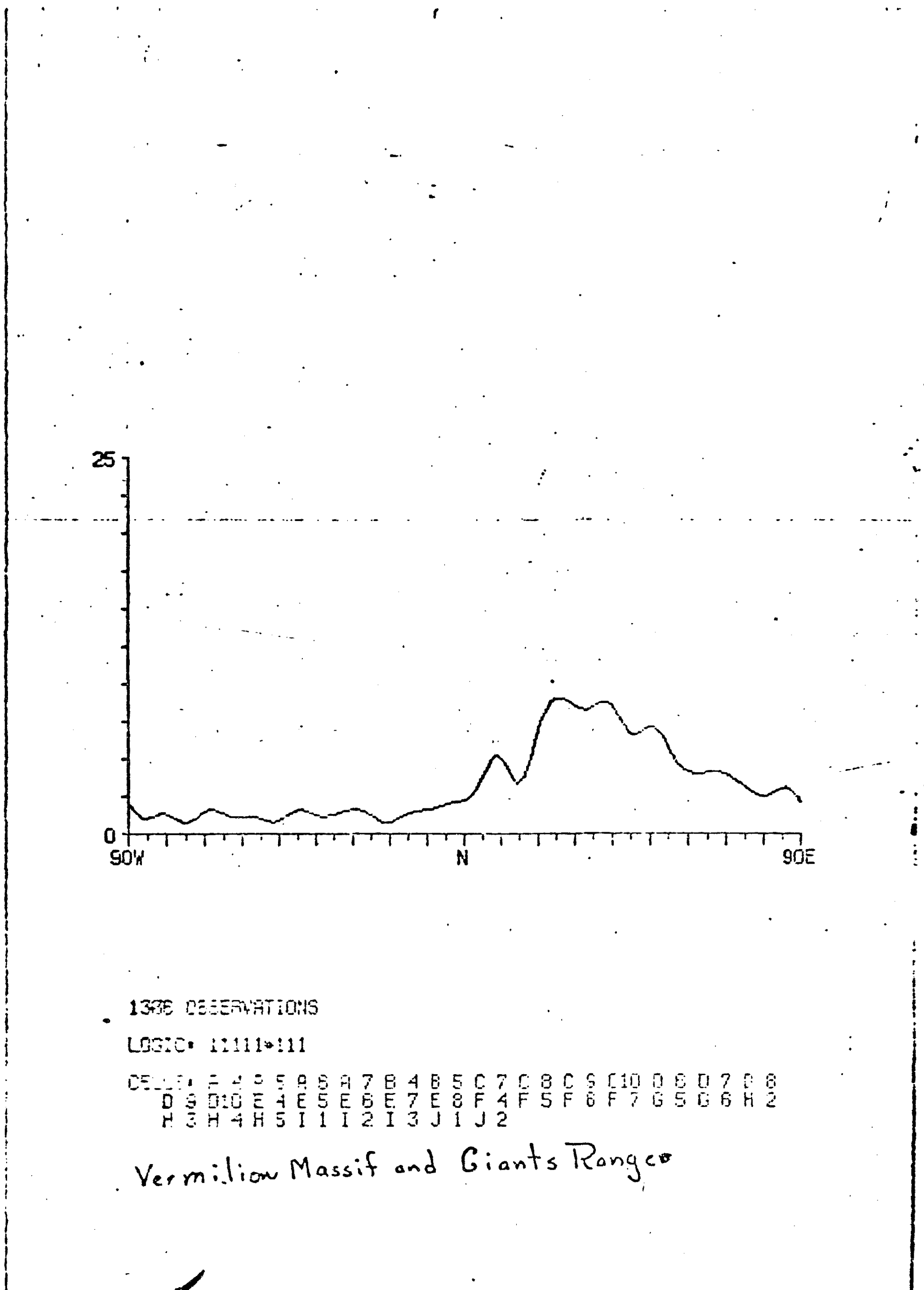


Figure ~~20~~ 15 - Lineament frequency vs. orientation diagram of the Giants Range batholith and Vermilion massif.

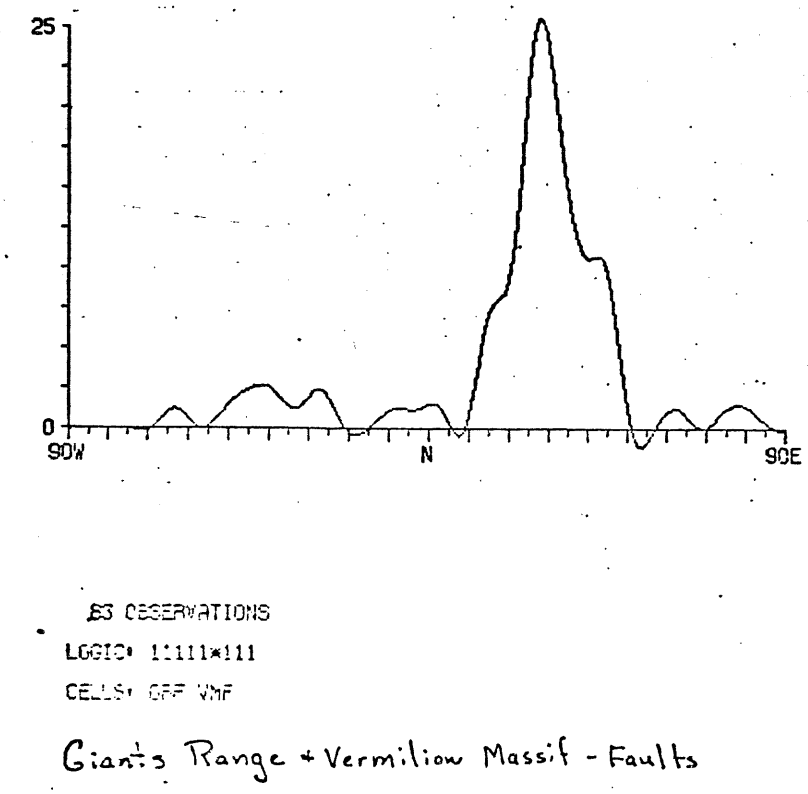
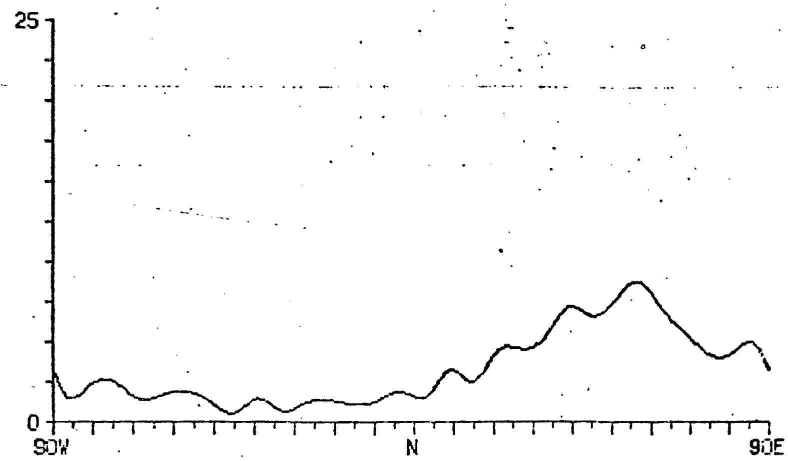


Figure 16 - Fault frequency vs. orientation diagram for the Giant's Range batholith and Vermilion massif.

faults (Figure 18) shows prominent trends at N.21°E., N.33°E., N.57°E., N.70-75°E., and N.87°E. These show good correspondence with the lineament trends in Figure 17. This is especially true when it is taken into consideration that class intervals of six degrees were used to plot the data on the histogram. This means that the accuracy of any peak is 3 degrees. For example, the N.24°E. lineament peak and the N.21°E. fault peak could be expressions of the same trend.

In summary, the lineament studies discussed above which were based on the data on the Lineament Map of the Hoyt Lakes-Kawishiwi map indicate the usefulness of a study of aerial photographs as an aid in geologic mapping and interpretation in glaciated areas. The close correspondence of lineament trends with fault trends in the Lower Precambrian indicates that <u>many of the lineament trends in the Duluth Complex are probably controlled by faults and/or joints</u>.

A more detailed analysis of lineament trends in the Hoyt Lakes-Kawishiwi area could be used to further define critical areas for mineral exploration and delineate aeas that might need more study to substantiate geologic interpretation. Lineament analysis might also be a means of determining alternative geologic interpretations and extending known geologic relations into areas with little or no exposures. An example of the possible relationship between lineaments and the sulfide mineralization in the Duluth Complex is the fact that both the pro-posed INCO mine and the AMAX mineralized zone lie near prominent lineaments that have been mapped or inferred to be faults (Cooper and Churchill 1975, Morey and Cooper 1977). A lineament study may also be an aid to understanding the move-ment of groundwater in an area. It is also apparent from the analysis of the Toimi drumlin field discussed above that another important aspect of this type of study is the analysis of glacial features.



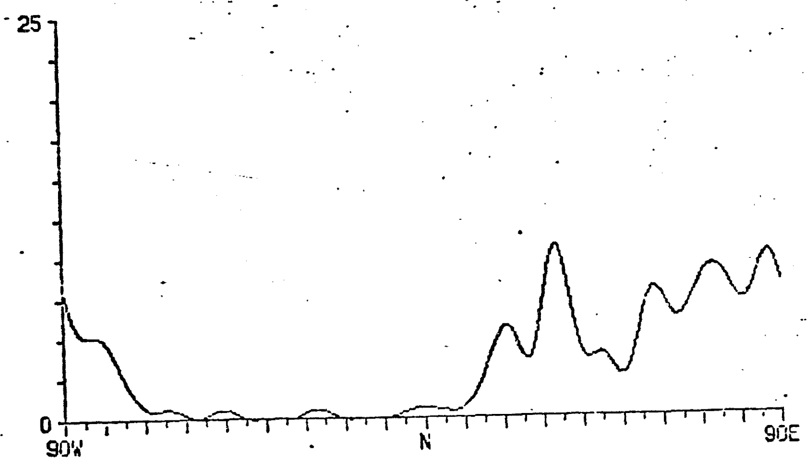
901 OBSERVATIONS

LOGIC: 11111*111

CELLS, A 2 A 5 A10 A11 A12 B 6 B 7 B 8 B 9 B10 B11 B12 C 4
C 5 C 6 D 4 D 5 F 2 F 3 G 1 G 2 G 3 G 4 H 1 J 3

Ely Greenstone, ~~and~~ Lake Vermilion Fm, Knife Lake Group,
Newton Lake fm.

Figure ~~12~~ 17 - Lineament frequency vs. orientation diagram of Lower Precambrian metavolcanic and metasedimentary rocks.



178 OBSERVATIONS
LOGIC> 1111.*111
CELLS: LVF KLF NLF EGF

Lake Vermilion Fm., Knife Lake Fm., Newton Lake Fm. and Ely Greenstone - Faults

Figure ~~13~~ 18 - Fault frequency vs. orientation diagram of Lower Precambrian metavolcanic and metasedimentary rocks.

In summary, Cooper (1977, 1978) has demonstrated that the Duluth Complex is extensively faulted and that the faults may have played an important role in determining sites of sulfide mineralization. Detailed field mapping is needed to fully determine the nature of the faults and if they do in fact play a role in the localization of mineralization along the base of the Duluth Complex.

E) Structure of the Duluth Complex

The major structural features in the Duluth Complex that have been recognized in the Study Area include mineralogic and/or modal layering, foliation, faults, and joints. Mineralogic and/or modal layering consists of layering defined by varying proportions of the minerals. In the Duluth Complex this usually consists of a layer which has a larger proportion of olivine near the base which abruptly or gradually decreases upward until the top of the layer is reached and a new layer with a significant amount of olivine starts again. The plagioclase content commonly varies inversely with the amount of olivine. Minor minerals such as pyroxene and oxides do not usually show any increase or decrease in conjunction with the modal layering.

Mineralogic layering also includes layers that are defined by variation in the grain size of a mineral. However, because of the lack of extensive exposures, this type of layering has not been identified, although it may be present. Modal layering can be produced by flow or gravity segregation of minerals from a melt during crystallization. Large scale segregation may produce mappable units with stratigraphic contacts and internal layering. The scale of the layering may be anywhere from a few millimeters to hundreds of meters. Foliation is defined by tabular laths of plagioclase being oriented with their 010 faces parallel to each other. The foliation is almost always parallel to or sub-parallel to modal layering where both are present. Foliation may be produced by gravity settling or flow in a crystallizing magma.

In general, the foliation and modal layering trend N.30-60°E. with a dip of 10-40°S.E. in the Hoyt Lakes-Kawishiwi area. The only structural features that have been defined on the basis of foliation and modal layering are the Bald Eagle Intrusion (Weiblen 1965), which has been described earlier, and a synformal or basin feature in the South Kawishiwi Intrusion (Green and others 1966, Phinney 1969). Both are found in the Gabbro Lake Quadrangle. The synform is approximately 6 km wide and appears to close off to the north. The nature of the southern extension of the synform is unknown, although reconnaissance mapping in the Greenwood Lake quadrangle immediately to the south suggests that it does not close off to form a basin. The trend of the foliation and modal layering in this area approximates the regional trend.

Only a few faults have been inferred to be present in the Study Area previous to work by Morey and Cooper (1977) and Cooper (1978). Sims (1973) inferred several faults to be present along the basal contact of the Duluth Complex in the Gabbro Lake quadrangle on the basis of offsets in the basal contact. Bonnichsen (1974) suggested that a north-south trending fault may be present east of Babbitt and just south of Reserve Mining Company pit on the basis of drill core information. He gave only an approximate location of the fault, but did suggest that it may separate rocks of the South Kawishiwi Intrusion from those of the Partridge River troctolite.

The only other structural features that have been recognized in the area are contacts between separate intrusions. Unfortunately, these contacts are only rarely seen in outcrop, thus eliminating any exact knowledge of the relationship of any one intrusive body to another. Commonly the contacts can be located within no more than 100 meters. Also hindering the determination of any age relationship between rock units is the absence of chilled margins. Therefore, age relationships depend on the type(s) of inclusions that might be found near inferred contacts and the petrology of the rocks.

The main study concerning the structure of the Duluth Complex in the Study Area has been done by Cooper (1978) who examined various structural features including foliation and/or modal layering, joints, and faults. The following is a summary of the relationships between these features.

Joints are fractures found in rocks along which no movement has taken place. Faults are fractures along which the rocks on one side have moved relative to the rocks on the other side. Foliation and/or modal layering can be thought of as a plannar feature which can be defined in the rock.

The orientation and spacing of the joints was directly related to mapped and inferred faults. The joints near mapped faults were observed to trend in one of two directions; either parallel to mapped or inferred faults and topographic lineaments trending N.15-30°E., or in a direction of N.15-20°W. A third major joint orientation was N.45-50°E. which is subparallel to aeromagnetic gradients which may be faults and mapped faults in the vicinity of Hoyt Lakes which cut the western margin of the Duluth Complex. Other joint sets trend parallel and perpendicular to the trend of foliation and/or modal layering and the basal contact of the Duluth Complex. From the joint data Cooper (1978) inferred that the South Kawishiwi intrusion is older than the Partridge River troctolite or the Powerline gabbro.

After the bodies were intruded cooling fractures or joints developed parallel and perpendicular to the modal layering and/or foliation and the basal contacts of the bodies. Following this all of the Duluth Complex underwent a period of extensive faulting. The major mapped and inferred faults trend N.15-30°E. and N.45-55°E. During the faulting, joint sets developed parallel to the faults and a third set (commonly sheared) developed trending N.15-20°W. (Cooper 1978). It was also observed that the density of fractures or joints increases near the mapped and inferred faults. Cooper (1978) concluded that the entire area underlain by the Duluth Complex is extensively faulted and that these faults may have played an important role in the localization of Cu-Ni sulfide mineralization. R.W. Cooper and Mike Foose (unpublished data) mapped an area approximately 26 km east of Babbitt and just southeast of Birch Lake and demonstrated the presence of mappable units which are cut by numerous faults. The faults trend in numerous directions and a complete analysis of the area has not yet been completed.

IV. COPPER-NICKEL SULFIDE MINERALIZATION

A) Location and History of Discovery

The original discovery of copper-nickel mineralization in the Duluth Complex in this area was made by Fred S. Childers in 1948, who was soon joined by Roger V. Whiteside. They drilled several test holes in the aea just south of the South Kawishiwi River into sulfide-bearing gabbro (Schwartz and Davidson 1952). The nature of the mineralization was first described by Schwartz and Davidson (1952). This was followed by the work of Schwartz and Harris (1952), Harris (1954), Grosh and others (1955), and Anderson (1956). In general they described the disseminated nature of the sulfides, the local abundance of iron formation and hornfels inclusions and the fine- to coarse-grained nature of the contact zone. Schwartz and Harris (1952) and Harris (1954) mapped the contact from the vicinity of the South Kawishiwi River to a point near the present Dunka Pit of Erie Mining Company. They also noted the presence of sulfides throughout the contact zone. Although the contact zone area was extensively examined and drilled by several mining and exploration companies there was not published work on the sulfides until Green and others (1966), Phinney (1969), and Bonnichsen (1970) examined the contact zone in the course of mapping part of the Duluth Complex. More recent work on the nature of the mineralization has been published by Bonnichsen (1972), Boucher (1975), and Weiblen and Morey (1976). Much work on the mineralization has been done by a number of individuals in the past few years for the Copper-Nickel Study to evaluate the effects of mining on the region.

The zone of Cu-Ni sulfide mineralization (at the present erosional level) is confined to a narrow band along the basal contact of the Duluth Complex. It extends from near the boundary of the BWCA on the north to the south near Hoyt Lakes. Mineralization is also found in the subsurface along the contact of the Duluth Complex with the country rock.

B) Nature of the Sulfide Mineralization

Disseminated sulfide mineralization is found throughout the contact zone from Hoyt Lakes to the BWCA and is the main type of mineralization found. The sulfides occur as interstitial grains to plagioclase and mafic minerals. Meineke and Listerud (1977) compiled all data obtained by the MDNR from various mining companies and outlined all known areas with 0.25 percent Cu. Figure 19 shows the location of the areas. These areas were thought to be of economic interest because of the grade and the occurrence of the sulfides near the present topographic surface. Also shown are areas with 0.50 percent Cu. Areas with less than 0.25 percent Cu were not shown as it was felt that at present they were not of economic interest. Locally thin massive areas of Cu-Ni mineraliza-tion are found. Because these areas are present locally and their occurrence is sporadic, the main interest is in the disseminated sulfides which persist over much larger areas. The sulfides are not restricted to any single rock type in the contact zone. Bonnichsen (1972b), Boucher (1975), and Weiblen and Morey (1976) have described in detail the texture and mineralogy of the sulfides, and the reader is referred to these publications for more detailed descriptions.

The major sulfide minerals are pyrrhotite, chalcopyrite, cubanite, and pentlandite. Minor sulfide minerals include violarite, mackinawite, pyrite, sphalerite, and bornite. Other minerals that have been identified in trace amounts are covellite, digenite, chalcocite, tenorite, cuprite, native copper, galene, and phase X (Bonnichsen 1972b, Boucher 1975, Weiblen and Morey 1976). Table 2 is a list of these sulfides and their composition.

As described earlier, the contact zone is approximately 100 to 300 meters thick and is characterized by extreme heterogeneity of rock type and texture. The zones of mineralization are not restricted to any single rock type and trangress all types of rocks. The upper and lower contacts of the contact are commonly ill defined and gradational over a few tens of meters. This is especially true of the upper contact. The lower contact is hard to define where the Duluth Complex is underlain by the Virginia Formation or the Biwabik Iron Formation (Renner 1969, Bonnichsen 1972b and 1974, Meineke and Listerud 1977). Where the Duluth Complex is underlain by the Giants Range batholith the lower contact is much easier to define. The average dip of the basal contact is 15-30° to the southeast, although local changes in the attitude are found which may be indicative of faulting (Weiblen and Cooper 1977, Meineke and Listerud 1977).

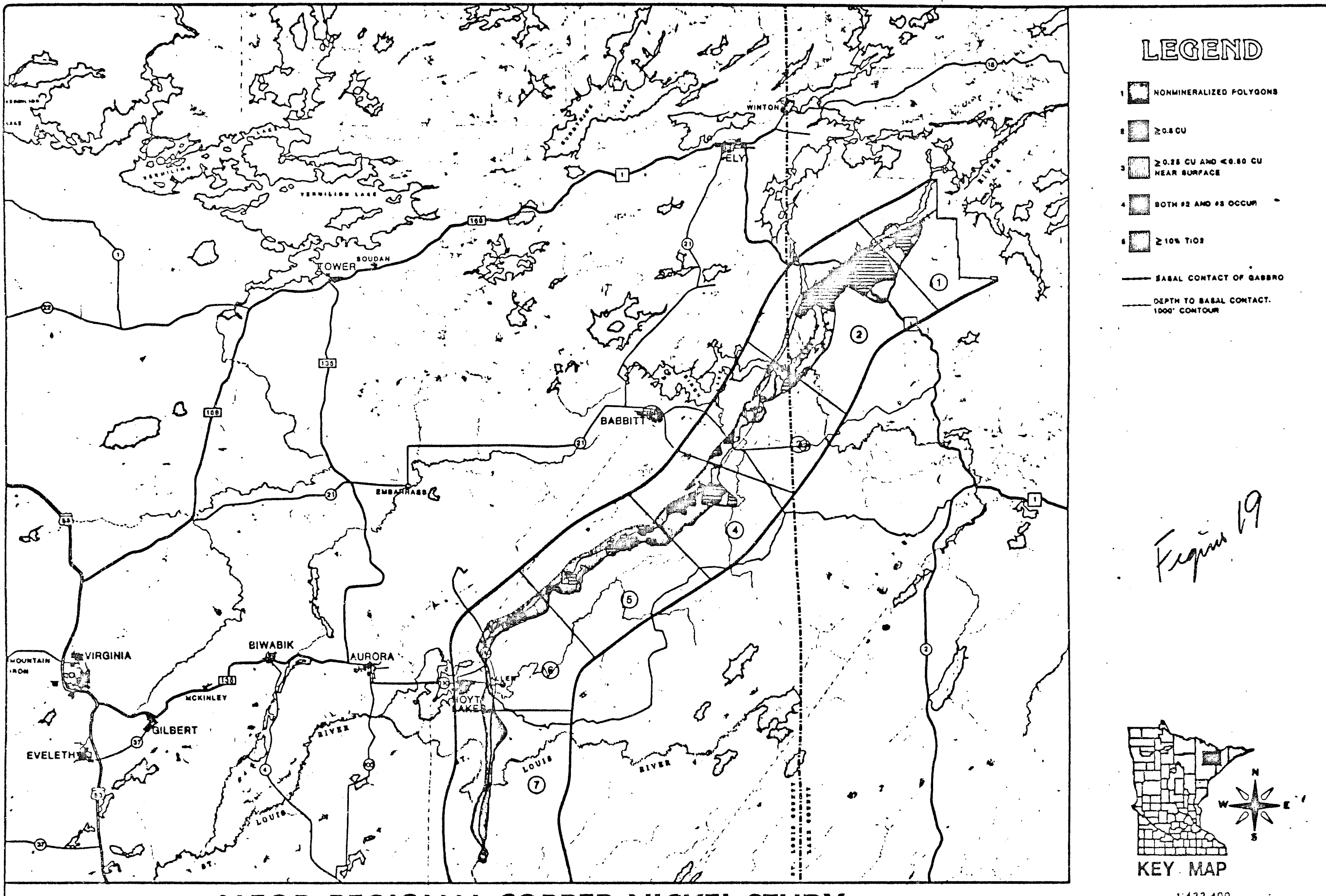


Figure 19

MEQB REGIONAL COPPER-NICKEL STUDY

MDNR POLYGON DISTRIBUTION

Table 2. Typical sulfides and their compositions.

MINERAL	IDEAL FORMULA
Pyrrhotite	$Fe_{1-x}S$ where x=0 to 0.2
Chalcopyrite	$CuFeS_2$
Cubanite	$CuFe_2S_3$
Pentlandite	$(Fe,Ni)_9S_8$
Violerite	$(Ni,Fe_3)S_4$
Mackinawite	FeS
Pyrite	FeS_2
Sphalerite	ZnS
Bornite	Cu_5FeS_4
Covellite	CuS
Digenite	Cu_7S_5
Chalcocite	Cu_2S
Tenorite	CuO
Cuprite	Cu_2O
Native Copper	Cu
Galena	PbS
Phase X	$Cu_3Fe_4S_6$

The type and/or nature of the mineralization does not vary significantly along the length of the mineralized zone. The only variations in the mineralization is seen in the trace minerals noted earlier and this is probably the result of local conditions rather than any regional change (Bonnichsen 1972b, 1974).

Meineke and Listerud (1977) summarized data concerning the Cu-Ni ratio and the sulfur content in mineralized areas. Although the Cu-Ni ratios varied from 2.71 to 4.00 for different areas there appeared to be no systematic areal variation. However, it must be stated that the data is relatively scattered and somewhat isolated. The average Cu-Ni ratio as determined by Meineke and Listerud (1977) for the entire mineralized zone is approximately 3.3 which compares well with the 3.1 estimate made by Bonnichsen (1974). The sulfur content in mineralized rocks of the Duluth Complex ranged from 0.72 to 6.72 percent and averaged (weighted) 2.64 percent for zones containing 0.5 percent Cu. Because of the small amount of data available Meineke and Listerud (1977) made no conclusions concerning the variation in sulfur content.

C) Potential

Bonnichsen (1974) and Meineke and Listerud (1977) made resource estimates on the amount of mineralized rock containing Cu-Ni sulfides. Since Meineke and Listerud (1977) had much more data available to them than did Bonnichsen (1974) most of the following data is taken from their work. They calculated approxima-tely 7.0 billion tons of mineralized rock containing 0.4 to 1.4 percent Cu and approximately 15.1 billion tons of mineralized rock containing 0.25 to 1.4 percent Cu in the MDNR Minesite area. The cutoff grade is 0.25 percent Cu. That is rock with less than 0.25 percent Cu is not considered economic to mine with present technology. These tonnages calculated by Meineke and Listerud are slightly higher than those calculated by Bonnichsen (1974). This indicates that the estimates give a good idea of the amount of mineralized rock present given the present data base as used by Meineke and Listerud (1977).

Meineke and Listerud (1977) classify the mineralized part of the Duluth Complex as a conditional resource. A conditional resource is described as a presently subeconomic resource that may eventually become a reserve (economically feasible) when conditions of economics or technology are satisfied. Much work has been done by numerous mining companies, mainly in the form of drilling, to find economic quantities of Cu-Ni sulfides. Two shafts have been sunk by INCO and AMAX, respectively, and INCO had proposed an open pit mine which was subsequently withdrawn. None of these activities has yet resulted in a producing mine. However, as Bonnichsen (1974) has pointed, the Duluth Complex remains the single, largest known resource of copper and nickel in the United States and the potential for eventual development and mining is good. Besides copper and nickel, the Duluth Complex is known to contain significant resources of titanium. Also present in possibly recoverable quentities ae gold, silver, cobalt, and platinum-group minerals (Meineke and Listerud 1977).

D) Correlation With Mineralogy and General Geology

In recent years a number of people have studied various aspects of the mineralogy and petrology of the Duluth Complex. The studies include those by Hardyman (1969), Renner (1969), Boucher (1975), Fellows (1976), Fukui (1976), Weiblen and Morey (1976), and Churchill (1978). The main study dealing with the relationship of sulfides to the general geology is that of Weiblen and Morey (1976). They propose mechanisms for the origin of sulfides by the direct diffusion of sulfur vapor from the country rock and inclusions with copper and nickel being scavanged from the Duluth Complex. They also suggest that indirect transfer of vapor along faults and fractures may have played an important role in concentrating Cu-Ni sulfides along the basal contact. They also suggest the possibility tha some of the sulfides may have originated as an immiscible sulfide melt. It is interesting to note that most of the major mineralized areas outlined by Meineke and Listerud (1977) lie along or near mapped or inferred faults in the Duluth Complex as shown by Morey and Cooper (1977). Although this is not proof that faults controlled mineralization, it is an idea that should be tested with further research.

The MDNR Minesite area has received much attention in the past few years because of the interest of several mining companies in developing Cu-Ni sulfide deposits. However, it must be realized that sulfides are not confined solely to the MDNR Minesite area. Disseminated Cu-Ni sulfides in the Duluth Complex have been described in the vicinity of Lake Gabimichigami by Nebel (1919) and in extreme northeastern Minnesota by Mogessie (1976).

V. SUMMARY AND CONCLUSIONS

The summary presented here is confined mainly to the MDNR Minesite area and the Duluth Complex as the general geology of the entire region was described earlier. Also, the Duluth Complex is of prime importance as it contains the copper-nickel sulfides.

The Duluth Complex was intruded as a series of intrusions that can be assigned to one of two magmas. The older anorthositic series and related rocks can be related to a low-alumina magma (Weiblen and Morey 1975). This magma produced rocks ranging from peridotite to granophyres, but most predominant were rocks with greater than 80 percent plagioclase and only minor amounts of mafic minerals.

Following intrusion of the anorthositic series the troctolitic series was intruded as a sequence of multiple intrusions. It has been related to a high-alumina magma. The inferred sequence of intrusions from oldest to youngest was the South Kawishiwi intrusion followed by the Partridge River troctolite and Powerline gabbro. The Bald Eagle intrusion of Weiblen (1965) is here considered to be part of the South Kawishiwi intrusion. During intrusion of the troctolitic series inclusions of the underlying country rock were incorporated into the magma and were metamorphosed to hornfels. These inclusions as well as mafic igneous inclusions were concentrated near the basal contact producing a heterogeneous contact zone. The intrusion resulted in extensive interfingering of the Duluth Complex with Middle Precambrian sedimentary rocks. The inclusions and country may have been a source of sulfur which migrated into the magma and scavanged copper and nickel producing magmatic sulfides (Weiblen and Morey 1976).

Following intrusion of the troctolitic series the area was extensively faulted. Although difficult to recognize the faults are an important feature which should be considered in evaluating the geology and resources of the Duluth Complex. Joints developed in association with the faulting and provide a means of recognizing the faults. The faults may have provided a means for the introduction of a sulfur rich vapor phase which helped to concentrate copper and nickel bearing sulfides along the contact of the Duluth Complex with underlying country rock. The recognition of extensive faulting in the Duluth Complex may help to explain the present distribution of sulfide mineralization, further enhance exploration in new areas for additional deposits, and in conjunction with mineralogic and petrologic studies help to understand the structural and tectonic evolution of the Duluth Complex. Open fractures in the underlying country rock during or after intrusion of the troctolitic series may have been sites of sulfide deposition as evidenced by zones of mineralization in the Giants Range batholith well removed from the Duluth Complex.

The area underwent extensive glaciation during the Pleistocene which covered much of the area to a varying degree with various types of glacial deposits.

The basal zone of the Duluth Complex contains greater than 15 billion tons of material containing 0.25 to 1.4 percent copper and is the largest known resource of copper and nickel in the United States. The deposits are considered to be subeconomic at the present time although several mining companies are or have been actively engaged in developing near surface and underground deposits. The deposits, although marginal at the present time, may become economic as technology for recovery of the minerals progresses and/or demand increases.

Besides the presence of Cu-Ni sulfide mineralization significant amounts of titanium mineralization have been found locally with over 220 million tons 10 percent (Meineke and Listerud 1977). Little exploration has been done for this type of resource. Other minerals such as gold, silver, cobalt, and platinum-group metals may be recoverable as a by-produce of processing the Cu-Ni sulfides although little or no exploration for platinum-group metals has been done. Other possible resources include vanadium, chromium, aluminum, and graphite, although exploration for these minerals has been done beyond that done during exploration of copper and nickel sulfides.

The Duluth Complex has a very real potential for being a major source of copper and nickel in the United States as well as other less abundant metals as exploration techniques and technology progress. A better understanding of the Duluth Complex is needed to fully evaluate the mineralogic, petrologic, and structural history and its relationship to the origin of the copper-nickel mineralization.

VI. REFERENCES

Bath, C.D., G.M. Schwartz and F.P. Gilbert. 1965. Aeromagnetic and geologic map of northeastern Minnesota, 1:250,000. U.S. Geol. Survey, Geophys. Inv. Map GP-472.

Beltrame, R.J. 1974. Report on field mapping in the Duluth Complex: Gabbro Lake quadrangle 1974. Minn. Geol. Survey, open-file report.

-------. 1975. Report on field mapping in the Duluth Complex: Gabbro Lake quadrangle 1974. Minn. Geol. Survey, open-file report.

Bonnichsen, B. 1969a. Metamorphic pyroxenes and amphiboles in the Biwabik Iron Formation, Dunka River area, Minnesota. Minn. Soc. America Spec. Paper 2.

-------. 1969b. Geology of the southern part of the Duluth Complex, Minnesota. Ann. Mining Symp., 30th Proc., Am. Inst. Mining Engineers, Duluth, MN.

-------. 1970. Geologic maps of the Allen, Babbitt, Babbitt N.C., Babbitt S.E., and Babbitt S.W. 7½ minute quadrangles, 1:24,000. Minn. Geol. Survey, open-file maps.

-------. 1971. Outcrop map of southern part of Duluth Complex and associated Keweenawan rocks, St. Louis and Lake counties, Minnesota, 1:125,000. Minn. Geol. Survey, misc. map series, M-11.

-------. 1972a. Southern part of Duluth Complex, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

-------. 1972b. Sulfide minerals in the Duluth Complex, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

-------. 1974. Geology of the Ely-Hoyt Lakes district, northeastern Minnesota. Minn. Geol. Survey, open-file report.

-------. 1975. Geology of the Biwabik Iron Formation, Dunka River area, Minnesota. Econ. Geology, Vol. 70.

Boucher, M.L. 1975. Copper-nickel mineralization in a drill core from the Duluth Complex of northern Minnesota. USBM, RI8084.

Cooper, R.W. 1976. Lineament analysis of the Hoyt Lakes-Kawishiwi area, St. Louis and Lake counties, northeastern Minnesota (with 1:48,000 lineament maps). Minn. Geol. Survey, open-file report.

Cooper, R.W. and R. Churchill. 1975. Field map of the INCO Minesite, Lake County, Minnesota. Minn. Geol. Survey, open-file map.

Craddock, C. 1972c. Structural evolution of the Keweenawan province (abstr.). Geol. Soc. America Abstracts with Programs, 1972, Vol. 4.

REFERENCES continued

Davidson, D.M., Jr. 1969. The Duluth Complex in the Perent Lake and Kawishiwi Lake quadrangles, Lake and Cook counties, Minnesota. Minn. Geol. Survey misc. map series M-7 and M-8, 1:24,000 (with text).

-------. 1972. Eastern part of Duluth Complex, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

Elftman, A.H. 1898a. The geology of the Keweenawan area in northeastern Minnesota, Part II. Am. Geologist, Vol. 21.

-------. 1898b. The geology of the Keweenawan area in northeastern Minnesota, Part III. Am. Geologist, Vol. 22.

Faure, G., S. Chadhuri and M.D. Fenton. 1969. Ages of the Duluth Gabbro Complex and of the Endion sill, Duluth, Minnesota. Jour. Geophys. Res., Vol. 74.

Fellows, S.N. 1976. Description and interpretation of the petrology of a portion of a drill core from the Duluth Complex near Babbitt, Minnesota: unpubl. M.S. thesis, Cornell Univ., Ithaca, NY.

French, B.M. 1968. Progressive contact metamorphism of the Biwabik Iron Formation, Mesabi Range, Minnesota. Minn. Geol. Survey Bull. 45.

Fukui, L.M. 1976. The mineralogy and petrology of the South Kawishiwi intrusion, Duluth Complex, Minnesota: unpubl. M.S. thesis, Univ. of Illinois-Chicago Circle, Chicago, IL.

Goldich, S.S., A.O. Nier, H. Baadsgaard, J.H. Hoffman and H.W. Krueger. 1961. The Precambrian geology and geochronology of Minnesota. Minn. Geol. Survey Bull. 41.

Goodwin, A.M. 1956. Facies relations in the Gunflint Iron Formation. Econ. Geology, Vol. 51.

Green, J.C. 1972. North Shore Volcanic Group, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

Green, J.C., W.C. Phinney and P.W. Weiblen. 1966. Gabbro Lake quadrangle, Lake County, Minnesota. Minn. Geol. Survey misc. map M-2.

Grout, F.F. 1918a. The pegmatites of the Duluth Gabbro. Jour. Geol., Vol. 26.

-------. 1918b. Internal structures of igneous rocks; their significance and origin; with special reference to the Duluth Gabbro. Jour. Geol., Vol. 26.

-------. 1918c. The lopolith; an igneous form exemplified by the Duluth Gabbro. Am. Jour. Sci., 4th ser., Vol. 46.

-------. 1918d. Two phase convection in igneous magmas. Jour. Geol., Vol. 26.

-------. 1918e. A type of igneous differentiation. Jour. Geol., Vol. 26.

Gruner, J.W. 1946. The mineralogy and geology of the taconites and iron ores of the Mesabi Range, Minnesota. Office of Commissioner Iron Range Resources and Rehabilitation, St. Paul; in cooperation with Minn. Geol. Survey.

Halls, H.C. 1966. A review of the Keweenawan geology of the Lake Superior region in the earth beneath the continents. Am. Geophys. Union Mon. 10.

Hanson, G.N. 1975. $^{40}Ar/^{39}Ar$ spectrum ages on Logan Intrusions, a Lower Keweenawan flow, and mafic dikes in northeastern Minnesota-northwestern Ontario. Can. Jour. Earth Sci., Vol. 12.

Hanson, G.N. and R. Malhotra. 1971. K-Ar ages of mafic dikes and evidence for low-grade metamorphism in northeastern Minnesota. Geol. Soc. America Bull., V. 82.

Hardyman, R.F. 1969. The petrography of a section of the basal Duluth Complex, St. Louis County, northeastern Minnesota. Unpubl. M.S. thesis, Univ. of Minnesota, Minneapolis, MN.

Harris, J.M. 1954. Further notes on field work in the copper-nickel prospect area, Lake and St. Louis counties, Minnesota. Minn. Geol. Survey Summary Report #7.

Hooper, P. and R.W. Ojakangas. 1971. Multiple deformation in the Vermilion district, Minnesota. Can. Jour. Earth Sci., Vol. 8.

Jackson, E.D. 1967. Ultramafic cumulutes in the Stillwater, Great Dyke, and Bushveld intrusions, in Wyllie, P.J. (ed), Ultramafic and related rocks. John Wiley and Sons, New York, NY.

-------. 1971. The origin of ultramafic rocks by cumulus processes. Fortschr. Miner., Vol. 48.

Mainwaring, P.R. 1975. The petrology of a sulfide-bearing layered intrusion at the base of the Duluth Complex, St. Louis County, Minnesota. Unpubl. Ph.D. thesis, Univ. of Toronto, Toronto, Ontario, Canada.

Mainwaring, P.R. and A.J. Naldrett. 1977. County-rock assimilation and the genesis of Cu-Ni sulfides in the Water Hen Intrusion, Duluth Complex, Minnesota. Econ. Geology, Vol. 72.

Mattis, A.F. 1972. Puckwunge Formation of northeastern Minnesota, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

Meuschke, J.L., N.S. Tyson, et al. 1963. Aeromagnetic map of the northern part of Lake County, Minnesota. U.S. Geol. Survey Geophysical Inv. Map GP-360.

Meineke, D.G. and W.H. Listerud. 1977. Mineral resources of a portion of the Duluth Complex and adjacent rocks in St. Louis and Lake counties, northeastern Minnesota. Report 93, MDNR, Division of Minerals, Minerals Exploration Section.

Morey, G.B. 1965. The sedimentology of the Precambrian Rove Formation in northeastern Minnesota. Ph.D. thesis, Univ. of Minn., Minneapolis, MN.

-------. 1967. Stratigraphy and sedimentology of the Middle Precambrian Rove Formation in northeastern Minnesota. Jour. Sed. Petrology, Vol. 37.

-------. 1969. The geology of the Middle Precambrian Rove Formation in northeastern Minnesota. Minn. Geol. Survey Spec. Pub. SP-7.

-------. 1972. Mesabi Range, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

-------. 1973a. Stratigraphic framework of Middle Precambrian rocks in Minnesota. Geol. Assoc. Canada Spec. Paper #12.

-------. 1973b. Mesabi, Gunflint, and Cuyuna ranges, Minnesota: Unesco, Genesis of Precambrian iron and manganese deposits. Proc. Kiev. Symp.

Morey, G.B. and R.W. Cooper. 1977. Bedrock geology of the Hoyt Lakes-Kawishiwi area, St. Louis and Lake counties, northeastern Minnesota; 1:48,000. Minn. Geol. Survey, open-file map.

Morey, G.B., J.C. Green, R.W. Ojakangas and P.K. Sims. 1970. Stratigraphy of the Lower Precambrian rocks in the Vermilion district, northeastern Minnesota. Minn. Geol. Survey Rept. Inv. 14.

Nathan, H.D. 1969. The geology of a portion of the Duluth Complex, Cook County. Unpubl. Ph.D. thesis, Univ. of Minn., Minneapolis, MN.

Ojakangas, R.W. 1972. Graywackes and related rocks of the Knife Lake Group and Lake Vermilion Formation, Vermilion District, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

O'Leary, D.W., J.D. Friedman and H.A. Pohn. 1976. Lineament, linear, lineation: some proposed new standards for old terms. Geol. Soc. America Bull., Vol. 87.

Olcott, P.G. and D.I. Siegel. 1978. Physiography and surficial geology of the Copper-Nickel Study Area, northeastern Minnesota. U.S. Geol. Survey, Water Resources Investigation 78-51, open-file report.

Phinney, W.C. 1967. Geologic map of a part of the Kangas Bay quadrangle, showing the Duluth Complex; 1:24,000. Minn. Geol. Survey, open-file map.

-------. 1969. The Duluth Complex in the Gabbro Lake quadrangle, Minnesota. Minn. Geol. Survey Rept. Inv. 9.

REFERENCES continued

Prince, L.A. and G.N. Hanson. 1972. Rb-Sr isochron ages for the Giants Range grai . . Geol. Soc. America Memoir 135.

Renner, J.L. 1969. The petrology of the contact rocks of the Duluth Complex, Dunka River area, Minnesota. Unpubl. M.S. thesis, Univ. of Minn., Minneapolis, MN.

Schulz, K.J. 1977. The petrology and geochemistry of Archean volcanics, western Vermilion district, northeastern Minnesota. Unpubl. Ph.D. thesis Univ. of Minn., Minneapolis, MN.

Schwartz, G.M. and D.M. Davidson. 1952. Geologic setting of the copper-nickel prospect in the Duluth Gabbro near Ely, Minnesota. Mining Engineering, Vol. 4.

Schwartz, G.M. and J.M. Harris. 1952. Notes on field work in the copper-nickel prospect area, Lake County, Minnesota. Minn. Geol. Survey Summary Rpt., No. 6.

Silver, L.T. and J.C. Green. 1963. Zircon ages for Middle Keweenawan rocks of Lake Superior region (abs.). Am. Geophys. Union Trans., Vol. 44.

Sims, P.K. 1972a. Vermilion District and adjacent areas, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

-------. 1972b. Banded iron-formations in Vermilion District, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

-------. 1972c. Metavolcanic and associated synvolcanic rocks in Vermilion District, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

-------. 1973. Geologic map of western part of Vermilion District, northeastern Minnesota, 1:48,000. Minn. Geol. Survey Misc. map M-13.

-------. 1976a. Precambrian tectonics and mineral deposits, Lake Superior region. Econ. Geology, Vol. 71.

-------. 1976b. Early Precambrian tectonic-igneous evolution in the Vermilion District, northeastern Minnesota. Geol. Soc. America Bull., Vol. 87.

Sims, P.K., G.B. Morey, R.W. Ojakangas and S. Viswanethan. 1970. Geologic map of Minnesota, Hibbing sheet. Minn. Geol. Survey.

Southwick, D.L. 1972. Vermilion granite-migmatite massif, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

REFERENCES continued

Stark, J.R. 1974. Surficial geology of the Hoyt Lakes-Kawishiwi area, northeastern Minnesota. Minn. Geol. Survey, open-file report.

-------. 1977. Surficial geology and ground-water geology of the Babbitt-Kawishiwi area, northeastern Minnesota with planning implications. Unpub. M.S. thesis, Univ. of Wisconsin, Madison, WI.

Stevenson, R.J. 1974. A mafic-layered intrusion of Keweenawan age near Finland, Lake County, Minnesota. Unpub. M.S. thesis, Univ. of Minn., Duluth, MN.

Taylor, R.B. 1964. Geology of the Duluth Gabbro Complex near Duluth, Minn. Minn. Geol. Survey Bull.

Tyson, R.M. 1976. Hornfelsed basalts in the Duluth Complex. Unpub. M.S. thesis, Cornell Univ., Ithaca, NY.

U.S. Geological Survey. 1969. Aeromagnetic map of the McNair-Grand Portage area, northeastern Minnesota. U.S. Geol. Survey Geophys. Inv. Map GP-639.

Wager, R.E., R. Alcock and W.C. Phinney. 1969. A comparison of the copper-nickel deposits of Sudbury and Duluth basins. Proc. 30th Ann. Mining Symp., Univ. of Minn. and Minn. Geol. Survey, open-file report.

Weiblen, P.W. 1965. A funnel-shaped, gabbro-troctolite intrusion in the Duluth Complex, Lake County, Minnesota. Unpub. Ph.D. thesis, Univ. of Minn., Minneapolis, MN

Weiblen, P.W. and R.W. Cooper. 1977a. Bedrock geology of the Hoyt Lakes-Kawishiwi area, St. Louis and Lake counties, northeastern Minnesota. Minn. Geol. Survey, open-file report.

-------. 1977b. Shape, size, and cooling history of troctolitic-gabbroic rocks in the Duluth Complex (abstr.). Inst. on Lake Superior Geology, 23rd Ann. Mtg., Thunder Bay, Ontario, Canada.

Weiblen, P.W., D.M. Davidson, G.B. Morey and M.G. Mudrey, Jr. 1972a. Geology of Cook County, in Precamrian Geology of northewestern Cook County, Minnesota: Field guidebook. Geol. Soc. America Ann. Mtg., 1972.

Weiblen, P.W., E.A. Mathez and G.B. Morey. 1972b. Logan intrusions, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.

Weiblen, P.A. and G.B. Morey. 1975. The Duluth Complex--a petrologic and tectonic summary. Proc. 48th Ann. Mtg., Minnesota section, AIME; 36th Ann. Mining Symposium, Univ. of Minn.

-------. 1976. Textural and compositional characteristics of sulfide areas from the basal contact zone of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota. Proc. 49th Ann. Mtg., Minnesota section, AIME; 36th Ann. Mining Symposium, Univ. of Minn.

REFERENCES continued

White, D.A. 1954. Stratigraphy and structure of the Mesabi range, Minnesota. Minn. Geol. Survey Bull. #38.

White, W.S. 1966a. Geologic evidence for crustal structure in the western Lake Superior basin, in: The earth beneath the continents. Am. Geophys. Union Mon. 10.

-------. 1966b. Tectonics of the Keweenawan basin, western Lake Superior region. U.S. Geol. Survey Prof. Paper 524-E.

Winter, T.C., R.D. Cotter and H.L. Young. 1973. Petrography and stratigraphy of glacial drift, Mesabi-Vermilion Iron Range area, northeastern Minnesota. U.S. Geol. Survey Bull. 1331-C.

Wolff, J.F. 1917. Recent geologic developments on the Mesabi range, Minnesota. Am. Inst. Mining Metall. Engineers Trans., Vol. 56.

Wright, H.E., Jr. 1972. Quaternary history of Minnesota, in Sims, P.K. and G.B. Morey (eds), Geology of Minnesota: a centennial volume. Minn. Geol. Survey.