Volume 3-Chapter 1

GEOLOGY AND MINERALOGY

Minnesota Environmental Quality Board
Regional Copper-Nickel Study
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PLEASE NOTE:

At this point, Chapters 1 and 2 of Volume 3 are being issued as a combined document. The introduction to Chapter 1 deals also with the results of Chapter 2, and the reference list at the end of Chapter 2 serves both chapters.

In the final printing, each chapter will stand by itself with separate introductions and lists of references.

A NOTE ABOUT UNITS

This report, which in total covers some 36 chapters in 5 volumes, is both international and interdisciplinary in scope. As a result, the problem of an appropriate and consistent choice of units of measure for use throughout the entire report proved insurmountable. Instead, most sections use the system of units judged most common in the science or profession under discussion. However, interdisciplinary tie-ins complicated this simple objective, and resulted in the use of a mix of units in many sections. A few specific comments will hopefully aid the reader in coping with the resulting melange (which is a reflection of the international multiplicity of measurement systems):

1) Where reasonable, an effort has been made to use the metric system (meters, kilograms, kilowatt-hours, etc.) of units which is widely used in the physical and biological sciences, and is slowly becoming accepted in the United States.

2) In several areas, notably engineering discussions, the use of many English units (feet, pounds, BTU's, etc.) is retained in the belief that this will better serve most readers.

3) Notable among the units used to promote the metric system is the metric ton, which consists of 2205 pounds and is abbreviated as mt. The metric ton (1000 kilograms) is roughly 10% larger (10.25%) than the common or short ton (st) of 2000 pounds. The metric ton is quite comparable to the long ton (2240 pounds) commonly used in the iron ore industry. (Strictly speaking, pounds and kilograms are totally different animals, but since this report is not concerned with mining in outer space away from the earth's surface, the distinction is purely academic and of no practical importance here).

4) The hectare is a unit of area in the metric system which will be encountered throughout this report. It represents the area of a square, 100 meters on a side (10,000 m^2), and is roughly equivalent to 2½ acres (actually 2.4710 acres). Thus, one square mile, which consists of 640 acres, contains some 259 hectares.

The attached table includes conversion factors for some common units used in this report. Hopefully, with these aids and a bit of patience, the reader will succeed in mastering the transitions between measurement systems that a full reading of this report requires. Be comforted by the fact that measurements of time are the same in all systems, and that all economic units are expressed in terms of United States dollars, eliminating the need to convert from British Pounds, Rands, Yen, Kawachas, Rubles, and so forth!

Conversions for Common Metric Units Used in the Copper-Nickel Reports

1 meter (m) = 3.28 feet = 1.094 yards

1 centimeter (cm) = 0.3937 inches

1 kilometer (km) = 0.621 miles

1 hectare (ha) = 10,000 sq. meters = 2.471 acres

1 square meter (m^2) = 10.764 sq. feet = 1.196 sq. yards

1 square kilometer (km^2) = 100 hectares = 0.386 sq. miles

1 gram (g) = 0.037 oz. (avoir.) = 0.0322 Troy oz.

1 kilogram (kg) = 2.205 pounds

1 metric ton (mt) = 1,000 kilograms = 0.984 long tons = 1.1025 short tons

1 cubic meter (m^3) = 1.308 yd^3 = 35.315 ft^3

1 liter (1) = 0.264 U.S. gallons

1 liter/minute (1/min) = 0.264 U.S. gallons/minute = 0.00117 acre-feet/day

1 kilometer/hour (km/hr) = 0.621 miles/hour

degrees Celsius (°C) = (5/9)(degrees Fahrenheit -32)

Standard abbreviations.

ha - hectare
st - short ton of 2000 lb
lt - long ton of 2240 lb
mt - metric ton of 2205 lb
mtpy - metric ton(s) per year

ppm - parts per million
ppb - parts per billion
um - micron or 10^{-6} meters
% - percent by weight unless otherwise noted

ELEMENT	SYMBOL	ELEMENT	SYMBOL	ELEMENT	SYMBOL
Actinium	Ac	Holmium	Ho	Rhenium	Re
Aluminum	Al	Hydrogen	H	Rhodium	Rh
Americium	Am	Indium	In	Rubidium	Rb
Antimony	Sb	Iodine	I	Ruthenium	Ru
Argon	Ar	Iridium	Ir	Samarium	Sm
Arsenic	As	Iron	Fe	Scandium	Sc
Astatine	At	Krypton	Kr	Selenium	Se
Barium	Ba	Lanthanum	La	Silicon	Si
Berkelium	Ba	Lawrencium	Lw	Silver	Ag
Beryllium	Be	Lead	Pb	Sodium	Na
Bismuth	Bi	Lithium	Li	Strontium	Sr
Boron	B	Lutetium	Lu	Sulfur	S
Bromine	Br	Magnesium	Mg	Tantalum	Ta
Cadmium	Cd	Manganese	Mn	Technetium	Tc
Calcium	Ca	Mendelevium	Md	Tellurium	Te
Californium	Cf	Mercury	Hg	Terbium	Tb
Carbon	C	Molybdenum	Mo	Thallium	Tl
Cerium	Ce	Neodymium	Nd	Thorium	Th
Cesium	Cs	Neon	Ne	Thulium	Tm
Chlorine	Cl	Neptunium	Np	Tin	Sn
Chromium	Cr	Nickel	Ni	Titanium	Ti
Cobalt	Co	Niobium	Nb	Tungsten	W
Copper	Cu	Nitrogen	N	Uranium	U
Curium	Cm	Nobelium	No	Vanadium	V
Dysprosium	Dy	Osmium	Os	Xenon	Xe
Eisteinium	Es	Oxygen	O	Ytterbium	Yb
Erbium	Er	Palladium	Pd	Yttrium	Y
Eutopium	Eu	Phosphorus	P	Zinc	Zn
Fermium	Fm	Platinum	Pt	Zirconium	Zr
Fluorine	F	Plutonium	Pu		
Francium	Fr	Polonium	Po		
Gadolinium	Gd	Potassium	K		
Gallium	Ga	Praseodymium	Pr		
Germanium	Ge	Promethium	Pm		
Gold	Au	Protactinium	Pa		
Hafnium	Hf	Radium	Ra		
Helium	He	Radon	Rn		

Volume 3-Chapter 1 GEOLOGY AND MINERALOGY

1.1 INTRODUCTION

1.1.1 Scope and Purpose

Geology is important to any study pertaining to possible mining in a region because this discipline elucidates the nature and formation of the earth and the mineral resources in the region. Any regional geology can be divided into 2 categories: regional bedrock geology (regional distribution of rock types), and regional surficial geology (distribution of material overlying those rock types). Included under the general category of bedrock geology are the subdisciples of structural geology, petrology, and mineralogy. Structural geology deals with the form, arrangement, and internal structure of the rocks and with the analysis of structures. Petrology is the study of the origin and occurrence of rocks and will be discussed with emphasis on the occurrence of the copper-nickel bearing (mineralized) rocks of the Duluth Complex. Mineralogy is the study of the origin, distribution, and composition of the minerals that make up the rocks of the region. This includes valuable ore minerals as well as gangue or waste minerals.

After elucidation of the bedrock, surficial, and Duluth Complex geology, the mineral resource potential of these rocks is discussed in Chapter 2. Without an understanding of the resource potential, no projections can be made regarding mine life or even whether or not mining will occur.

The following sections are based on information from a variety of sources. The Minnesota Geologic Survey has supplied regional bedrock geology (petrology, structure, and mineralogy). Surficial geology information was obtained through a contract with the U.S. Geological Survey. Fiber generation analysis was performed by the Minnesota Department of Health. Chemical analyses of rock samples were done by Barringer, Ltd. of Toronto, Canada, and the University of Minnesota's Mineral Resources Research Center. Many of the samples for use in the above analyses were obtained from the study region with the assistance of the Minerals Division of the Minnesota Department of Natural Resources. These samples were geologically characterized by the Minnesota Geologic Survey and subjected to a variety of simulated mining processes at the Mineral Resources Research Center.

1.1.2 Summary

The principal results of this and the following chapter include the finding that a large, low-grade resource of copper-nickel sulfide exists in northeastern Minnesota along the basal contact of the Duluth Gabbro Complex. Recent estimates indicate the presence of 4.0×10^9 mt of resource averaging 0.66% Cu and 0.20% Ni. The principal deposits appear to exist as relatively isolated pockets stretching along the contact from an area just south of Ely, to sites south of Hoyt Lakes, a distance of over 40 mi. The deposits are typically overlain by glacial till varying in thickness from zero to 60 ft, with 100 to 200 ft present in a few isolated instances. Based on the information presently available, a set of "resource zones" which contain the areas of known mineralization have been defined to facilitate the impact assessment process and are shown in Figure 1. It is expected that any copper-nickel mines which may be developed in the Study Area in the future will lie within the belt defined by these resource zones. Associated with the mineral resource zones is a broader area, termed the "development zones," also indicated on Figure 1 as the region within which the bulk of the facilities serving any actual mine are likely to be located.

Figure 1

The bulk of the resource appears to be represented by a low-grade disseminated material at depths ranging from surface outcrops to 3,000 ft and deeper. Both open pit and underground mining may be used to recover this resource. This resource is physically and chemically similar to adjacent waste rock and rock which might be classified as lean ore in the event mining proceeds. The only significant difference among these types appears to be the sulfide content. In addition, small quantities of higher grade, semi-massive resources are also known to exist, grading in the range of 3% Cu. This material is both physically and chemically different from the disseminated resources.

Preliminary tests indicate that both types of resource can be successfully treated for concentration of valuable sulfides. Recoveries of 90-95% of contained copper and 65-75% of contained nickel appear achievable. In addition, it appears that, although the natural occurrence of asbestiform minerals in the Duluth Complex appears to be quite rare, mineral fibers and fiber-like fragments will be produced in the concentration process. The amount of amphibole fibers and fiber-like fragments produced, important because of possible human health concerns, is proportional both to the amount of amphibole present in the rock, and to the degree of crushing and grinding during the milling process. The tailing water slurries from the processing of copper-nickel ores will likely contain on the order of 10^{12} to 10^{13} mineral fibers/liter of water, of which some 20-30% or more may be amphibole. This represents 10^9 to 10^{10} fibers per gram of dry tailing material. These fibers in suspension in tailing water would be expected to be present in any untreated discharge from a tailing basin. Data on the treatment of water by flocculation indicates the method is quite effective, reducing fiber concentrations by 4 to 5 orders of magnitude.

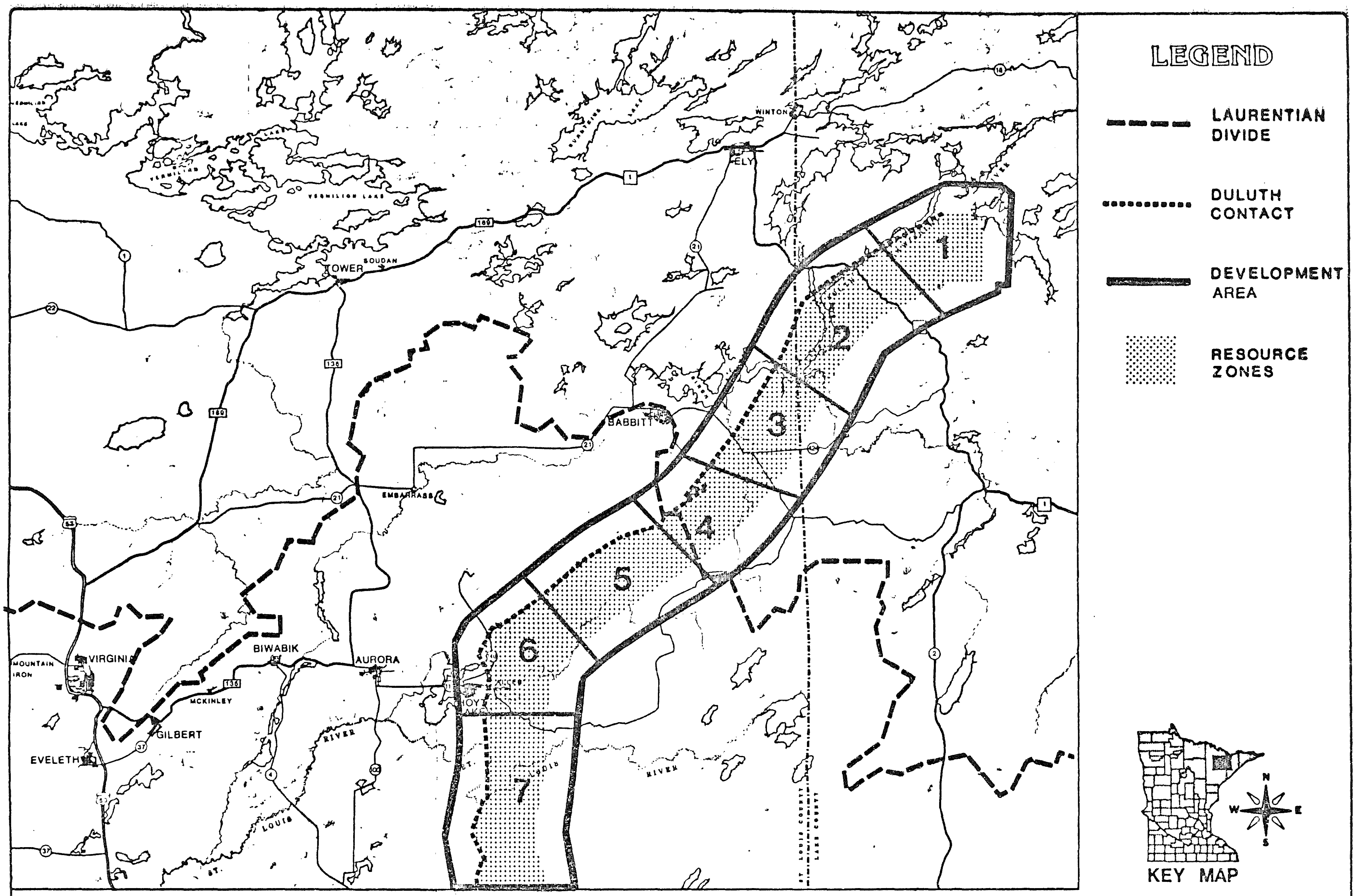

FIGURE 1

MEQB REGIONAL COPPER-NICKEL STUDY

MN CU-NI DEVELOPMENT AND RESOURCE ZONES

The potential composition of ore, tailing material, and concentrates have been modeled to facilitate impact assessment. Tables 1 and 2 present the models for the chemical composition of disseminated ore, tailing, and concentrate from an open pit and an underground mine, respectively. Mines with the capacity to supply from 5 to 20 X 10^6 mt of ore per year are envisioned, and used in the models. Typically, 95-97% of the ore mined is discarded as waste to a tailing basin. In addition, for open pit mining operations (possibly 11.33 to 20.00 X 10^6 mtpy capacity) the large quantity of waste rock to be disposed of is indicated by the models which discard 1.3 mt tons of waste rock for every metric ton of ore mined.

Tables 1 & 2

The 3-5% of the ore which is sent to a smelting operation as a concentrate for recovery of the valuable metals it contains would have to amount to some 635,000 mtpy, according to the model, in order to feed a large modern smelter/refinery complex producing 100,000 mtpy of metal (approximately 84,600 mtpy of copper and 15,400 mtpy of nickel plus small quantities of gold, silver, and other precious metals). Such an operation would require all the output of a 20.00 X 10^6 mtpy open pit mine or a 12.35 X 10^6 mtpy underground mine. In addition to the valuable metals, the smelter would also produce roughly 600,000 mtpy of slag for disposal, and 450,000 mtpy of sulfuric acid to be sold or neutralized on site.

1.2 GENERAL GEOLOGY OVERVIEW

Much of the information in the following discussions was taken from a report prepared for the Regional Copper-Nickel Study (Cooper 1978b). This report should be referred to for further information.

Table 1. Open pit disseminated ore, tailing, and concentrate models.[a]

ELEMENT	DISSEMINATED ORE	TAILING	CONCENTRATE	UNITS
Si(SiO_2)	22.32(47.79)	22.83(48.87)	7.25(15.53)	PCT
Al(Al_2O_3)	9.22(17.42)	9.46(17.88)	1.81(3.43)	PCT
Fe(FeO)	8.70(11.19)	8.90(11.45)	2.53(3.26)	PCT
Mg(MgO)	4.55(7.53)	4.65(7.69)	1.55(2.57)	PCT
Ca(CaO)	5.54(7.75)	5.68(7.95)	1.14(1.61)	PCT
Na(Na_2O)	2.18(2.94)	2.24(3.02)	0.39(0.53)	PCT
K(K_2O)	0.35(0.42)	0.36(0.43)	0.08(0.10)	PCT
Ti(TiO_2)	0.92(1.53)	0.95(1.57)	0.10(0.17)	PCT
P(P_2O_5)	0.03(0.07)	0.03(0.07)	0.01(0.03)	PCT
Mn(MnO)	0.12(0.16)	0.12(0.16)	0.03(0.04)	PCT
Cr(Cr_2O_3)	0.03(0.05)	0.03(0.05)	0.04(0.06)	PCT
B	571.9	580.5	310.1	PPM
Ba	705.1	724.0	129.6	PPM
Be	0.54	0.56	0.06	PPM
Sr	278.0	278.3	50.2	PPM
V	167.2	169.9	85.5	PPM
Th	4.3	4.34	3.0	PPM
Zr	96.2	98.5	25.7	PPM
S	1.095	0.281	25.870	PCT
Cu	0.494	0.056	13.825	PCT
Ni	0.114	0.031	2.647	PCT
Fe	1.235	0.290	30.001	PCT
Co	0.011	0.007	0.132	PCT
Zn	132.9	99.9	1137.0	PPM
Pb	4.6	2.8	60.7	PPM
Ag	2.4	1.4	34.3	PPM
As	9.5	8.8	31	PPM
Hg	0.075	0.0717	0.174	PPM
Mo	1.4	0.5	28.1	PPM
Cd	9.5	8.5	40	PPM

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[a] See the text for a discussion of the assumptions and methodology used to derive these models.

Table 2. Underground disseminated ore, tailing, and concentrate models.[a]

ELEMENT	DISSEMINATED ORE	TAILING	CONCENTRATE	UNITS
Si(SiO_2)	21.96(47.01)	22.76(48.72)	7.25(15.53)	PCT
Al(Al_2O_3)	9.08(17.14)	9.47(17.88)	1.81(3.43)	PCT
Fe(FeO)	8.56(11.01)	8.89(11.43)	2.53(3.26)	PCT
Mg(MgO)	4.47(7.41)	4.63(7.67)	1.55(2.57)	PCT
Ca(CaO)	5.45(7.63)	5.68(7.96)	1.14(1.61)	PCT
Na(Na_2O)	2.15(2.90)	2.25(3.03)	0.39(0.53)	PCT
K(K_2O)	0.34(0.41)	0.35(0.43)	0.08(0.10)	PCT
Ti(TiO_2)	0.90(1.51)	0.94(1.58)	0.10(0.17)	PCT
P(P_2O_5)	0.03(0.07)	0.03(0.07)	0.01(0.03)	PCT
Mn(MnO)	0.12(0.16)	0.12(0.17)	0.03(0.04)	PCT
Cr(Cr_2O_3)	0.03(0.05)	0.03(0.05)	0.04(0.06)	PCT
B	562.7	576.4	310.1	PPM
Ba	693.8	724.4	129.6	PPM
Be	0.53	0.56	0.06	PPM
Sr	273.6	285.7	50.2	PPM
V	163.7	167.9	85.5	PPM
Th	4.2	4.3	3.0	PPM
Zr	94.7	98.4	25.7	PPM
S	1.658	0.346	25.870	PCT
Cu	0.800	0.094	13.825	PCT
Ni	0.185	0.051	2.647	PCT
Fe	1.834	0.308	30.001	PCT
Co	0.017	0.011	0.132	PCT
Zn	204.1	153.6	1137.0	PPM
Pb	7.8	4.9	60.7	PPM
Ag	4.0	2.4	34.3	PPM
As	14.7	13.8	31	PPM
Hg	0.117	0.114	0.174	PPM
Mo	2.3	1.5	28.1	PPM
Cd	14.7	13.3	40	PPM

[a] See the text for a discussion of the assumptions and methodology used to derive these models.

Minnesota lies on the southern margin of a great region of exposed Precambrian rocks, older than 570 million years. Although a few exposures are present, the Precambrian rocks in the southern portion of the state are generally hidden by younger rocks. This obscuring mantle is relatively undisturbed, and thickens to the south. In northeastern Minnesota, however, this covering is absent.

The state's landscape is inherited largely from the period of Pleistocene Continental glaciation, some 20 thousand years ago. In northeastern Minnesota, the glaciation resulted in a varying but generally thin covering of loose glacial till, with frequent exposures of the underlying Precambrian rocks. It is in these exposed areas that the first traces of copper and nickel were found. Subsequent findings of substantial quantities of copper-nickel resources in these areas explains the current focus on mining possibilities there.

The regional geology of the Study Area (Figure 2) consists of Lower Precambrian (older than 2.5 billion years) metavolcanic, metasedimentary, and granitic rocks of the western Vermillion district, Middle Precambrian (between 2.5 and 1.7 billion years) metasedimentary rocks, and various mafic intrusive rocks assigned to the Upper Precambrian (between 1,700 and 570 million years) Duluth Complex.

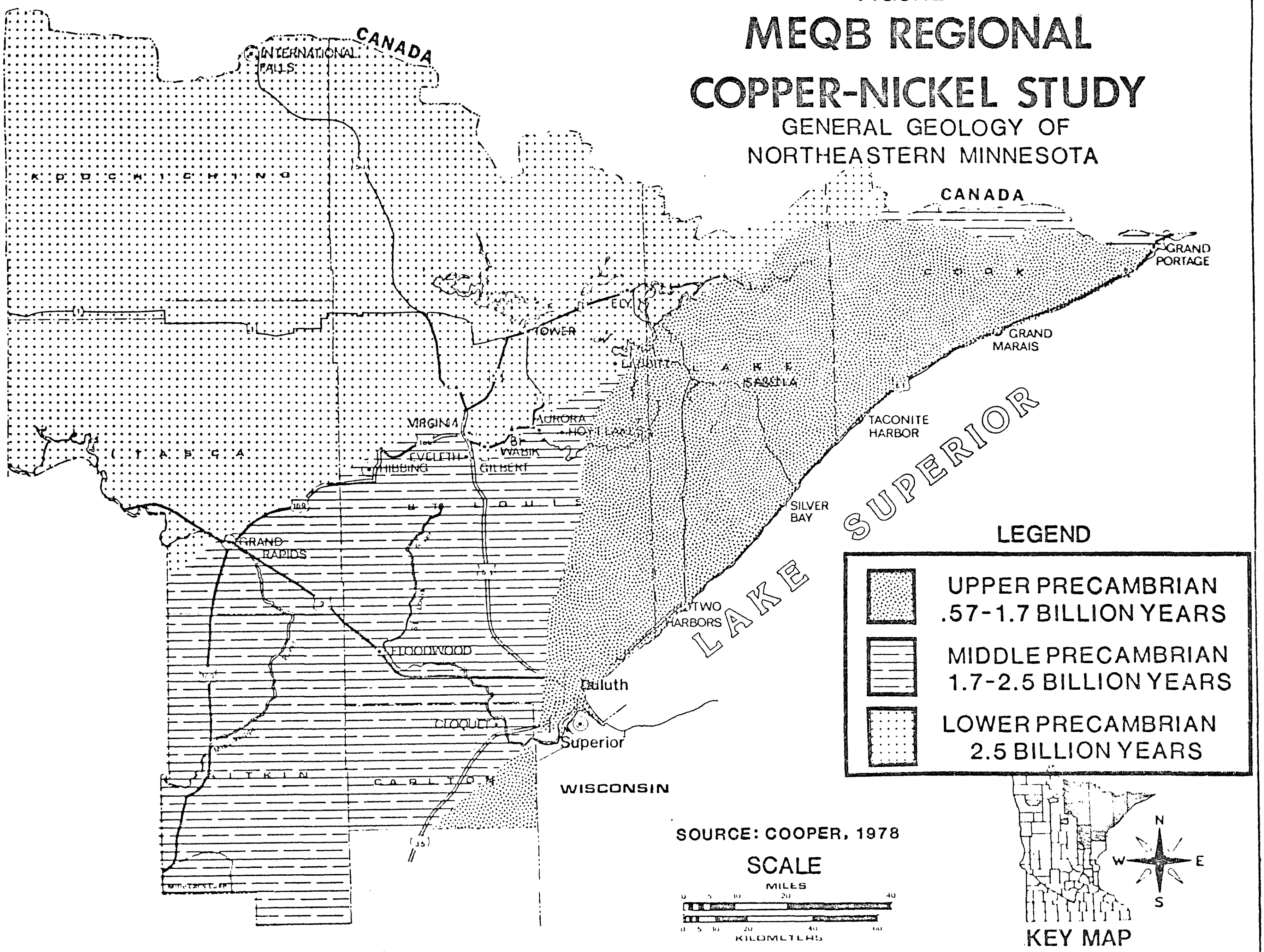
Figure 2

The general chronologic and stratigraphic sequence of Precambrian rocks in northeastern Minnesota is summarized in Table 3, and a generalized map of the geology of northeastern Minnesota is presented in Figures 3 and 4. 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.

FIGURE 2

MEQB REGIONAL COPPER-NICKEL STUDY

GENERAL GEOLOGY OF NORTHEASTERN MINNESOTA



SOURCE: COOPER, 1978

Table 3, Figures 3 & 4

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 eastward into Ontario. The belt is termed the Warwa belt in Canada while in Minnesota it is part of the Vermilion district. The stratigraphic sequence of the Vermilion district consists of 4 formations as defined by Morey et al. (1970) and Sims (1976). The oldest formation is the Ely Greenstone which consists dominantly of mafic volcanic rocks. Exploration for base metal deposits of Cu, Ni, Co, Pb, and Zn in these rocks is still going on. 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.

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 Vermilion district while the Knife Lake Group predominates in the eastern part (Figures 3 and 4). 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. The Lake Vermilion Formation and Knife Lake Group are considered, in part, to be stratigraphically equivalent.

Overlying the Knife Lake Group in the vicinity of Ely is the Newton Lake Formation which consists of subaqueous mafic and felsic volcanic rocks. Also present are interformational sediments, volcanoclastic sediments, and various types of pyroclastic deposits.

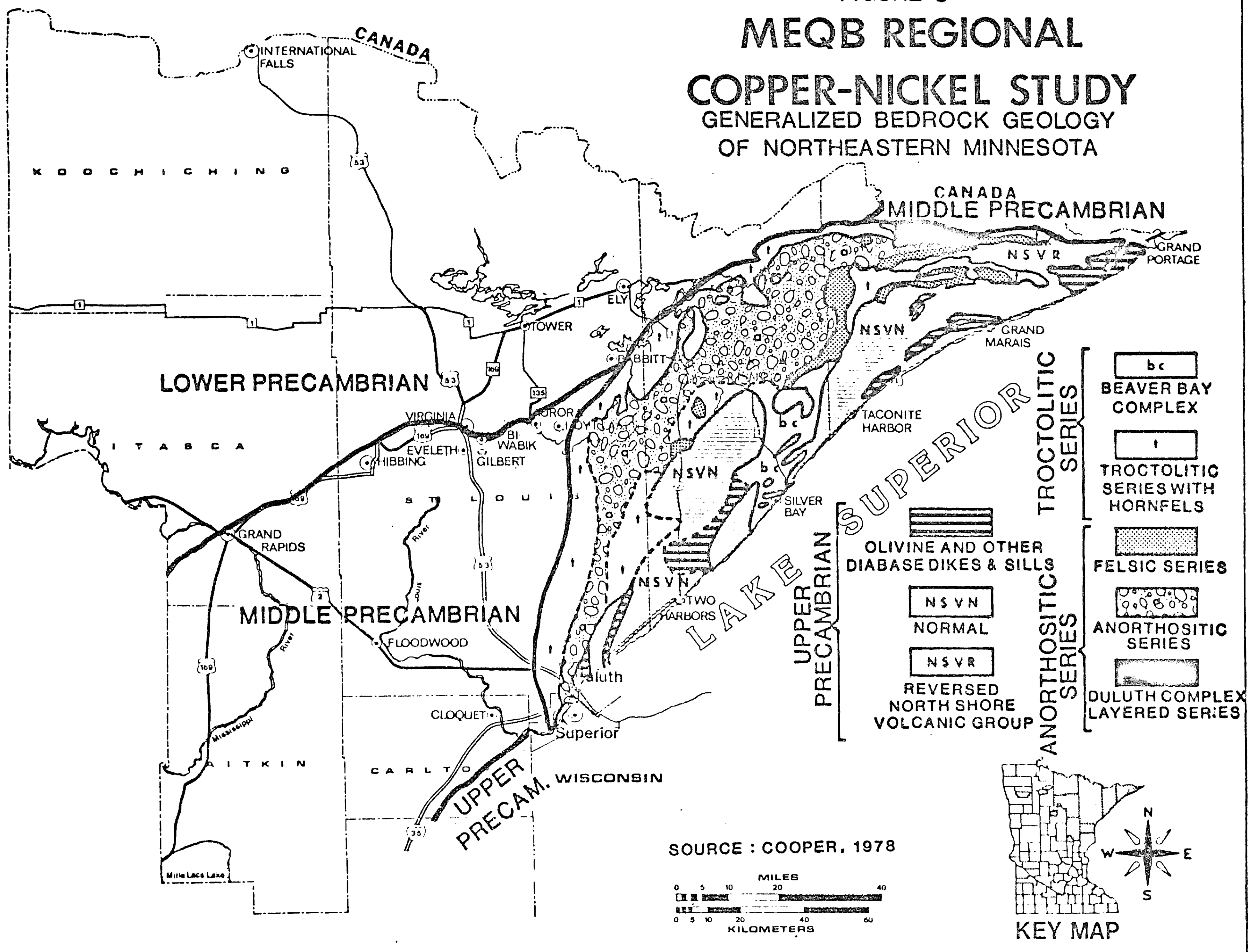
Table 3. Stratigraphic succession and geochronology of the precambrian of northeastern Minnesota and northern Wisconsin (modified from Goldich et al. 1961, and Morey 1965).

ERA	PERIOD-SYSTEM	MAJOR SEQUENCE	FORMATION	OROGENY	INTRUSIVE ROCKS
0.9 b.y.					
			Hinckley ss.		
			Fond du Lac ss.		
			Freda ss.		
Late		Oronto Group	Nonesuch shale		
	Keweenawan		Copper Harbor cgl.		
		North Shore	Undivided		sills at Duluth
		Volcanic Group			Beaver Bay Complex
					Duluth Complex-Mellen gabbro
					Logan intrusives
			Puckwunge F.m.		
1.7 b.y.			uncomformity	Penokean	
Middle		Animikie	Virginian F.m.-Rove-Thomson		
	Huronian		Biwabik-Gunflint Fe-Fm		
Precambrian		Group	Pokegama Quartzite		
					Snowbank pluton
2.5 b.y.			uncomformity	Algoman	Giants Range batholith
					Vermilion massif
	Timiskamian		Newton Lake F.m.		
Early		Knife Lake	Upper Knife Lake Group		
7 b.y.				Laurential	Saganata tonalite
		Group	Lower Knife Group		
Precambrian			Lake Vermilion F.m.		
	Ontarian	Keewatin	Soudan Iron Formation		
		Group	Ely Greenstone		

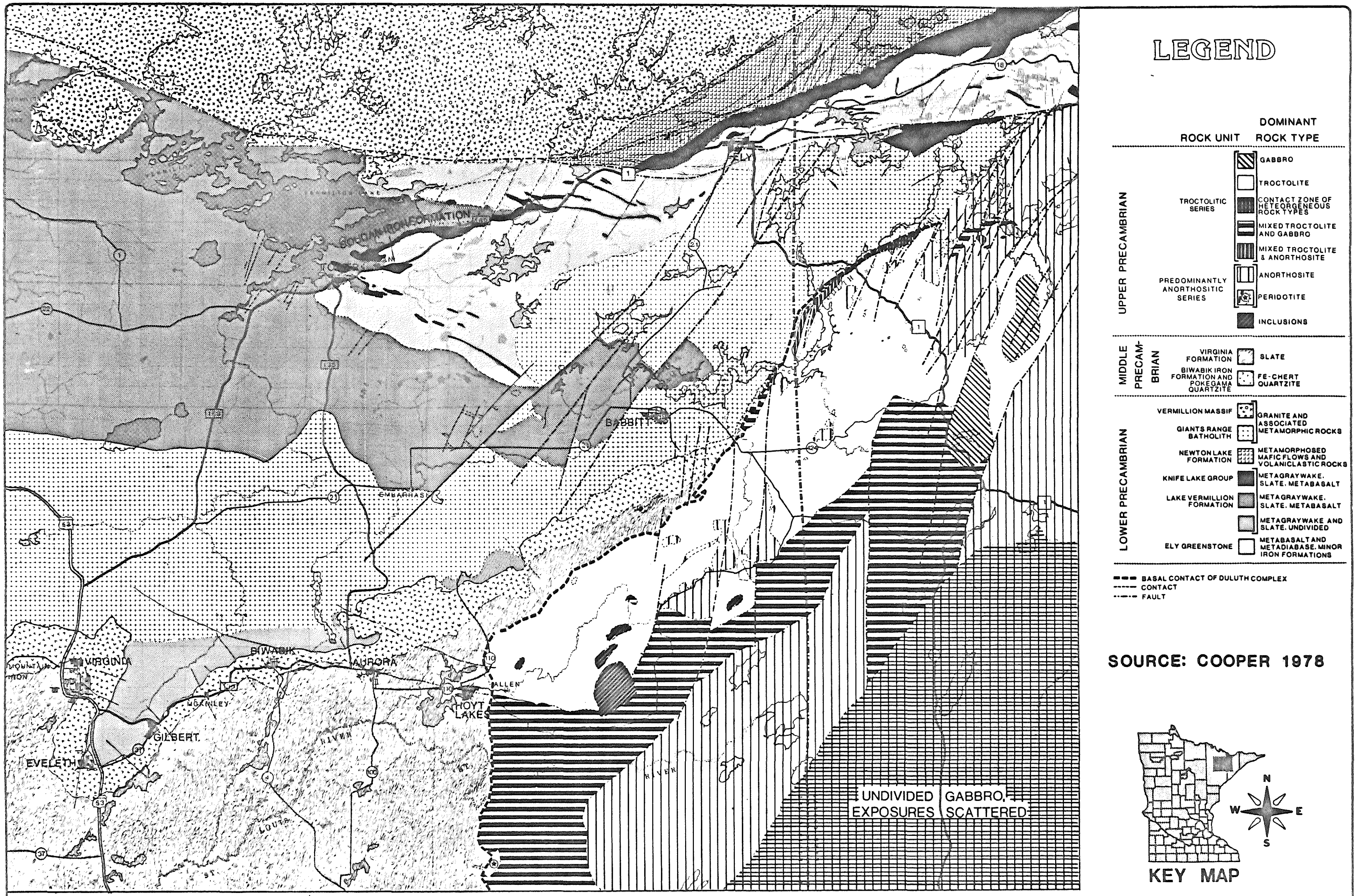
FIGURE 3

MEQB REGIONAL COPPER-NICKEL STUDY

GENERALIZED BEDROCK GEOLOGY OF NORTHEASTERN MINNESOTA



SOURCE : COOPER, 1978



SOURCE: COOPER 1978

FIGURE 4

MEQB REGIONAL COPPER-NICKEL STUDY

BEDROCK GEOLOGY
STUDY AREA

All of the volcanic and sedimentary rocks of the Vermilion district have been metamorphosed in varying degrees. The majority of the rocks are greenschist facies with amphibolite facies becoming dominant near the "granitic" intrusives in the area. The Vermilion district in general has been subjected to at least 3 periods of faulting and deformation.

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 billion years ago. The earliest of these intrusions was the Saganaga tonalite which cut the Ely Greenstone and part of the Knife Lake Group. 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 Giants Range batholith which underlies much of the northwestern part of the Study Area is composed mainly of monzonite and quartz monzonite, a rock similar to granite but with roughly equal proportions of plagioclase and potassium feldspar. 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 not known to contain copper-nickel mineralization except locally near the contact with the Duluth Complex.

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 (Figures 3 and 4).

The Mesabi Range, comprised of the Pokegama 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°E.strike, 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.

The Pokegama Quartzite forms a thin basal unit of feldspathic quartzite and graywacke along with some quartzose argillite. It is discontinuously exposed in the area and therefore is not shown on Figure 4.

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 magnetic iron ore containing 25 to 30% Fe. The iron formation has been divided into 4 members which are: 1) lower cherty; 2) lower slaty; 3) upper cherty; and 4) upper slaty. 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 presence of folds and faults. 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.

The iron formation has been metamorphosed to pyroxene hornfels facies by the Duluth Complex. The degree of metamorphism decreases away from the contact until it is essentially unaltered at a distance of 10 mi. Figure 5 (after French 1968) shows the zones of decreasing metamorphism as a function of distance from the contact. The increased temperatures caused by intrusion of the Duluth Complex produced olivine, orthopyroxene, clinopyroxene, and amphibole, as well as other less abundant minerals in the iron formation.

Figure 5

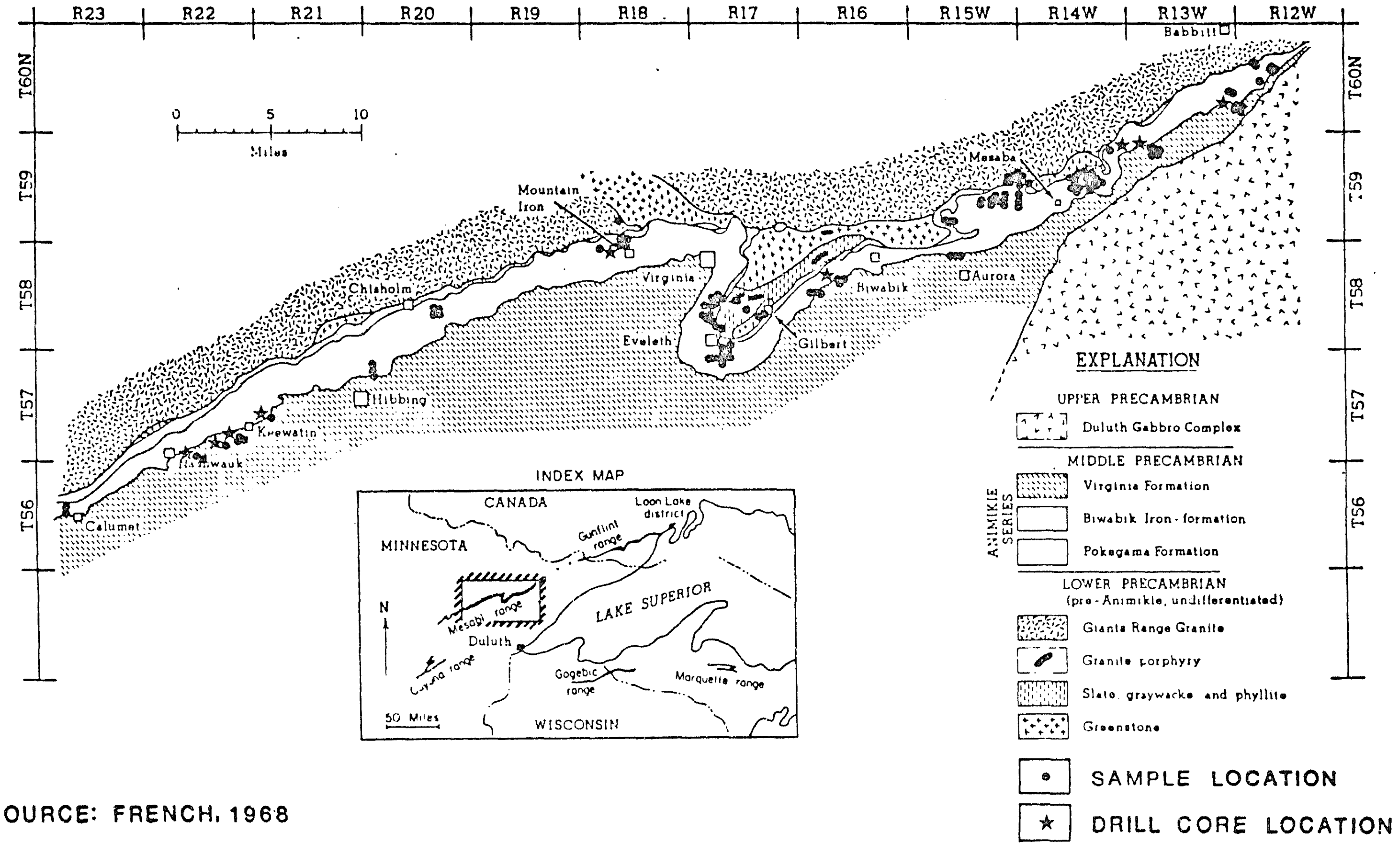
The Virginia Formation conformably overlies the Biwabik Iron Formation and has the same general attitude. It extends over the same area but is inferred to extend much further south under the glacial drift and is thought to be equivalent to the Middle Precambrian Thomson Formation in east-central Minnesota (Figure 1). It is dominated by argillite, graywacke, and siltstone. Mineralogically the unmetamorphosed Virginia Formation is made up of quartz, plagioclase, and microcline with chlorite, muscovite, and opaque minerals making up the finer-grained fraction. The Virginia Formation has been metamorphosed by the Duluth Complex to a hornfels with cordierite, biotite, and feldspar. Pyrrhotite, graphite, and orthopyroxene are minor constituents with ilmenite, chalcopyrite, quartz, and other metamorphic minerals occurring locally.

Late Precambrian (Keweenawan) rocks are exposed over much of northeastern Minnesota (Figure 4) 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 3 units which are: 1) the Puckwunge Formation; 2) the North Shore Volcanic Group; and 3) the Duluth Complex.

The Puckwunge Formation forms a thin (approx. 100 ft) basal unit of the Keweenawan Series. It is exposed north of Hovland (Figure 3) and consists of cross-bedded sandstone with a local occurrence of a basal conglomerate. It

FIGURE 5

GENERALIZED GEOLOGIC MAP OF THE MESABI RANGE, SHOWING LOCATION OF SAMPLES AND BOUNDARIES OF THE FOUR METAMORPHIC ZONES



SOURCE: FRENCH, 1968

strikes east-west and dips gently southward. The Puckwunge Formation disconformably overlies the Rove Formation and in turn is unconformably overlain by the 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 (150 mi). It generally consists of subaerial lava flows and interflow sedimentary rocks reaching a thickness of 7.5 to 9 km (4.7 to 5.6 mi). The flows have been dated at 1.1-1.2 billion years by Rb-Sr dating. 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, which intrude the lava flows.

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 recognition of subtle changes in the attitudes of the flows has defined 2 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 direction of lava movement was away from the lake. The lava flows consist mainly of several varieties of basalt and 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.

The Duluth Complex is a long arcuate mafic intrusion of Keweenawan age. It has been dated at approximately 1.1 to 1.2 billion years. The Duluth Complex extends from Duluth on the south, north-northeast toward Ely and then east-northeast to a point near Hovland (Figure 3). It presents a gross dish shape with a gentle dip of 10°-30° to the east, southeast, and south as one progresses from Duluth to Ely to Hovland. The Duluth Complex has been subdivided into 3 gross units on the basis of mineralogy and texture by nearly all who have worked in the area. The 3 units are the anorthositic series, the troctolitic series, and the felsic series or granophyres (Figure 3). It is the troctolytic series that is of principal interest as pertains to the occurrence of copper-nickel mineralization, but a discussion of all of the series is important to an understanding of the history of copper-nickel mineralization in the Duluth Complex.

The anorthositic series consists of rocks which have greater than 80% plagioclase with olivine, augite, and various oxide minerals occurring interstitially to the tabular plagioclase crystals. Plagioclase is usually the only cumulate mineral with the interstitial minerals being intercumulus, forming from melt trapped in the plagioclase framework. 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 3). 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.

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 minerals. Plagioclase is the predominant mineral making up 50 to 80% of the rocks with olivine the second most abundant mineral making up 10 to 40%. Locally the percentage of olivine increases or decreases so that the rock is a picrite or anorthosite, respectively. Olivine commonly crystallizes slightly later than the plagioclase while pyroxene (clino- and ortho-) and oxide minerals are usually intercumulus.

Felsic rocks are scattered throughout the eastern part of the Duluth Complex (Figure 3). 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.

The overall structure of the Duluth Complex was thought to be like that of a dish-shaped structure that dips gently to the east and south. This uncomplicated picture persisted from the early work by Elftman (1898a and b) and Grout (1918a-e) until the past few years. Then 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) suggested 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 (Figure 6). 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.

Figure 6

1.3 SURFICIAL GEOLOGY

Surficial materials may be mainly the result of weathering of the country rock or they may be composed of materials transported from afar by wind, water, or glaciation. In areas where erosional processes have predominated, surficial materials may be thin or absent. Where deposition has been most important they may be very thick. An understanding of the nature and sequence of erosional and depositional processes, and the origin of materials explains the distribution and properties of surficial materials and allows extrapolation in areas where few samples have been taken.

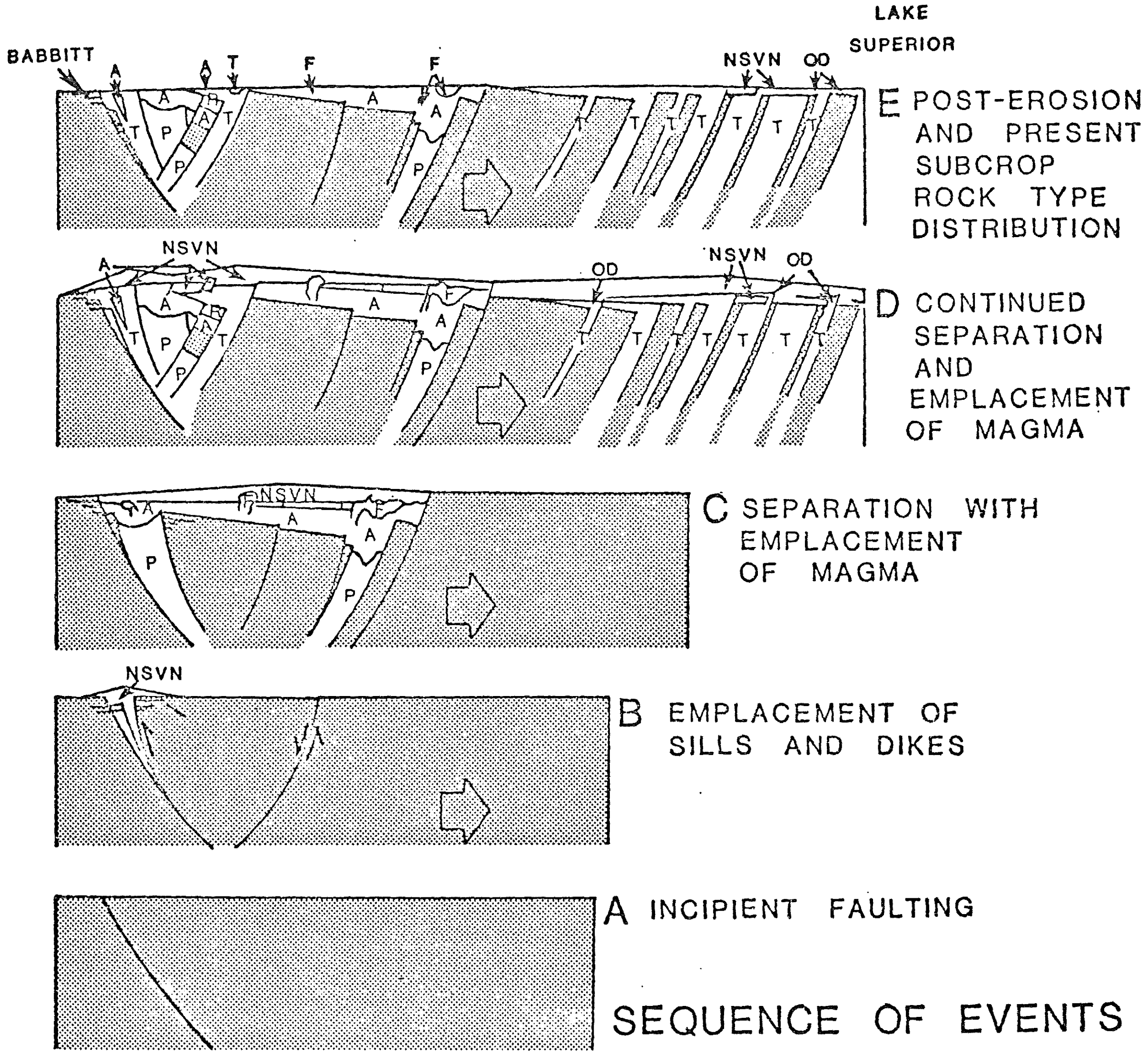
The distribution and nature of surficial materials has a direct bearing on the mining industry because they may affect siting of facilities, costs of overburden stripping, availability of construction materials, environmental impacts on natural systems, and ease of reclamation.

The distribution of surficial materials generally varies between broad physiographic provinces, each characterized by particular types of surficial materials having their origins in a particular combination of depositional and erosional processes.

FIGURE 6

GENERALIZED STRUCTURE SECTIONS ILLUSTRATING THE INFERRED RELATIONSHIPS BETWEEN TECTONISM AND MAGMATISM IN THE DULUTH COMPLEX AND ASSOCIATED ROCKS AND A SERIES OF STAGES IN THE EVOLUTION OF THE KEWEENAWAN TERRANE, NORTHWEST-SOUTHEAST.

SOURCE: WEIBLEN & MOREY, 1975



ROCK TYPES LEGEND

A	ANORTHOSITE
P	PERIDOTITIC
F	FELSIC
T	TROCTOLITIC-GABBROIC
OD	OLIVINE DIABASE
NSVR	NORTH SHORE VOLCANIC GROUP

1.3.1 Glacial History and Physiography

The most prominent physiographic feature in the Study Area is the Giants Range, a granite batholith extending from north of Grand Rapids to Birch Lake. The range has a relief of 200 to 400 ft above the surrounding landscape, attaining elevations as high as 1,910 ft above sea level. It is transected just east of Biwabik by a natural break, the Embarrass Channel. This channel is occupied by 3 impoundments: Embarrass Lake, Wynne Lake, and Sabin Lake. The local name for the range in this area is the "Embarrass Mountains."

The Giants Range is flanked on the southeast by the Biwabik Iron Formation, the target of a belt of large open pit mines. This formation, in turn, is flanked by the intrusive Duluth Gabbro which extends as the predominant bedrock to the east of the Study Area. In this area, the narrow (1-2 mi) zone of copper-nickel mineralization lies along the contact between the Biwabik Formation and the Duluth Gabbro. Olcott and Siegel (1978) include both the Giants Range and the Biwabik Formation in their Embarrass Mountains Taconite Mining Province.

Both north and south of the Giants Range, the landscape is dominated by glacial features. Figure 7 illustrates the chronology and extent of late Wisconsin glaciations in Minnesota. Because of the variability inherent in radiocarbon dating, available dates may not always confirm the sequence of events as it is understood from more powerful evidence, such as the stratigraphic record. This situation applies to the dates given for the Bemis and Nickerson-Alborn phases in Figure 7. All independent evidence points to an earlier date for the St. Louis sublobe than for Lake Agassiz, which was formed as the sublobe melted. At least 2 lobes directly affected the Study Area during the Wisconsin glacial period (Wright 1972). The Rainy Lobe of the Laurentian Ice Sheet advanced over the entire area eroding the landscape north of the Giants Range and depositing the eroded material to the south (Winter et al. 1973). Two phases (advances) of this lobe left their record in the Study Area, the St. Croix phase and the Vermillion phase. At a later date, the St. Louis sublobe of the Des Moines lobe advanced eastward through the Agassiz lowland and entered the Study Area during its Alborn phase. The Superior lobe, advancing out of the Lake Superior basin, is generally believed to have terminated at the Highland moraine, east of Isabella (Wright 1972).

Figure 7

Stark (1977) believes the Superior lobe extended westward beyond the Highland moraine into the Study Area between the Little Isabella River and Slate Lake. The contortion of the 2 southernmost moraines of the Rainy Lobe around the Superior sublobe moraines suggests that the Superior sublobe may have advanced into the area slightly before the Rainy lobe. An indirect effect of the Superior lobe in its Automba phase was the blockage of the St. Louis River creating Glacial Lake Upham I southwest of Virginia.

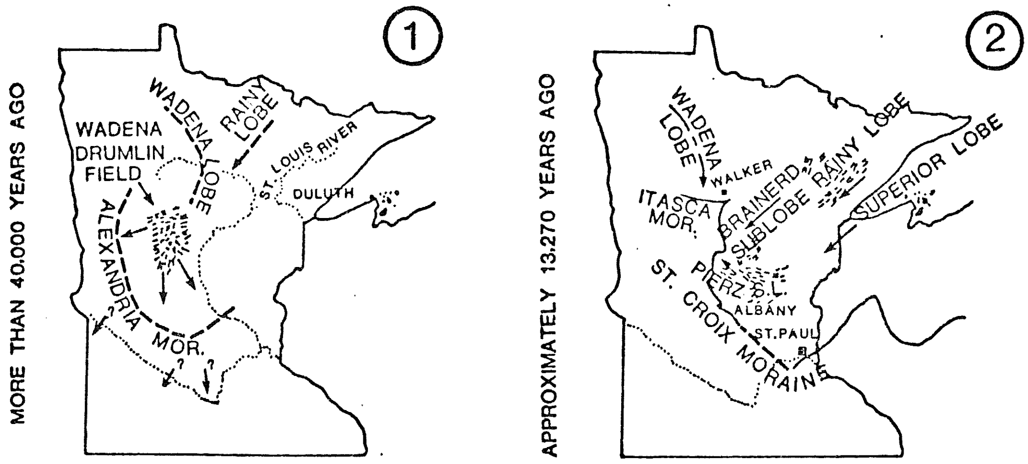
Nine physiographic regions can be distinguished within the Study Area (Figure 8). The 8 regions of glacial origin are discussed below.

Figure 8

The southeast portion of the Study Area (Figure 8) forms the Drumlin Bog Physiographic Province (Olcott and Siegel 1978). This area is generally known as the Toimi Drumlin Field (Wright and Watts 1969). The northeast-southwest trend of the parallel spoon-shaped hills reflects the direction of retreat of the St.

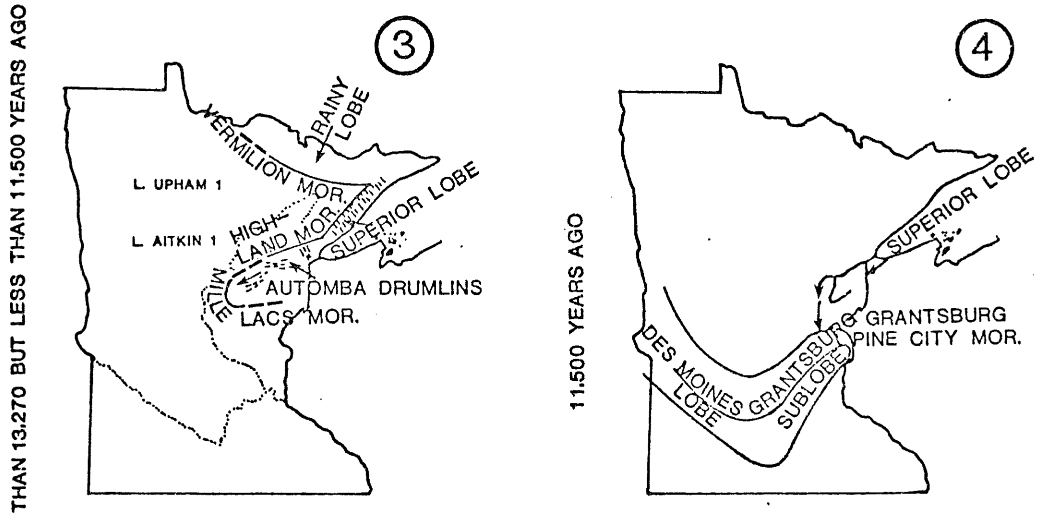
FIGURE 7

PHASES OF WISCONSIN GLACIATION IN MINNESOTA



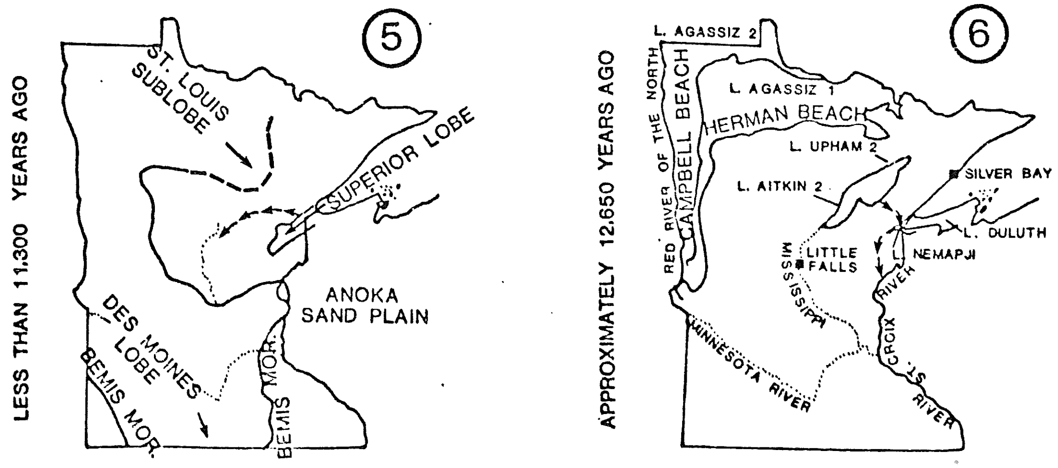
HEWITT PHASE

ST. CROIX PHASE



AUTOMBA PHASE

SPLIT ROCK-PINE CITY PHASE



BEMIS PHASE

NICKERSON-ALBORN PHASE

SOURCE : WRIGHT, 1972

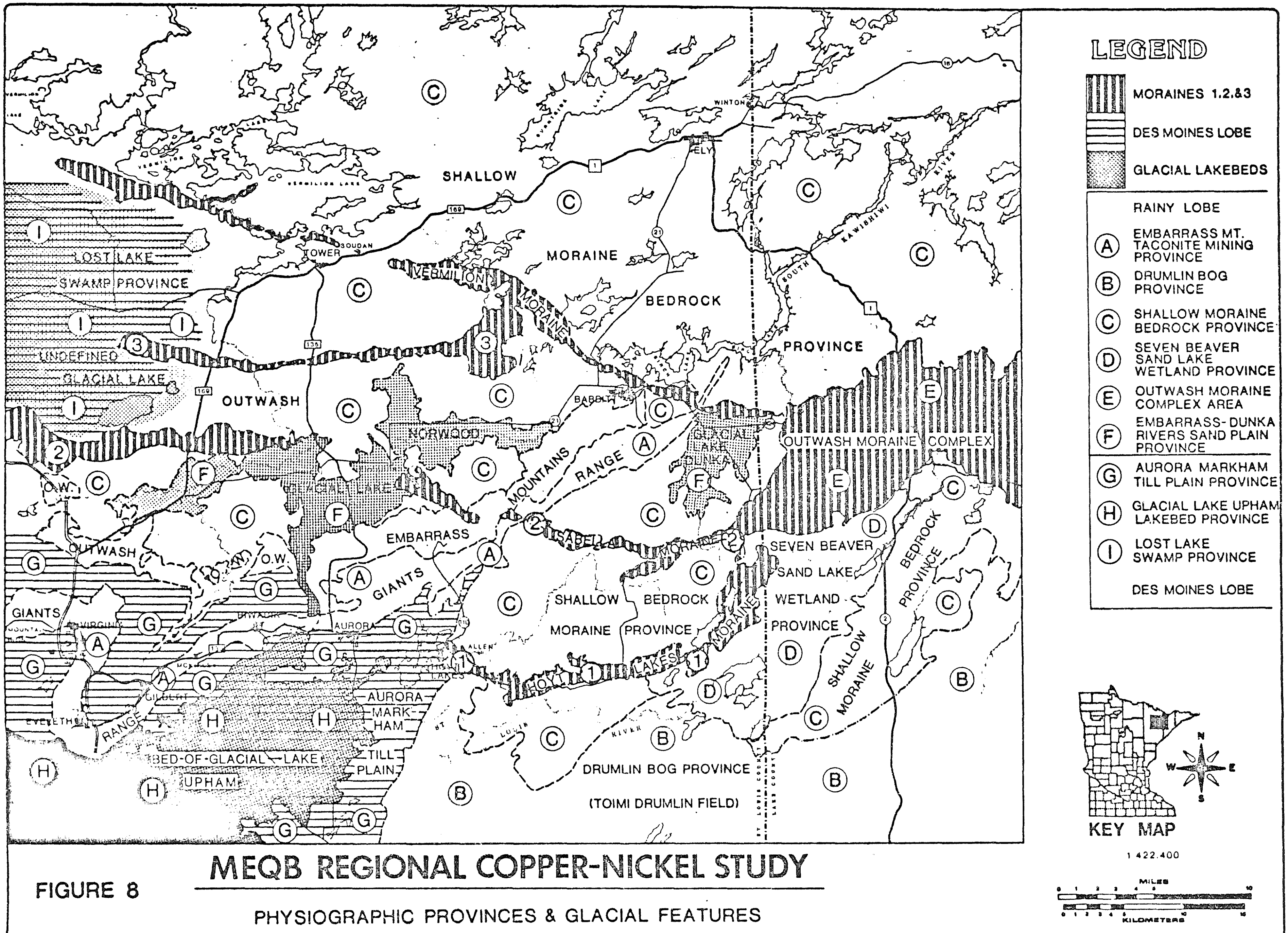


FIGURE 8

MEQB REGIONAL COPPER-NICKEL STUDY

PHYSIOGRAPHIC PROVINCES & GLACIAL FEATURES

Croix phase of the Rainy Lobe. A minimum age for the formation of the drumlins is in the range of 14,000 to 15,000 yr, based on radiocarbon dates of sediments from Weber Lake, just south of Mt. Weber (Wright and Watts 1969). Altitudes in the drumlin field range from 1,400 to 2,015 ft, whereas the drumlins themselves rise 30 to 50 ft above the intervening wetlands and are composed of red, sandy till (Stark 1977).

Topography north of the drumlin field reflects the later Automba-Vermillion phase of the Rainy Lobe. During its retreat, a series of still-stands produced a set of parallel end moraines between the Toimi Drumlin Field and Birch Lake. This Vermillion moraine complex (Wright and Watts 1969) has been separated by Stark (1977) into the first (most southerly), second, and third (most northerly) moraines. The area between the moraines is characterized by a rolling topography with some exposed bedrock. Olcott and Siegel (1978) consider this area as part of their extensive Shallow Moraine Bedrock Province (Figure 8).

From the Stony River eastward toward Isabella, the 3 end moraines are confluent (Figure 8) and form a physiographic province called the Outwash Moraine Complex Province (Olcott and Siegel 1978). The area is characterized by knobby hills and kettle lakes resulting from slow melting of ice blocks buried in glacial debris. Perhaps the Rainy Lobe ice remained stagnant in this area while it retreated from one end moraine to another farther west. Stark (1977) suggests that this province was overridden by Superior lobe ice extending beyond the Highland Moraine.

The broad plain of the Seven Beaver-Sand Lake Wetland Province (Olcott and Siegel 1978) is today occupied by an extensive peatland drained by the North and Stony rivers (Figure 8). Elevations range from 1,600 to 1,800 ft with the Laurentian

Divide passing through the wetland. The nature and origin of the underlying deposits has not been traced throughout the entire basin, but those at the north end are outwash deposits associated with the Outwash Moraine Complex Province. These deposits take their origin either from Rainy Lobe Outwash (Wright 1978) or from Superior lobe outwash (Stark 1977).

North and east of Birch Lake and extending into the BWCA the Shallow Bedrock Moraine Province (Olcott and Siegel 1978) is characterized by exposed bedrock ridges with intervening areas of shallow ground moraine and wetlands. The higher proportion of exposed bedrock in the part of the province between Gabbro Lake and Lake Vermillion is accounted for by the erosive action of both phases of the Rainy Lobe as it passed over this area.

The province appears to continue westward north of Vermillion Lake and may have been onlapped at lower elevations by an eastern extension of Glacial Lake Agassiz. This extensive lake was formed during the retreat of the St. Louis sublobe when ice blocked the normal northwesterly drainage. Calcareous lake deposits that are most likely to have been brought from the west have been found as far east as Lamb Lake in the BWCA (Wright 1972). South of Lake Vermillion the presence of a brown, silty till overlying Rainy Lobe till suggests that the St. Louis sublobe extended at least as far east as just north of Virginia (Winter et al. 1973).

Large, flat plains in the central and southwestern portion of the Study Area are the result of glacial lakes from several periods (Figure 7). The Embarrass-Dunka Rivers Sand Plain Province (Olcott and Siegel 1978) was formed by the impoundment of normal drainage by the Vermillion phase of the Rainy Lobe. Agricultural lands in the valley of the Pike and Embarrass rivers lie in the bed of Glacial Lake

Norwood. This lake extended almost to Babbitt but was not quite continuous with the bed of Glacial Lake Dunka, now occupied by an extensive wetland along the Dunka River. Altitudes in this province range from 1,400 to 1,600 ft.

Two separate physiographic provinces not considered by Olcott and Siegel (1978) are glacial lakebeds in the western part of the Study Area (Figure 8). Northwest of the bed of Glacial Lake Norwood and southwest of Lake Vermilion, the upper reaches of the Sturgeon and Little Fork rivers lie in the bed of an undefined glacial lake whose history has not been investigated (Winter et al. 1973). Much of the area is occupied today by a wetland called the Lost Lake Swamp.

South of the Giants Range (Figure 7), the flat agricultural area in the valleys of the Swan and St. Louis rivers between Hibbing and Virginia was twice occupied by glacial lakes (Wright and Watts 1969; Winter et al. 1973). At the same time that retreating ice from the Rainy Lobe blocked northward drainage forming Glacial Lake Norwood, ice from the Superior lobe blocked the outlet of the St. Louis River. The resulting impoundment formed Glacial Lake Upham I (Figure 7, phase 3). After the retreat of the Superior lobe and recession of this lake, the St. Louis River was again blocked, this time by the retreating Alborn phase of the St. Louis sublobe, and Lake Upham II was formed (Figure 7, phases 5 and 6).

The Aurora-Markham Till Plain Province (Olcott and Siegel 1978) lies south of Aurora and buries the west edge of the Toimi Drumlin Field (Figure 8). Because of the red clay nature of the till, the area has sometimes been considered to have been glaciated by the Superior lobe (Prettyman 1976). A more reasonable explanation (Wright and Watts 1969; Winter et al. 1973) is that while the St. Louis River was impounded by the Automba phase of the Superior Lobe, it accumulated sediments whose origin was in the Lake Superior basin. After the retreat of the Automba phase and the recession of Lake Upham I, the St. Louis sublobe overrode the bed of Lake Upham I, depositing reworked red lake clays on the western flank of the Toimi Drumlin Field. Elevations of the till plain range from 1,400 to 1,500 ft and current land use is primarily agricultural.

1.3.2 Nature of Surficial Materials

Five major till types have been recognized by investigators in the Study Area. In the eastern part of the area the Outwash Moraine Complex is characterized by a red, sandy till and the Toimi Drumlin Field and Shallow Moraine Bedrock Province by a brown, bouldery till. This brown till unit extends westward beyond the western boundaries of the Study Area, but from Virginia westward it is sandwiched stratigraphically between an underlying brown, silty till, and a similar overlying till of later origin. Characteristics of each of these till types are discussed below.

The red, sandy till in the eastern portion of the Babbitt-Kawishiwi area is characterized by Stark (1977) as brown to reddish-brown (10 yr on the Munsell color scale) sandy till with few boulders. Pebbles are derived mainly from Keweenawan lavas and Duluth Complex rock types. An average of 21% of all pebbles are derived from the North Shore Volcanic Group.

Rainy Lobe till, which is the major surficial material in the mineral resource zones (see section 2.1.1), is brown to gray (2.5 yr on the Munsell color scale) bouldery till. Cobbles and boulders make up 30% by volume in a sandy matrix. The most common pebble types are derived from granitic and Duluth Complex bedrock. In the Babbitt-Kawishiwi area, Stark (1977) found that the Duluth Complex/granitic pebble ratios are roughly proportional to the distance from the Duluth Gabbro contact. North Shore Volcanics constitute only 1% of all pebbles.

Other Precambrian rock types derived from regions north of the Study Area are present in minor amounts. Clay found in samples from the southwestern portions of the Study Area is mostly montmorillonite (Winter et al. 1973), whereas clay analyses from the Filson Creek area indicate that kaolinite and chlorite are predominant (Olcott and Siegel 1978).

South of Aurora (on the Aurora-Markham till plain) the surficial till is characterized as calcareous, red clayey till dominated by montmorillonite and illite. The till contains both rocks of northwestern origin (11% shale, limestone, and dolomite) and rocks of eastern origin (basalt, felsite, and gabbro) but is dominated by local granites.

Throughout most of the area from Virginia and the east end of Lake Vermillion westward, Rainy Lobe till is overlain by a surficial brown, silty till characterized by a medium to light brown color and sandy matrix. Both the clay content and pebble lithology of this till are similar to that of the red-clay till, but there is a higher proportion of limestone.

Underlying the Rainy Lobe till unit as far eastward as the Dunka mine is an early Wisconsin or pre-Wisconsin basal till. The basal till is characterized by a dark-brown color and dominated by illite as the major clay mineral. Granitic and metamorphic pebbles of local origin predominate, but indicator rocks from both northeastern and northwestern sources are present.

Unlike unsorted glacial tills, glaciofluvial materials deposited in high energy environments have a tendency to be more sorted in particle size. Ice contact features, such as eskers, are often deposited in areas where ice and rapidly flowing waters are in contact. Finer particle sizes are removed by the waters and coarser materials are deposited. Less confined outwash streams produce deposits concentrated in the 230-10 m size class (0.06-2 mm). The difference in particle size distribution for till, outwash, and ice contact features in the Study Area is illustrated in Figure 9. Within the Study Area, glaciofluvial deposits are stratified sands and gravels whose pebble lithology resembles that of the neighboring till units. The major such area in the mineral resource zones is the outwash body and associated ice contact area in the Lake Dunka Plain southeast of Babbitt. The depth of this body is not as great as that of the large outwash body west of Babbitt in the Lake Norwood basin.

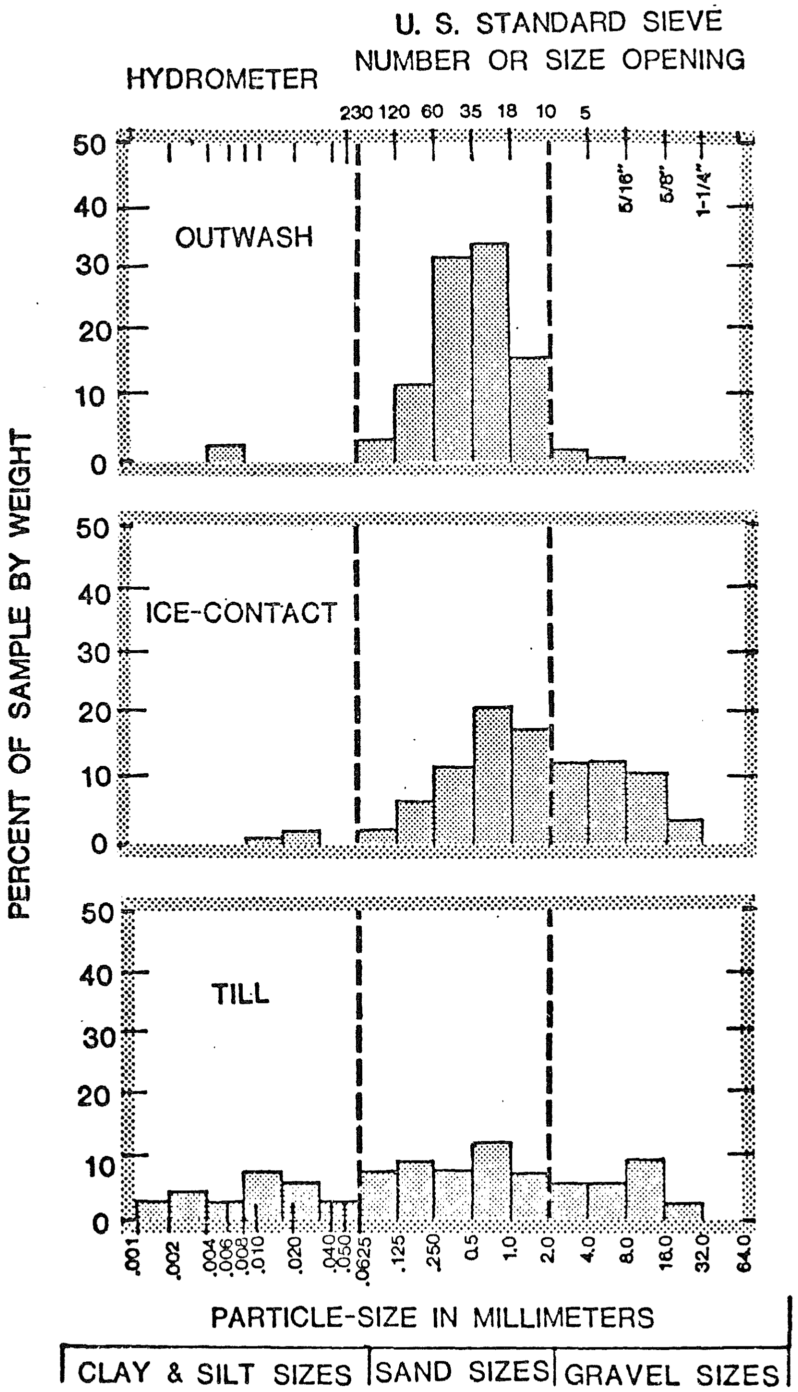
Figure 9

In addition to surficial materials of glacial origin, large portions of the Study Area are covered by swamp and bog deposits of postglacial origin. These organic deposits may overlie any type of glacial material or bedrock. They range from sedge peats to sphagnum peats and woody peats. Depths of peat up to 5 m have been found in the Dunka River basin (Stark 1977), whereas in the Seven Beaver-Sand Lake Wetland depths up to 10 m have been reported (Finney 1966). The inorganic fraction of the peat in the latter wetland is dominated by quartz, plagioclase, orthoclase (probably representing input from weathering of uplands), and opal (mainly biogenic).

Depths of surficial materials are more dependent on the topography of the underlying bedrock than on the type of surficial material (see following section). Several bedrock valleys exist in the area; one extends west from Birch Lake, one south of the Embarrass Channel to Eveleth, one southwest from Virginia, and one just south of Hibbing. Depth of surficial deposits is greatest in these areas, all north and/or west of the mineral resource zones and all underlain by basal till. North and east of the Giants Range upland surficial materials are

FIGURE 9

PARTICLE SIZE HISTOGRAMS OF TILL, ICE-CONTACT, AND OUTWASH SAMPLES



SOURCE: OLCOTT AND SIEGEL, 1978

thin, generally less than 14 m and less than 3 m in the northeast (Figure 8). Depth to bedrock along moraine fronts appears somewhat greater than in areas covered by ground moraine, but few borings are available for comparison. Within the mineral resource zones there is a general trend from deeper surficial materials in the south to the very thin cover in the north, with the exception of deeper outwash deposits in resource zone 3.

Certain of the surficial materials just discussed have special importance in the context of potential copper-nickel development in the resource zones. These materials may be used as borrow material for construction purposes in the mining operation itself. Since this potential exists, it is appropriate to include a specific discussion on the topic at this point.

1.3.3 Construction Materials

In order to understand the context in which certain surficial materials may be useful to the mining industry as construction materials, it is appropriate to digress for a moment and discuss the major construction material needs for a mining operation. Many of the construction needs associated with a mining operation are located at the site of the mine and could be met by waste materials from the operation itself. The major requirement for construction materials at some distance from the mine is associated with the building of the tailing basin dam. In order to understand the scale of such a dam, the Regional Study has constructed a set of hypothetical development models, each containing a model of a tailing basin and associated dam (see Volume 2-Chapter 3). These models will be used here to provide a focus for the discussion of construction material requirements. Tailing basins are often sited in lowlands to take advantage of local relief. However, the Regional Study's models for tailing basins are based on the assumption that the basin will be sited on a flat upland. With respect to the need for construction materials, the models thus represent the worst case because they require that dams be built around the entire basin.

Several alternative methods of dam construction are available (see Chapter 3, section 3.3.4 for further discussion). Figure 10 presents generalized cross-sections of several dams and suggests the model of construction and nature of required materials. Although the coarse fraction of tailing (greater than 200 M or 74 um in diameter) may be used once the dam is established, native borrow or specially prepared material is necessary for the starter dam, which must be built before tailing material is available. The starter dam may be constructed of any material that will interlock and retain its competence. Preferred material should be angular and should be well graded. Either glacio-fluvial materials or till may be used. Because of the variability of glacial materials, the suitability of tills and sands for tailing basin construction must be assessed on a site-specific basis (Golder 1978).

Figure 10

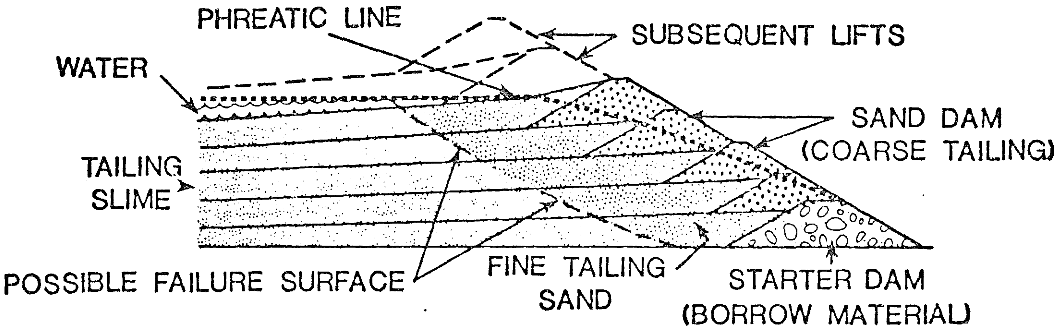
Estimates of needed materials have been developed for each of the Regional Study's 3 mine models. Because basin size (and hence length of the dam) is dependent on total production, the 20.00 X 10^6 mtpy model requires the most construction materials. Table 4 presents the volume of construction materials needed for the starter dam, drain, and subsequent lifts for each of the 3 mine models.

Table 4

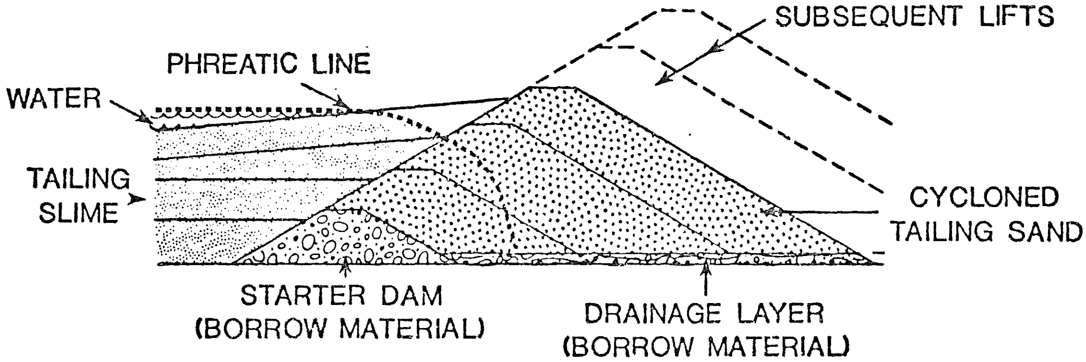
FIGURE 10

ALTERNATIVE TAILING DAM DESIGNS

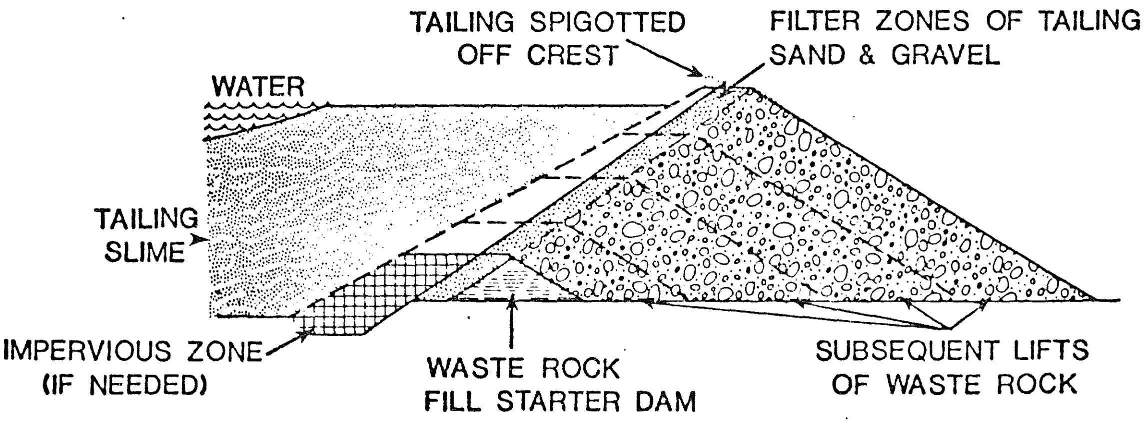
A. UPSTREAM METHOD USING BORROW MATERIAL FOR STARTER DAM



B. DOWNSTREAM METHOD USING BORROW MATERIAL FOR STARTER DYKE



C. DOWNSTREAM METHOD USING WASTE ROCK



SOURCE: GOLDER, 1978

Table 4. Volume of material necessary for construction of tailing dams.[a]

CHARACTERIZATION OF DAM	MODEL SIZE X 10^6 mtpy		
	12.35	16.68	20.00
Dam length, km	10.83	12.91	14.29
Component Volumes, 10^6 m^3			
Starter dam, 3% (sand, gravel, till)	0.4	0.5	0.5
Drain, 12% (waste rock, till, crushed rock)	1.5	1.8	2.0
Tailing sand, 85%	10.9	13.9	14.4
Total (1.18 X 10^6 m^3/km)	12.8	14.2	16.9

[a] Assumes a downstream construction method (see Volume 2-Chapter 3), and dam height of 21.3 m (75 ft).

In order to identify the areas from which construction materials may be obtained for use in dam construction, it is necessary to discuss the costs of obtaining these materials. The selection of material used for dam construction will be highly dependent on these costs. The choice between use of wasterock or material from a borrow source will depend on the distance between the mine and the basin site. Average distances from mine to tailing basin in Canada are 2.01 km (1.25 mi) and the maximum distance is around 16.1 km (10.00 mi)(Golder 1978). The estimated cost of tailing pipeline is \$264/m (\$80/ft). Because of this high pipeline cost, basins will generally be located as near as feasible to mines. Table 5 presents comparative costs for excavation and loading, and placement of glacial till and wasterock as well as haulage costs. If the assumption is made that suitable borrow materials are available within 1.6 km of the tailing basin, it can be seen from the table that costs of transporting waste rock are more economical if the dam sections being constructed are less than 6.4 km from the mine, but costs of the 2 materials are equalized at 6.4 km. Use of till is less expensive than waste rock beyond this distance. Costs for excavation of glaciofluvial deposits should be comparable to or less than those for till.

Table 5

Given the expected large size of a copper-nickel tailing disposal area, as indicated by the 16.3 km^2 basin used in the model for the 20.00 X 10^6 mtpy open pit mine, it is highly likely that portions, at least, of the dam or dams containing the tailing from an actual development, will lie far enough from waste rock and tailing sources to make the use of borrow material economically desirable. In any case, as noted earlier, initial sections of dam will need to employ borrow material because coarse tailing and waste rock will not be

Table 5. Comparative costs of using native borrow material or waste rock for tailing dam construction.[a]

Glacial Till

\$1.85/m^2	for excavation and loading
\$0.44/m^2	per km for haulage
\$1.14/m^2	for placement and compaction

Waste Rock

\$0.28/m^2	for processing (i.e. sorting of oversize)
\$0.44/m^2	per km for haulage
\$0.71/m^2	for placement, dozing, and spreading

SOURCE: Golder and Associates 1978.

[a] Specific values result from conversion of English to metric units and should be treated as typical values only.

available yet. Such borrow may be obtained from within the planned limits of the basin, as well as from the surrounding area.

All of the considerations (physical requirements, costs, distances) presented in the previous discussions were used to determine the relevant areas adjacent to potential mining operations which needed to be surveyed for available construction materials. It is apparent that the relevant area is limited to the region in and immediately adjacent to the copper-nickel development zones. Surficial materials in this area can be broadly classified as organic deposits (peat), till, and glaciofluvial deposits (sand and gravel). The characteristics and particle size distribution of till and outwash were presented previously. The distribution of these 3 major classes of materials in the copper-nickel development zones is shown in Figure 11. Representative depths of surficial materials are also presented in this figure. Depth data were obtained from 2 types of drillholes, those drilled to bedrock and those that terminated within the surficial material. As can be seen from the map, till is widely distributed and should be available wherever it is needed. Glaciofluvial sand and gravel are restricted in their distribution with concentrations of ice contact or outwash features near the Whiteface Reservoir, along the St. Louis River, near Hoyt Lakes, in the Dunka River area, along the Stony River, east of Slate Lake, and along the east side of Birch Lake. Large portions of the area likely to receive tailing basins have no nearby source of sand and gravel.

Figure 11

The actual area needed for excavation of borrow materials required for starter dams and drains according to the Regional Study's model will vary with the depth of the borrow material. Table 6 summarizes this required surface area and can be

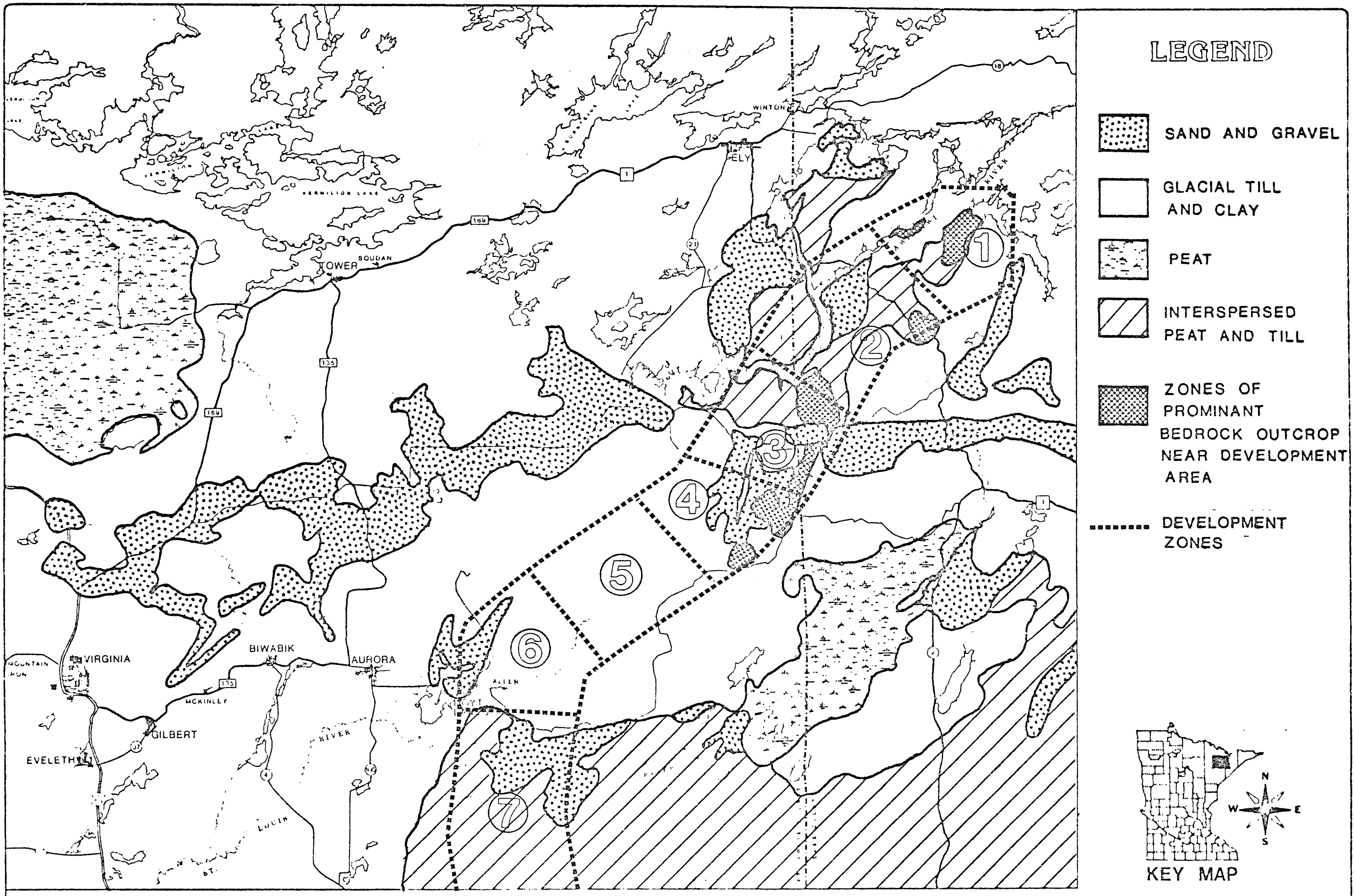


FIGURE 11

MEQB REGIONAL COPPER-NICKEL STUDY

GENERALIZED DISTRIBUTION OF SURFICIAL MATERIALS IN STUDY AREA used in conjunction with the map (Figure 11) to identify portions of the area in which supplies of sands and gravels may be available.

Table 6

If sand and gravel rather than till are preferred for starter dams, it appears that the greatest surface area would be disturbed to meet construction needs on the east side of Birch Lake and near the Stony River. Within development zones, the least surface area disturbance for gravel pits would occur in the Dunka Outwash body. Potential utilization of the Dunka Outwash body may be limited by the presence of extensive overlying wetlands and the high water table.

1.3.4 Soils

Soils of the Study Area (Figure 11A) are the result of the weathering of parent material (either glacial deposits or bedrock) over a long period of time. The texture (particle size) and mineralogy of the soil are derived from the parent material. Within the Study Area fine textured clay soils are found in the beds of glacial lakes or in areas where reworked lake clays were deposited after being overridden by a glacier, such as in the Aurora Till Plain. Loamy soils of medium texture are derived from mixed glacial tills and occur throughout much of the area. Sandy soils are confined to areas where waters associated with glaciers sorted out the fine material and left the sands. Examples of such materials are outwash plains, where meltwaters rushed in front of a glacier, or eskers, which mark the courses of subglacial rivers. Thin soils occur in areas where erosion exceeded deposition, such as the northeastern part of the Shallow Moraine Bedrock Province. Waterlogging in low areas has prevented the decomposition of centuries worth of plant debris, causing the formation of organic soils (peats).

Table 6. Borrow surface area required to fulfill tailing basin construction needs at various depths of surficial materials.

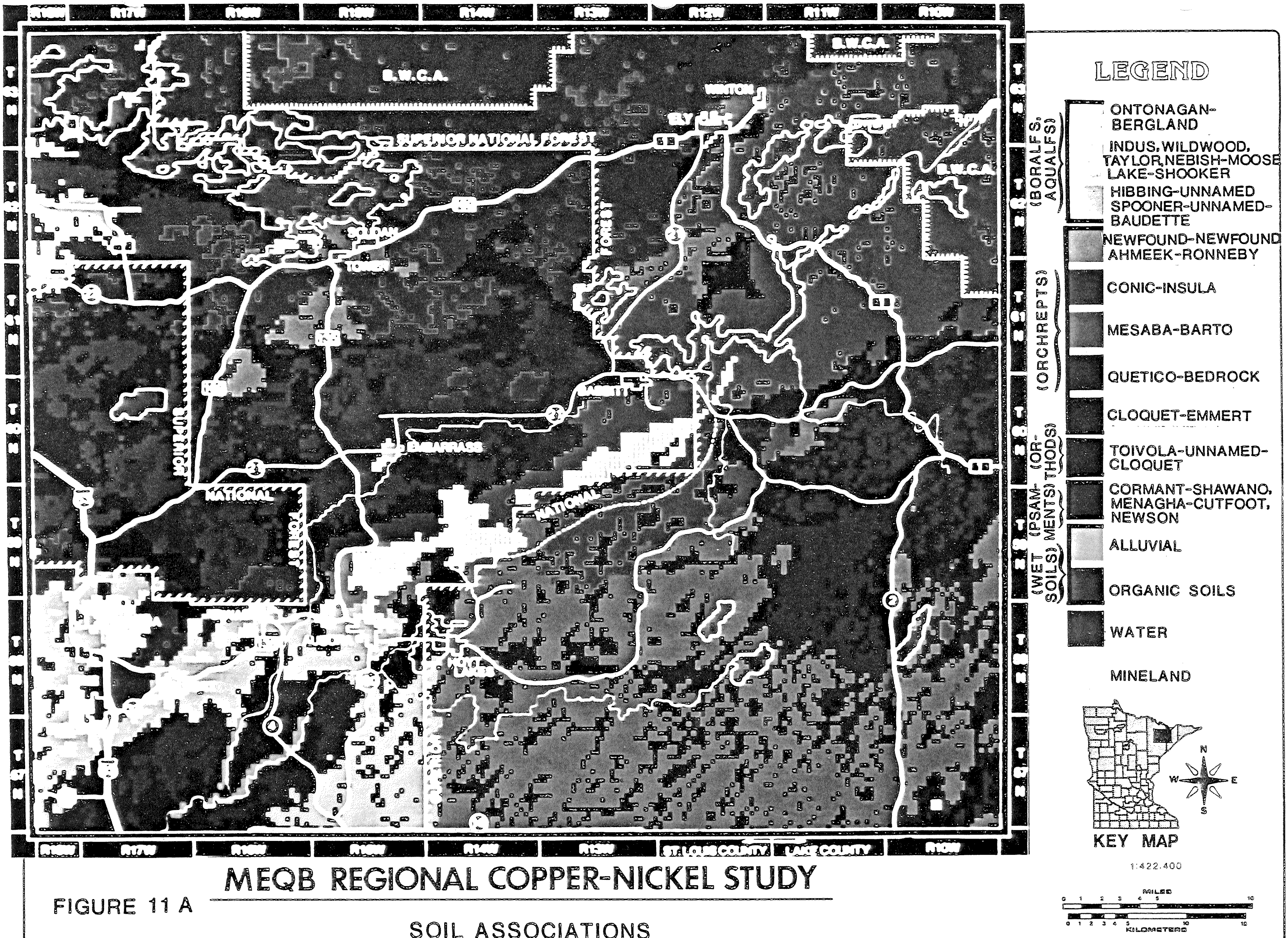
	MODEL SIZE, 10^6 mtpy ore					
	12.35		16.68		20.00	
DEPTH (m)	Starter Dam Requirements (ha)	Drain Requirements (ha)	Starter Dam Requirements (ha)	Drain Requirements (ha)	Starter Dam Requirements (ha)	Drain Requirements (ha)
5	7.6	30.6	9.2	36.7	10.7	41.3
10	3.8	15.3	4.6	18.4	5.4	20.6
15	2.5	10.2	3.1	12.2	3.6	13.8
20	1.9	7.6	2.3	9.2	2.7	10.3
30	1.3	5.1	1.5	6.1	1.8	6.9
40	1.0	3.8	1.1	4.6	1.4	5.2
50	0.8	3.1	0.9	3.7	1.1	4.1
60	0.6	2.5	0.8	3.1	0.9	3.4
70	0.5	2.2	0.7	2.6	0.8	3.0
80	0.5	1.9	0.6	2.3	0.7	2.6

Figure 11A

Over long periods of time, climate, vegetation, texture, and mineralogy interact to generate recognizable layers within the soil. Leaching of rainwater through accumulated vegetative debris (the litter layer) carries minerals downward producing a mineral-depleted A horizon and an enriched B horizon. In acid situations, such as occur on sandy soils under conifers, iron and aluminum accumulate in the B horizon, producing a yellow layer under oxidizing conditions. If such soils are waterlogged, the reduced iron and aluminum lend this layer a grey color.

The mineralogy and texture of the soil are important in controlling some of its chemical attributes such as pH and cation exchange capacity (ability to bind ions). Organic soils generally have higher cation exchange capacities than mineral soils and within mineral soils, finer clays have a higher cation exchange capacity than coarser, sandy soils. Soil pH depends on the mineralogy of the soil, its buffering capacity (ability to resist changes in pH), and the nature of the overlying vegetation. For example, soils higher in calcium have higher pH values than those high in iron and low in calcium. In northern Minnesota, coniferous litter contributes to the acidification of soils more than deciduous litter and soils under deciduous stands generally have higher buffering capacity.

The hierarchical system of soil classification used in the United States classifies soils descriptively on the basis of characteristics of the horizons that reflect processes of soil formation. Levels of classification proceed from order (the highest) to series (the lowest). Series of soils are similar to other members of the same soil family with respect to response to management, but



MEQB REGIONAL COPPER-NICKEL STUDY

FIGURE 11 A

SOIL ASSOCIATIONS

differ in texture, mineralogy, temperature, or depth of root penetration. Soil series are named after geographic locations (e.g. the Hibbing soil). Groups of series that co-occur in the field have been lumped into soil associations for purposes of soil mapping. Association maps do not show exactly which series are at a given location but include a key suggesting likely proportions of series in the area.

Thirty-two named and 5 unnamed soil series have been identified in the Study Area and are distributed among 23 soil associations. A given series may occur in more than one association. Table 7 summarizes the physical and chemical attributes of the associations. Table 8 gives the percent of the Study Area covered by each association, as well as the proportion of each of the terrestrial biology divisions and mineral resource zones covered by each association (see section 2.1.1, and Volume 4-Chapter 2).

Tables 7 & 8

In addition to the soil associations defined by the Soil Conservation Service (SCS), soils of the Superior National Forest have been independently classified by D.H. Prettyman, Forest Soil Scientist, U.S. Forest Service, Duluth. Prettyman's classification scheme is based upon soil landscape units, which incorporate soil texture and glacial landforms. Prettyman has collected data for several parameters that are useful to foresters who are responsible for managing lands within the national forest. See Patterson and Aaseng (1978) for a description of these landscape units and a cross-tabulation with the soil associations. The cross-tabulations is for the area in and adjacent to the mineral resource zones and shows that landscape units tend to be more specific than associations for mineral soils, whereas the reverse is true for organic soils.

Table 7. Characteristics of soil associations in the Study Area.

ASSOCIATION	TOPOGRAPHY	TEXTURE	MOISTURE	AVERAGE pH 0-6"	AVERAGE pH 6-12"	CATION EXCHANGE CAPACITY meq/100g 0-6"	CATION EXCHANGE CAPACITY meq/100g 6-12"	DEPTH TO BEDROCK	DEPTH TO WATER TABLE
1 Ontonagen-Bergland	nearly level to gently sloping	very fine	holds water well	4.5-6.0	5.0-7.8	ND	ND	5-10'	1-5'
4 Ahmeek-Ronneby	undulating	coarse-loamy	moderate	5.0	5.3	31.3	21.6	5-10'	20"-2'
5 Newfound-Newfound	undulating	coarse-loamy	wet	5.4	5.7	23.4	15.2	5'	2'-5'
6 Unnamed-Toivola	undulating	coarse-loamy to sandy skeletal	droughty	5.3	5.5	26.4	19.5	40"-6'	5'
7 Toivola-Unnamed-Cloquet	undulating to steep	coarse-loamy to sandy skeletal	droughty	5.5	5.8	23.6	17.9	40"-6'	5-6'
8 Mesaba-Barto	undulating to hilly	coarse-loamy to loamy	moderate to dry	5.0	5.3	28.4	23.1	8-40"	20"-5'
9 Conic-Insula	undulating to hilly	coarse-loamy to loamy	moderate to dry	4.0-6.0	4.5-6.0	ND	ND	8-40"	5'
10 Quetico-Bedrock	undulating to very steep	loamy and bedrock	droughty	5.1	5.2	24.7	17.9	0-8"	5'
11 Indus-Wildwood	nearly level	very fine montmorillonitic	wet	5.6-6.5	5.6-7.8	ND	ND	5'	5-3'
12 Taylor-Indus	nearly level-undulating	very fine montmorillonitic	moderate	5.6-6.5	5.6-7.8	ND	ND	5'	1-5'
17 Nebish, Mooselake Shooker	hilly	fine loamy	moderate to wet	5.1-7.3	6.6-8.4	ND	ND	5-10'	surface to 10' varies w/season

Table 7 continued.

ASSOCIATION	TOPOGRAPHY	TEXTURE	MOISTURE	AVERAGE pH 0-6"	AVERAGE pH 6-12"	CATION EXCHANGE CAPACITY meq/100g 0-6"	CATION EXCHANGE CAPACITY meq/100g 6-12"	DEPTH TO BEDROCK	DEPTH TO WATER TABLE
25 Cormant-Shawano	nearly level	mixed	wet to very dry	5.6-7.3	6.1 7.8	ND	ND	5-6'	0-6'
26 Menagha-Cutfoot	undulating	mixed	droughty or wet	4.5-	4.5-	ND	ND	5'	6'
31 Alluvial	nearly level	sandy, fine or organic	wet	ND	ND	ND	ND	5-10'	0-6'
34 Spooner-Unnamed-Baudette	nearly level	fine-silty	wet	5.1-7.8	5.1-7.3	ND	ND	5-10'	0-6'
35 Mesaba-Barto	undulating	coarse-loamy to mixed	moderate to dry	4.1-6.5	5.2-5.8	22	ND	8-40"	20"-5'
41 Cloquet-Emmert	undulating	coarse-loamy to sandy skeletal	droughty	4.5-6.5	4.5-6.5	ND	ND	6-10'	10'
48 Nemaji-Newson	nearly level	mixed	wet	4.5-6.0	5.1-6.0	ND	ND	10'	1-2'
49 Unnamed-Hibbing	nearly level	fine, mixed	moderate	5.3	5.5	18.9	13.7	10'	5'
50 Hibbing-Unnamed	undulating	fine, mixed	moderate	5.3	5.5	ND	ND	10'	5'
57 Greenwood	nearly level	organic	wet	4.3	4.0	57	ND	5'	surface
58 Mooselake	nearly level	organic	wet	5.5	5.6	79.8	119.1	5'	0-2'
59 Washkish-Lobo	nearly level	peat	peat	3.4-4.5	4-4.5	ND	ND	5'	0-2'

Table 7 continued.

ASSOCIATION	LITTER WEIGHT	BASE SATURATION		Cu, ppm		Ni, ppm		Fe, ppm		Zn, ppm		Cd, ppm		Cr, ppm		Pb, ppm	
		0-6"	6-12"	0-6"	6-12"	0-6"	6-12"	0-6"	6-12"	0-6"	6-12"	0-6"	6-12"	0-6"	6-12"	0-6"	6-12"
1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
4	ND	28.2	14.7	0.4	0.3	0.6	0.4	245	128	2.9	0.4	0	0	0	0	2.1	0
5	18421 kg/ha	41.3	22.3	0.6	0.3	0.7	0.1	177	74	5.7	0.4	0.04	0	0.1	0.005	1.6	0.2
6	ND	40.0	23.6	0.5	0.5	0.5	0.3	136	151	6.5	0.9	0	0	0	0.01	0.8	0.2
7	49901 kg/ha	28.9	22.7	0.3	0.3	0.3	0.2	120	75	2.3	1.1	0	0	0.2	0.05	0.7	0.3
8	45853 kg/ha	21.8	30.2	1.0	0.2	0.6	0.3	183	115	2.3	0.4	0	0	0.2	0	1.0	0
9	ND	ND		0.6	0.6	0.8	0.3	216	121	4.1	0.3	0.3	0	0.1	0	1.3	0.2
10	ND	32.4	23.9	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
11	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
12	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
17	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
25	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
26	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
31	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
34	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
35	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
41	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
48	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
49	ND	26.3	14.5	0.6	0.4	0.7	0.2	160	140	3.1	0.3	0	0	0.3	0.4	0.7	0
50	62140 kg/ha	ND	ND	11.1	ND	9.1	ND	15490	ND	95.4	ND	ND	ND	ND	ND	ND	ND
57	ND	17.5	ND	1.7	0	1.9	0	710	0	7.3	0	0.2	ND	0.1	ND	3.1	0
58	ND	56.1	62.7	2.7	2.5	4.5	4.6	1072	1192	4.3	2.9	0.11	0.15	0	0	2.5	7
59	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

ND=no data

Table 8. Proportion of Study Area, terrestrial biology divisions, and mineral resource zones in each soil association.

SOIL ASSOCIATION	PROPORTION OF STUDY AREA (%)	PROPORTION OF TERRESTRIAL BIOLOGY DIVISIONS(%)							PROPORTION OF MINERAL RESOURCE ZONES(%)						
		1	2	3	4	5	6	7	1	2	3	4	5	6	7
1 Ontonagen-Bergland	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4 Ahmeek-Ronneby	0.05	0	0	0	0	0.1	0.1	0	0	0	0	0	0	0	0.2
5 Newfound-Newfound	13.52	0.4	8.8	5.2	50.0	40.9	8.6	5.6	0	0	0.04	11.5	22.8	70.7	70.5
6 Unnamed-Toivola	0.67	0	2.5	0	0	2.9	0.8	0.36	0	0	0	0	0	0	0
7 Toivola-Unnamed-Cloquet	11.20	12.0	54.8	14.6	5.5	6.2	10.6	6.4	0	0	24.2	13.4	0.4	4.5	1.0
8 Mesaba-Barto	12.71	68.1	0.1	24.4	11.7	1.0	1.0	5.8	93.3	94.6	52.3	46.1	40.4	0	0
9 Conic-Insula	18.71	2.4	0	3.0	0	0	8.4	65.1	0	0	0	0	0	0	0
10 Quetico-Bedrock outcrop	0.32	0	0	0	0	0	0.3	0.8	0	0	0	0	0	0	0
11 Indus-Wildwood	0.80	0	0	0	0	0	2.0	0.3	0	0	0	0	0	0	0
12 Taylor-Indus	0.09	0	0	0	0	0	0.1	0.2	0	0	0	0	0	0	0
17 Nebish-Mooselake-Shooker	a	0	0	0	0	0	0	a	0	0	0	0	0	0	0
25 Cormant-Shawano	0.67	0	0.1	0	0	0	1.8	0	0	0	0	0	0	0	0
26 Menagha-Cutfoot	4.88	4.0	0	0	0	0	11.7	0.3	0	0	0.3	0	0	0	0
31 Alluvial	0.18	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0
34 Spooner-Unnamed-Baudette	0.20	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0
35 Mesaba-Barto	0.32	0.4	0	1.3	0	0	0.9	0	0	0	0.3	3.3	0	0	0
41 Cloquet-Emmert	3.95	0.4	0	0	0	0	10.6	0.1	0	0	0	0	0	0	0
48 Nemaji-Newson	0.07	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0
49 Unnamed-Hibbing	1.05	0	0	0	1.0	0.5	2.5	0	0	0	0	0	0	0	0
50 Hibbing-Unnamed	3.58	0	0	1.8	3.6	1.8	8.2	0	0	0	0	0	0	0	0.1
57 Greenwood	3.43	0.8	0	0	.3	1.2	8.0	1.1	0	0	0	0	0	1.0	7.0
58 Mooselake	18.90	9.5	33.3	17.7	25.9	43.3	19.7	8.0	6.5	4.9	12.2	16.9	33.9	23.7	22.1
59 Washkish-Lobo	0.20	0	0.2	0	0	1.0	0.3	0	0	0	0	0	0	0	0
60 Mine	2.52	0.2	0	31.0	1.7	0	3.1	0.1	0	0	5.9	12.9	2.4	0	0
62 Water	1.98	1.8	0.1	0	0.3	1.3	0.3	6.2	a	0.5	0.6	0	0	0	0

a = less than .01%

Soil Chemical Characterizations--Soil chemical properties were determined as a part of the Plant Pathology (1976) and Terrestrial Biology (1977) sampling programs. Sampling in each year had different objectives, and, as a result, different designs were employed.

In 1976 sampling was over a broader area than in 1977. Unlike 1977, however, soils were not a criterion in site selection, and some associations (e.g. 5, 7, and 58) were sampled frequently, whereas others were not sampled at all (most noticeably association 9). Parameters sampled in 1976 included cation exchange capacity (CEC), pH, base saturation, $SO_4^=$, and F. Also extractable (with EDTA) Fe, Cu, Zn, Cr, Cd, Ni, and Pb, and available (ammonium acetate extraction) Ca, Mg, K, Na, and Mn were determined. Two soil depth intervals (0 to 6 in. excluding the forest floor, and 6 to 12 in.) were sampled. Soils for analysis were obtained from 34 sites. Twelve samples per depth per site were collected and pooled. Thus, a single value for each parameter was obtained for each depth interval at each site. Sites were sampled twice--once in mid-June and once in mid-August. Soil associations covering approximately 60% of the Study Area were sampled, although only one site each occurred on associations 4, 49, and 57. By contrast, association 5 was sampled at 11 sites.

1976 Sampling

The results of the 1976 soil sampling are presented in Table 9 and are discussed systematically by parameter.

Table 9

Base Saturation--Base saturation integrates soil exchangeable hydrogen and cation exchange capacity data. Soils from the Study Area can be combined into three

Table 9. Summary of 1976 soil chemical analyses.

SOIL ASSN.	% OF STUDY AREA	DEPTH (in.)	C.E.C.[a] (meg/100g)	BASE SATURATION (%)	pH	$SO_4^{=}$ (ppm)	Ca^{++} (ppm)	Mg^{++} (ppm)	Fl (ppm)	Mn (ppm)	Cu (ppm)	Fe (ppm)	Zn (ppm)	Ni (ppm)	Cd (ppm)	Cr (ppm)	Pb (ppm)
4	0.1	0-6	31.3-2	28.2-2	5.0-2	16-2	1420-2	204-2	7.8-2	22.7-2	0.4-2	245-2	2.9-2	0.6-2	0-2	0-2	2.1-1
		6-12	21.6-1	14.7-1	5.3-1	23-1	444-1	78-1	10.3-1	2.1-1	0.3-1	128-1	0.4-1	0.4-1	0-1	0-1	0-1
5	13.5	0-6	23.4-19	41.3-19	5.4-20	17-20	1535-20	219-20	8.8-22	46.4-22	0.6-22	177-22	5.7-22	0.7-22	0.04-22	0.1-22	1.6-22
		6-12	15.2-9	22.3-9	5.7-10	14-10	626-10	84-10	7.7-12	5.5-12	0.3-12	74-12	0.4-12	0.1-12	0-12	0.005-12	0.2-12
6	0.7	0-6	26.4-2	40.0-2	5.3-2	19-2	1780-2	222-2	9.3-2	24.1-2	0.5-2	136-2	6.5-2	0.5-2	0.10-2	0-2	0.8-2
		6-12	19.5-2	23.6-2	5.5-2	18-2	758-2	104-2	9.3-2	6.8-2	0.5-2	151-2	0.9-2	0.3-2	0-2	0.01-2	0.2-2
7	11.2	0-6	23.6-16	28.9-16	5.5-16	18-16	1077-16	167-16	6.2-16	23.4-16	0.3-16	120-16	2.3-16	0.3-16	0-16	0.2-16	0.7-16
		6-12	17.9-13	22.7-13	5.8-10	18-13	572-13	104-13	6.4-13	8.0-13	0.3-13	75-13	1.1-13	0.2-13	0-13	0.05-13	0.3-13
8	12.7	0-6	28.4-2	21.8-2	5.0-6	20-6	950-6	159-6	7.7-6	23.0-6	1.0-6	183-6	2.3-6	0.6-6	0-6	0.2-6	1.0-6
		6-12	23.1-1	30.2-1	5.3-1	19-1	347-1	64-1	7.4-1	3.4-1	0.2-1	115-1	0.4-1	0.3-1	0-1	0-1	0-1
10	0.3	0-6	24.7-3	32.4-3	5.1-4	22-4	1256-4	216-4	7.4-4	65.8-4	0.6-4	216-4	4.1-4	0.8-4	0.03-4	0.1-4	1.3-4
		6-12	17.9-1	23.9-1	5.2-2	24-2	365-2	107-2	7.9-2	89.5-2	0.6-2	121-2	0.3-2	0.3-2	0-2	0-2	0.2-2
49	1.1	0-6	18.9-2	26.3-2	5.3-2	15-2	775-2	132-2	8.8-2	42.8-2	0.6-2	160-2	3.1-2	0.7-2	0-2	0.3-2	0.7-2
		6-12	13.7-2	14.5-2	5.5-2	26-2	287-2	67-2	9.6-2	1.75-2	0.4-2	140-2	0.3-2	0.2-2	0-2	0.35-2	0-2
57	3.4	0-6	57-1	17.5-1	4.3-2	56-2	1755-2	422-2	11.9-1	23.7-2	1.7-2	710-2	7.3-2	1.9-2	0.2-1	0.1-1	3.1-2
		6-12	N.A.[b]	N.A.	4.0-1	45-1	1200-1	265-1	6.2-1	0-1	0-1	0-1	0-1	0-1	N.A.	N.A.	0-1
58	18.9	0-6	79.8-9	56.1-9	5.5-10	105-10	4528-10	2757-10	8.0-10	151.0-9	2.7-9	1072-9	4.3-9	4.5-9	0.11-7	0-7	2.5-9
		6-12	119.1-1	62.7-1	5.6-5	97-5	4806-5	2940-5	8.2-4	15.6-4	2.5-4	1192.8-4	2.9-4	4.6-4	0.15-4	0-4	0.7-4

[a] Values are: $\bar{x}$-n where n is number of analyses, most sites were sampled twice. Thus, for example, x's for S.A. #49 were obtained by averaging values from one site that was sampled twice.

[b] N.A.=not available.

groups of similar base saturation. Mineral soils appear to have values either greater than 40% (associations 5 and 6) or less than about 30% (associations 4, 7, 8, 10, and 49). Soils of the latter class are generally coarser textured and/or are quite shallow. Soils with higher base saturations do not have correspondingly higher CEC values. This suggests that differences are more related to the higher ratio of bases to H^+ than to the greater availability of exchange sites. Within the mineral soils, base saturations are typically less in the 6 to 12-in. interval than in the 0 to 6-in. interval. Organic soils differ from mineral soils in that they generally have much higher CEC and base saturations. This is not true, however, in the very acid soils of association 57. The pH in these organic soils are 4.0 to 4.3; nearly one unit lower than other soils, which are in the range of 5.0 to 5.8.

$SO_4^=$--Sulfate levels in mineral soils were not observed to vary with soil associations. Mineral soil levels are, however, much lower than levels in organic soils. The former generally are in the range 15 to 25 ppm, whereas the latter are typically greater than 45 ppm. Differences associated with sampling depth were observed only in organic soils where sulfate levels decrease with increasing depth.

Calcium and Magnesium--Concentrations of these 2 major cations parallel, to some extent, values for base saturation. Among the mineral soils, values are highest in associations 5 and 6. The organic soil association 58 has concentrations that are, respectively, 4 to 5 and 10 times higher for Ca and Mg compared to mineral soils. Calcium concentrations for soil association 57 are typical of the highest mineral soil values, whereas Mg concentrations are twice those in associations 5 and 6. Except for soil association 58, concentrations in the 6 to 12-in. interval are 1/2 to 1/3 those in the 0 to 6-in. interval.

Fluoride--Concentrations of fluoride are uniformly 6 to 11 ppm for all soils. More often than not, values are higher in the 6 to 12-in. interval but not significantly so.

Manganese--The organic soil association 58 has the highest manganese values (150 ppm), although these high values are confined to the 0 to 6-in. interval. Among the mineral soils, values for Mn are highest (40 to 65 ppm) in the surface horizons of associations 5, 10, and 49. Values for other soils were consistently 20 to 25 ppm. Analyses for 6 to 12-in. intervals are 1/10 to 1/3 those of surface intervals for all soils.

Copper--Mineral soil copper concentrations range from 0.2 to 0.6 ppm except in soil association 8 where values in the 0 to 6-in. interval average 1.0 ppm. Values in organic soils are higher (1.5 to 3.0 ppm) but more variable. Concentrations generally decrease slightly with depth. High copper concentrations (2.6 ppm for June and 1.7 ppm for August) were observed for soil association 8 at plot P20. This plot has shallow soils over Gabbro bedrock and lies just east of the South Kawishiwi River. Because of the shallow soils, the 6 to 12-in. interval was not sampled at this plot. Foliage of aspen leaves sampled at the site did not have high concentrations of copper.

Iron--Iron concentrations in organic soils are typically 5 to 6 times higher than in mineral soils. The latter are in the range 75 to 250 ppm, whereas the former range from 700 to 1,200 ppm. Except for associations 6, 49, and 58, mineral soil values at 6 to 12 in. are 1/2 to 2/3 those at 0 to 6 in.

Zinc--Values for Zn are 2 to several times higher in surface soils than at lower depths. No clear differences exist between mineral and organic material. Some mineral soils clearly have higher values than others. Values within soil associations are quite variable. Abnormally high values (10 to 20 ppm) were consistently observed in 0 to 6 in. soils at plots P24 and P25. Both of these plots are on soil association 5 in the northwest portion of the Study Area.

Nickel--Concentrations of nickel are highest in peat soils. Within mineral soils, the highest values are at the surface. Values generally exceed 1 ppm only in organic soils.

Cadmium--Concentrations of cadmium are mostly less than 0.1 ppm; the lower detection limit. Only occasionally were values of 0.2 to 0.3 ppm observed.

Chromium--As with cadmium, chromium values were generally at or below the detection limit of 0.1 ppm. Values higher than 0.1 ppm were observed only during the June sampling period, and values never exceeded 0.8 ppm.

Lead--Concentrations of Pb were higher in 0 to 6 in. intervals than in soils of the 6 to 12-in. intervals, and they were higher in peat than in mineral soils. Within mineral soils, soil associations 5 and 8 had concentrations approximately twice those in associations 6, 7, and 49. The highest lead concentrations, up to 22 ppm, were observed on soil association 5 at plots P25 and P28.

1977 Sampling

Sampling in 1977 was more intensive, but was largely restricted to the area in and adjacent to the mineral resource zones. Forty-eight sites were selected among the most prevalent soil and vegetation types. Soils were sampled only during late July except at 2 sites where samples were also collected in early June and mid-September. For sites with mineral soil, 12 samples each were obtained for the forest floor and the 0 to 5 cm and 5 to 10 cm intervals. In peat soils, sampling intervals were 0 to 5, 5 to 10, and 55 to 60 cm. After drying, samples were quantitatively pooled so that, for each site, 3 samples from each depth interval were available for analysis. Parameters evaluated were total (nitric-perchloric acid digestion) K, Mg, Ca, P, Sr, Ba, Cu, Zn, Mn, Fe, Al, Ti, V, Be, Si, B, Ag, As, Pb, Zr, Th, Co, Cd, Cr, Ni, Mo, Se, and Na.

Soil chemical analysis data were summarized for 9 elements: Cu, Ni, Fe, Mn, Zn, Ca, Mg, P, and K. Means (X) and standard error of the means (SEM), calculated as a percent of the mean, were determined for these elements in each of the 5 soil associations that were sampled in 1977 and are given in Table 10. An overall mean and variability quotient (SEM/X*100) of the 4 mineral soil associations combined were also calculated for each element. Results for organic and mineral soils are treated separately in the discussion below.

Table 10

Organic Soils

Only soil association 58 was sampled. Generally, concentrations of most elements (Zn, Fe, Mn, Mg, P, and K) decreased with increasing soil depth. The reverse was true for Ni and Ca, however, and Cu followed no apparent trend.

Variability in concentration (as measured by Vq=SEM/X*100) increased with soil depth for Cu, Mn, Zn, Mg, and P. Only for Fe did variability decrease with increasing soil depth. Nickel, Ca, and K showed no trend. Of those elements that exhibited an increase in variability with depth, the rate of increase in Vq occurred more rapidly between the 0 to 5 cm and 5 to 10 cm depths for Mg, Zn, and Mn and between the 5 to 10 cm and 55 to 60 cm depth for Cu and P. Overall, the variability of the average metal concentrations in organic soil were relatively high. The Vq values were all over 10% except for Cu, Zn, K, and P at the 0 to 5

Table 10. Chemical analysis summary for soil associations (1977 data).

SOIL ASSN.	% OF STUDY AREA	DEPTH (cm)	n[a]	Cu (ppm)		Ni (ppm)		Mn (%)		Zn (ppm)		Fe (%)	
				$\bar{X}$[b]	(SEM%)[c]	$\bar{X}$	(SEM%)	$\bar{X}$	(SEM%)	$\bar{X}$	(SEM%)	$\bar{X}$	(SEM%)
5	13.5	Litter	11	14.2	(7.0)	9.5	(20.5)	948	(20.5)	120.5	(10.3)	11,930	(12.9)
		0-5		25.8	(6.2)	75.6	(12.0)	.080	(11.3)	71.0	(10.0)	4.43	(3.7)
		5-10		27.0	(3.3)	55.8	(10.1)	.063	(10.7)	66.9	(4.8)	4.78	(6.3)
7	11.2	Litter	10	12.8	(4.2)	19.7	(14.4)	768	(11.7)	90.5	(12.3)	11,700	(11.3)
		0-5		26.4	(6.6)	154.3	(25.2)	.100	(7.6)	94.7	(6.4)	6.00	(4.7)
		5-10		29.8	(8.7)	115.3	(11.5)	.080	(3.6)	92.4	(5.3)	6.26	(2.4)
8	12.7	Litter	13	13.1	(4.6)	7.6	(24.1)	986	(10.5)	97.6	(10.6)	10,800	(13.4)
		0-5		27.3	(13.4)	71.4	(13.8)	.076	(9.4)	77.6	(5.5)	5.22	(5.3)
		5-10		30.4	(13.3)	82.2	(10.9)	.064	(8.6)	80.1	(4.4)	5.45	(4.8)
50	3.6	Litter	3	11.1	(5.2)	9.1	(19.0)	2,080	(40.0)	95.4	(22.6)	15,490	(4.3)
		0-5		15.1	(10.7)	49.5	(35.1)	.061	(23.7)	67.8	(9.3)	2.89	(.4)
		5-10		16.2	(2.9)	28.2	(12.3)	.051	(14.7)	65.9	(7.8)	3.60	(5.8)
58	18.9	0-5	8	10.1	(6.8)	6.7	(18.2)	383	(18.2)	45.2	(6.8)	12,870	(26.5)
		5-10		8.7	(9.6)	7.0	(26.8)	286	(32.6)	33.7	(13.2)	9,830	(26.4)
		55-60		10.6	(22.5)	13.7	(12.7)	151	(37.4)	11.7	(16.3)	4,990	(19.2)
Upland Combined (5,7,8,50)													
	41.0	Litter	37	13.0	(2.5)	11.5	(12.1)	1,003	(10.5)	102	(6.2)	11,760	(6.6)
		0-5		25.6	(5.9)	93.2	(13.6)	82.5	(5.6)	78.7	(3.5)	5.00	(3.8)
		5-10		28.1	(6.0)	78.9	(8.4)	66.8	(4.8)	78.3	(3.4)	5.26	(3.5)

[a] n = number of samples analyzed.
[b] $\bar{X}$ = mean value.
[c] SEM% = standard error of the mean, calculated as a percent of the mean.

Table 10 continued.

SOIL ASSN.	% OF STUDY AREA	DEPTH (cm)	n[a]	Ca (%) $\overline{X}$[b]	Ca (%) (SEM%)[c]	Mg (%) $\overline{X}$	Mg (%) (SEM%)	P (%) $\overline{X}$	P (%) (SEM%)	K (%) $\overline{X}$	K (%) (SEM%)
5	13.5	Litter	11	10,790	(8.7)	2,150	(9.7)	910	(4.1)	1,510	(10.5)
		0-5		2.03	(5.6)	1.22	(2.6)	0.135	(11.0)	1.10	(2.8)
		5-10		2.12	(6.5)	1.35	(3.8)	0.129	(8.6)	1.14	(3.1)
7	11.2	Litter	10	11,970	(15.2)	3,330	(7.1)	696	(7.9)	1,230	(6.8)
		0-5		2.88	(9.9)	1.62	(5.7)	0.163	(9.7)	.92	(3.8)
		5-10		3.02	(6.1)	2.05	(14.5)	0.164	(9.7)	.94	(2.7)
8	12.7	Litter	13	12,600	(17.2)	2,040	(6.5)	881	(7.1)	1,320	(9.6)
		0-5		2.31	(3.8)	1.48	(3.4)	0.145	(7.0)	1.02	(4.9)
		5-10		2.36	(5.3)	1.61	(3.3)	0.154	(11.7)	1.03	(4.1)
50	3.6	Litter	3	5,700	(8.3)	2,150	(14.0)	817	(7.3)	1,520	(5.1)
		0-5		1.35	(6.4)	0.99	(4.1)	0.088	(3.3)	1.42	(2.4)
		5-10		1.51	(6.4)	1.21	(2.9)	0.120	(5.8)	1.42	(2.8)
58	18.9	0-5	8	5,990	(18.2)	2,300	(15.3)	747	(10.2)	1,026	(6.7)
		5-10		6,290	(20.3)	2,280	(16.3)	720	(10.8)	794	(13.1)
		55-60		6,490	(17.4)	1,820	(16.8)	534	(13.8)	286	(10.3)
Upland Combined (5,7,8,50)											
	41.0	Litter	37	11,530	(8.1)	2,430	(5.4)	836	(3.8)	1,370	(5.1)
		0-5		2.23	(5.7)	1.40	(3.2)	0.142	(5.3)	1.05	(2.9)
		5-10		2.41	(5.6)	1.53	(2.8)	0.146	(6.1)	1.07	(2.7)

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[a] n = number of samples analyzed.

[b] $\overline{X}$ = mean value.

[c] SEM% = standard error of the mean, calculated as a percent of the mean.

cm depth, and for Cu at 5 to 10 cm depth. The largest values were found for Fe (19 to 27%) and Mn (18 to 37%), whereas those of K were consistently low.

For most elements, the variability of the 3 samples within a site was generally lower than the variability of the average values from all 8 plots. The Vq values were under 10% for all metals except K at the 55 to 60 cm depth and Fe and Mn at all 3 depths. Values for Vq ranged from 29.7% (Mn) to 5.1% (P) at the 5 to 10 cm depth, from 39.6% (Ni) to 4.8% (P) at the 5 to 10 cm depth, and from 19.9% (Mn) to 7.8% (P) at the 55 tp 66 cm depth. There was no relationship between depth and variability.

Mineral Soils

Chemical analysis of mineral soils included samples from soil associations 5, 7, 8, and 50. Average concentrations of most elements (Cu, Fe, Mg, P, and K) increased with depth. Only Ni and Mn decreased. Zinc showed no depth-related trends.

All elements except Zn, Mn, and P were found in greater concentrations in the soil than in the litter. All average concentrations in the soil were less than an order of magnitude higher than the litter concentrations.

There was less variability in the average element concentration of soil than litter for all elements except Cu and P. This decrease in variability at a greater depth may be due to the absence of soil disturbance and the sporadic influx of various elements from organic matter.

The overall variability of both litter and soil was relatively low. The Vq values for litter were under 10% for all elements except Mn (10.5%) and Ni (12.1%). Only Ni (13.6%) at the 0-5 cm interval had a Vq greater than 10% in soil. The highest Vq for the 5-10 cm interval also occurred with Ni. The lowest variability in litter was for Cu (2.5%) whereas the lowest soil variability in both the 0 to 5cm (2.9%) and 5 to 10 cm (2.7%) intervals was for K.

Comparison of Organic and Mineral Soil

Average forest-floor values for the four soil associations on mineral soil were higher for all metals at all depths compared to organic soils. The average metal concentration of organic soil at the 0-5 cm depth, however, was usually within the range of average litter values. Only Cu, Ni, and Zn concentrations for organic soils were below the range of litter values, although litter and organic soil averages differed greatly only for Zn. The differences between litter and organic soil values generally increased with increasing organic soil depth. Copper, Ni, and Ca reached their highest concentrations at the 55 to 60 cm interval in organic soils and were exceptions.

Although Vq values for the combined mineral soil group were much lower than those of the organic soil group, a direct comparison is not appropriate as large differences exist in the number of sites in each group. Generally, metal concentrations increased with depth in mineral soil but decreased with depth in organic soil. Nickel followed no depth-related trend in either soil type. Manganese and Zn in mineral soil, and Ca and Cu in organic soil also showed no depth-related trends.

Comparisons of Mineral Soil Associations

At both depths, the average concentrations of all elements except K varied with soil association. The highest average concentrations were nearly always found in soil association 7, whereas the lowest were always found in soil association 50.

Soil associations 8 and 5 generally ranked second and third, respectively. No apparent relationship existed between soil association and litter element concentration.

For both litter and mineral soil a comparison of average and Vq values for mineral soil asociations reveals that deviant values (those that differ greatly from those of the other 3 soil associations) nearly always occurred in association 7 or 50. In soil association 7, unusually high average values were found in both soil depths for Ni and Zn, and in the 5 to 10 cm soil layer for Mn. High average values were also found in the litter for Ni and Mg. In soil association 50, low average values were found for Fe at both soil depths and for P at the 0 to 5 cm layer. Mean concentrations for K for both soil depths were much greater compared to other soil associations. In the litter, high average values were found for Mn, Ca, and Fe. The only atypical average value found in soil associations other than soil association 7 or 50 was for Zn in the litter of soil association 5.

Extremes in variability were all confined to associations 7 and 50. Unusually high Vq values were found in the litter of soil association 7 for Ni, and the 5 to 10 cm soil depth for Mg. Variability in association 50 was high in the litter for Mn and Fe. Very low Vq values were found in the litter of association 50 for Zn and in the 5 to 10 cm interval of soil association 7 for Mn.

The observed chemical relationships among the 4 soil associations appear to relate to soil texture. The highest average concentrations (except for K) were found on soil association 7, which is classified as a gravelly soil. Soil associations 5 and 8, which were similar and had lower values than association 7, are finer textured and are classified as loamy soils. Soil association 50, which had the lowest concentrations for all but K, is classified as clay soil.

Several additional factors may account for the low values reported for soil association 50. First, soil association 50 originated from calcareous Des Moines lobe till, whereas the other soils originated from the more granitic Rainy Lobe till. Second, soil association 50 is represented by only 3 plots. All other soil associations were sampled in at least 8 plots. Thus, higher Vq values would be expected for soil association 50 compared to other soil associations. Third, sampling of soil association 50 was confined to plots with coniferous vegetation, whereas the other 3 mineral soil associations were sampled under both coniferous and deciduous vegetation. Increased leaching and slower element cycling rates would result in lower values in surface soil (A) horizons under conifers.

Comparisons of total soil concentrations obtained for soils in the Study Area with worldwide values from Aubert and Pinta (1977) are given in Table 11 and show that values for soils of the Study Area are within the range of worldwide average values for all elements except nickel. Values for this element are 2 to 3 times the worldwide average values. Variations within the Study Area appear to be related to origin of parent rocks. Soils of soil association 50 are derived from rocks of marine sedimentary origin and are relatively low in Ni (30-50 ppm). Soils of all other soil associations originated from granitic rocks and it would appear that the nickel contained in these rocks influenced soil concentrations. Soils derived from these granitic rocks have higher concentrations for several other metals compared to soil association 50, but values do not exceed the range of worldwide values. For more information on this topic, see Patterson and Aaseng (1978).

Table 11

Table 11. Total element concentrations (ppm) in soils of the Study Area compared with world-wide average values.

	AUBERT AND PINTA (1977)		CU-NI STUDY AVERAGE CONCENTRATIONS					
			Soil Association					Sample
ELEMENT	Average	Range[a]	50	5	8	7	All	Depth(cm)
B	20-50	5-150						0-5
								5-10
Cr	100-300	t -4,000					117	0-5
							111	5-10
Co	10-15	.05-300					17	0-5
							19	5-10
Cu	15-40	t -250	15	26	27	26	26	0-5
			16	27	30	30	28	5-10
Pb	15-25	t - 1,200						0-5
								5-10
Mn	500-1,000	t - 10,000	610	800	760	1,000	825	0-5
			510	650	640	800	668	5-10
Ni	20-30	t - 500	50	76	71	154	93	0-5
			28	56	82	115	79	5-10
Zn	50-100	t - 900	68	71	78	95	83	0-5
			66	67	80	92	83	5-10

SOURCE: Patterson and Aaseng (1978).

[a] t = trace.

Litter Decomposition

Decomposition is an essential process governing the rate of element cycling in terrestrial ecosystems. Soil microflora and micro- and mesofauna play important roles in decomposing litter in forests, and heavy metals pollution has been shown to restrict the activities of these organisms (Bond et al. 1976; Tyler 1974, 1975a and b, 1976). When decomposition rates are reduced, essential nutrients are bound in accumulating litter, and ultimately, ecosystem production is decreased.

Several factors affect litter decomposition including soil temperature and moisture content, plant species contributing to litter and the degree of decomposition of organic matter. Such factors as pH and chemical composition of litter influence its suitability as a substrate for different organisms. All of these factors have been recently reviewed by Williams and Gray (1974) and will not be discussed in detail in this report.

Six of the 48 plots studied in 1977 were selected as sites for litter decomposition studies and are shown in the map in Figure 12. Nylon-mesh bags containing weighed fresh aspen litter were placed in the 4 corners of each plot in May. One bag was collected from each corner at approximately 4-week intervals. Weight loss between initial weight and weight at the time of collection was used as a measure of litter decomposition. Although the rate of decomposition varied among plots, it was slowed on most plots during midsummer.

Figure 12

Rates of decay for the 6 sites were calculated using the equation suggested by Gosz et al. (1973)

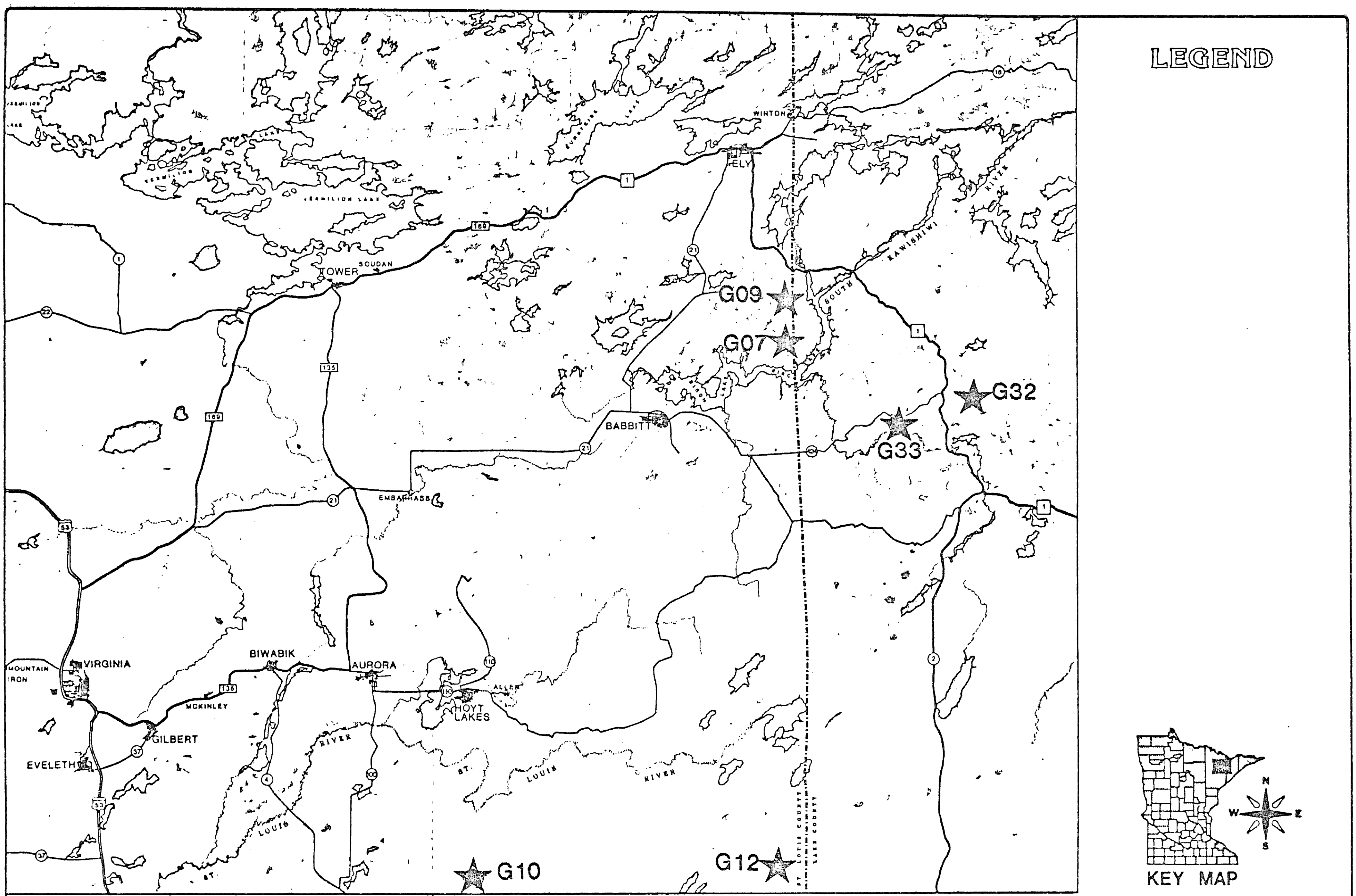


FIGURE 12

MEQB REGIONAL COPPER-NICKEL STUDY

MAP SHOWING THE LOCATION OF LITTER DECOMPOSITION STUDY SITES.

1:422,400

MILES

KILOMETERS

$$X = X_o e^{-kt}$$

where X is the weight of the litter remaining at time t, Xo is the original weight, and e is the base of natural logarithms. The factor k is referred to as the "decomposition constant." The number of years required to decompose half the litter and 95% of the litter on the 6 study plots is presented in Table 12, along with decomposition rates for data from a nearby study by Grigal and McColl (1977) and from Gosz et al. (1973) for Hubbard Brook, New Hampshire.

Table 12

Weight of the undecomposed litter layer varied within each of the upland associations sampled. Within the Mesaba-Barto association, (8), litter weights in pine stands are comparable to or higher than the upper range of litter weights for deciduous stands. Four of 5 deciduous stands on the Newfound soil association (5) in the Toimi Drumlin Field have low litter weights. Litter weights in jack pine stands on this soil association are lower than litter weights in jack pine on other soils.

Among the 6 litter decomposition study plots, high decomposition rates were observed on one of the 2 plots on association 5, and it seems likely that rapid litter decomposition is at least partially responsible for the lack of humus buildup in the forest floor.

Correlations of forest floor weights and overstory vegetation on coarser textured soils indicate a direct relationship between forest floor development and total tree basal area (Figure 13). Decomposition rates on these soils are typical of those recorded elsewhere in the region. The basal area-forest floor weight relationship does not hold for aspen stands on the fine-textured Newfound-

Table 12. Litter decay rates calculated for data from this study and recalculated from data of Grigal and McColl (1977). Also included are data from Gosz et al. (1973).

			TIME PARAMETERS, yr	
PLOT	$\frac{X}{X_o}$	k	half-time $\frac{(0.693)}{k}$	95% loss time $\frac{3}{(k)}$
G08	0.779[a]	0.53	1.3	5.7
G09	0.758[a]	0.59	1.2	5.1
G10	0.724[a]	0.68	1.0	4.4
G12	0.627[a]	0.99	0.7	3.0
G32	0.768[a]	0.56	1.2	5.4
G33	0.721[a]	0.69	1.0	4.3
Grigal & McColl (data recalculated)				
Aspen 71(1)[2]	0.590[b]	0.53	1.3	5.7
(2)	1.352[c]	0.52	1.3	5.8
Aspen 72(1)	0.647[b]	0.44	1.6	6.8
(2)	0.585[c]	0.27	2.6	11.1
Aspen 73(1)	0.507[b]	0.68	1.0	4.4
Aster 72(1)	0.194[b]	1.64	0.4	1.8
Aster 73(1)	0.136[b]	2.00	0.4	1.5
Gosz et al.				
Yellow Birch	---	0.85[b]	0.8	3.5
Sugar Maple	---	0.51	1.4	5.9
Beech	---	0.37	1.9	8.1

[a] t = 0.471 yr

[b] t = 1 yr

[c] t = 2 yr

Newfound association (5). For a more detailed discussion, see Patterson (1978).

Figure 13

1.4 BEDROCK GEOLOGY

1.4.1 Petrology

As was stated previously, the Duluth Complex can be divided into 3 major rock series. These are the older anorthositic and felsic series and a younger troctolitic-gabbroic series. Also important in a discussion of the petrology of the gabbroic host rocks are the inclusions (a fragment of older rock included in the host rocks) which are found along and near the basal contact of the mineralized (sulfide-bearing) rock. The Duluth Complex does not terminate sharply along its basal contact with the adjacent formation, but terminates in a complex zone of inclusion. Inclusion type and location is important because there seems to be a correlation between inclusions and their sources and the amount of mineralization present.

Metamorphosed inclusions are found along the entire basal contact of the Duluth Complex from the area in the south, near Hoyt Lakes, to the area of the North Kawishiwi River in the BWCA on the north. The size of the inclusions varies from a few centimeters in diameter to bodies nearly 1,000 m across. Table 13 is a summary listing of these inclusion types.

Table 13

The Biwabik-type iron formation inclusions are easily identified because of their very distinctive quartz-magnetite iron silicate mineralogy and their characteristic bedding.

FIGURE 13

GRAPH OF FOREST FLOOR WEIGHTS VS. TOTAL OVERSTORY BASAL AREA. REGRESSION LINE IS FOR NORTH PLOTS ONLY.

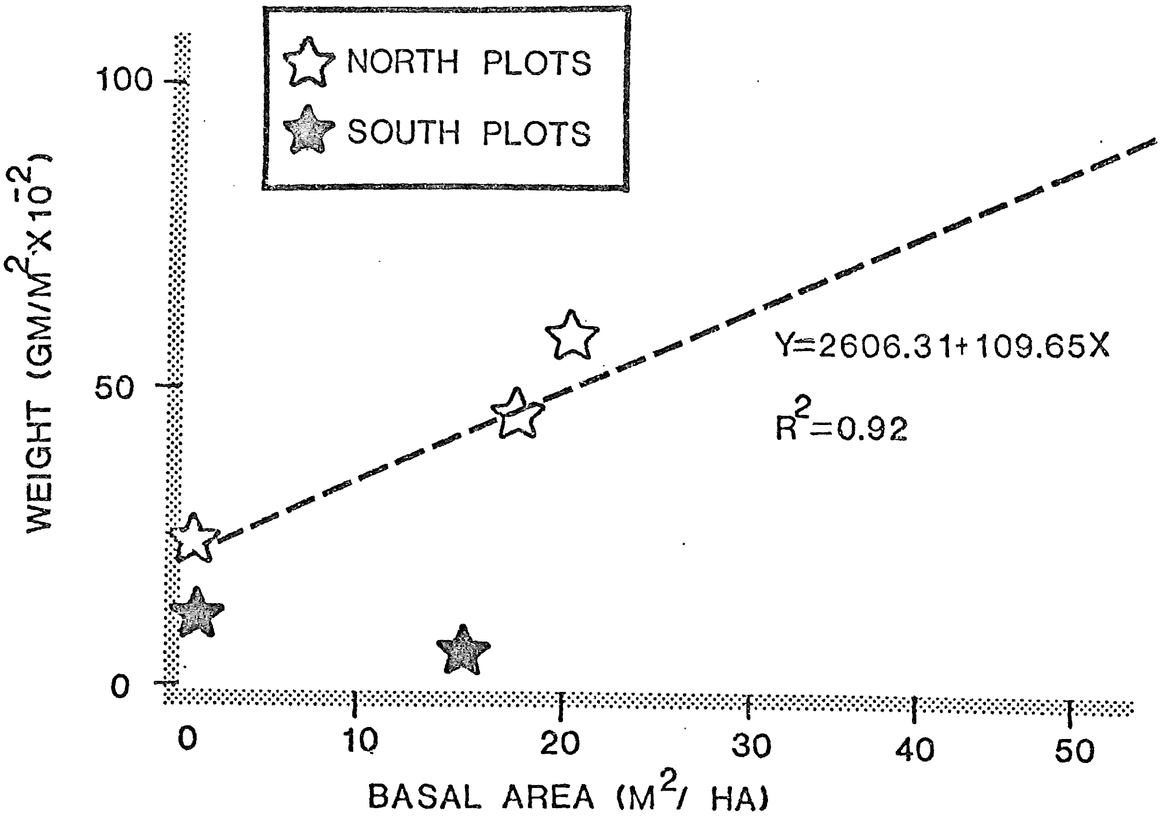


Table 13. Inclusion types.

Biwabik-type Iron Formation

Virginia Formation

Early gabbro and troctolite (early Duluth Gabbro)

Giants Range Granite

The bulk of the 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 which forms the footwall in the Babbitt-Hoyt Lakes area. They are characterized by locally recognizable 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. In the Kawishiwi area a unit informally referred to as the Spruce breccia contains greater than 30% hornfels inclusions. Most of these represent metasedimentary rocks. The Spruce breccia has been found in the contact zone from Birch Lake to Filson Creek in Sec. 19, T.62N., R.10W. and has been encountered extensively in drill core.

Some hornfelsic rocks of the contact zone in the Kawishiwi area appear to be recrystallized fine-grained troctolite or gabbro (early intrusions of the multiple intrusion Duluth Complex). Hornfels in units of this type could represent chilled marginal rocks of early troctolitic-gabbroic intrusions which have been included in later intrusions. 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.

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

Anorthositic and Felsic Series

The anorthositic and felsic series rocks are shown in Figure 14. Included in this series are the peridotitic and noritic rocks which are found in the area. The best exposures of norite are those on Gabbro Lake in Sections 9 and 16, T.62N., R.10W. They consist of approximately 65% plagioclase (An_{35-46}) and 24% hyperstene, with augite, opaques, and biotite present in minor amounts. The norite at these localities cuts other rocks of the anorthositic series.

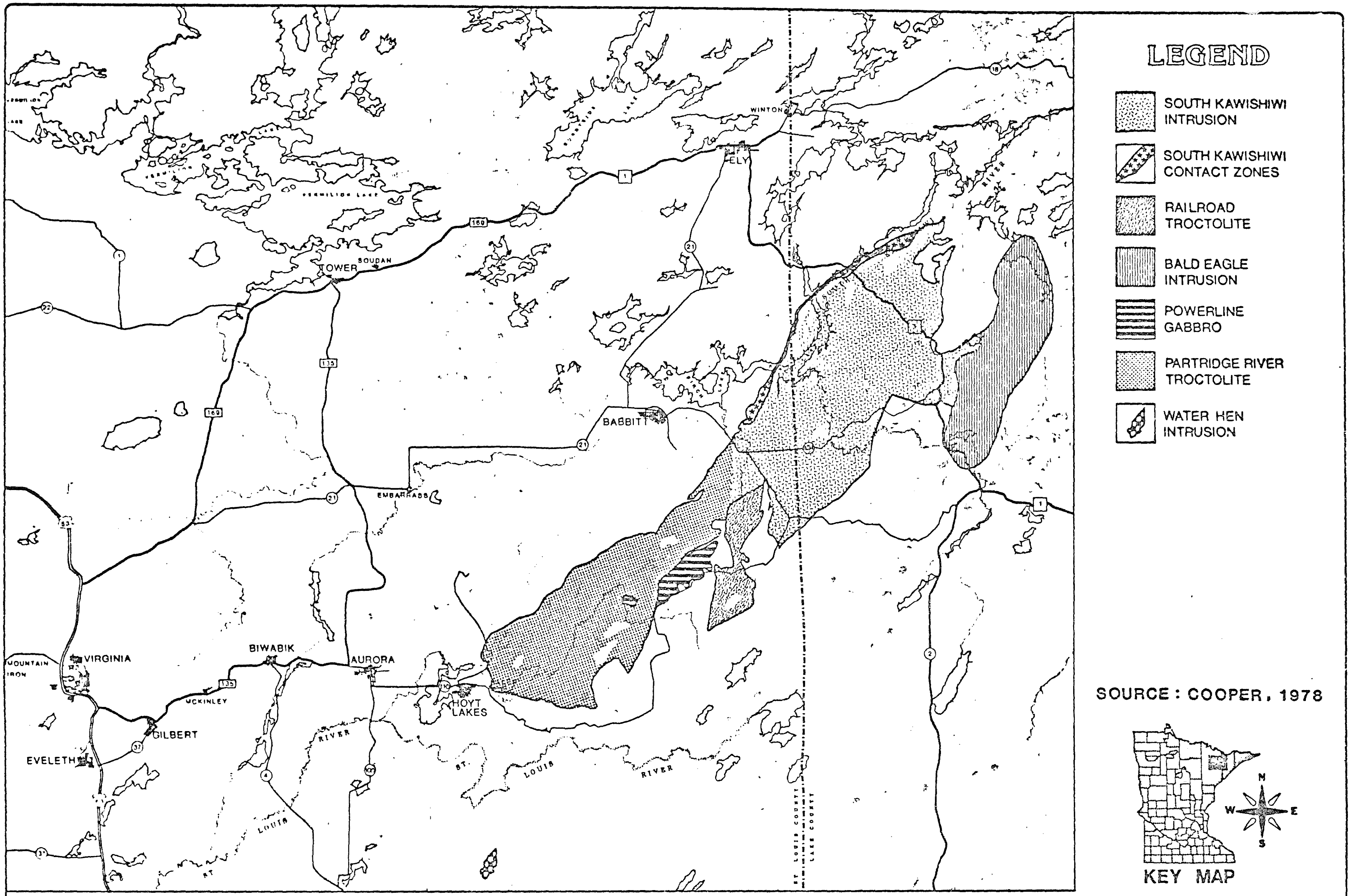
Figure 14

Small, meter-sized masses of pyroxene-oxide-olivine peridotite have been found locally in the Study Area in the troctolitic series rocks. 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 and reported 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 (Figure 14). It consists mainly of a layered sequence of dunite, peridotite and troctolite. The Water Hen Intrusion has Cu-Ni mineralization as described by Mainwaring (1975). Apparently because of the depth at which the mineralization occurs and the relatively small size of the intrusion, no company is actively working on the prospect. However, Exxon does hold land leases in the area.

Anorthositic rocks are the most common rock type in the anorthositic rock series in the region. They have been divided into 3 units on the basis of texture and composition, gabbroic anorthosite, anorthosite gabbro, and anorthositic gabbro undivided.

Gabbroic anorthosite was defined by Phinney (1969) and contains an average of 87% plagioclase (An_{58-70}), 6% hypersthene, and 3% 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.



SOURCE : COOPER, 1978

FIGURE 14

MEQB REGIONAL COPPER-NICKEL STUDY

BEDROCK GEOLOGY OF MAPPED TROCTOLITIC INTRUSIONS

Anorthositic gabbro 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 easily recognized in the field. 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.

Anorthositic gabbro undivided forms the majority of the anorthositic series rocks exposed in the Study Area. The average range in composition is 75 to 88% plagioclase (An_{55-85}), 3 to 8% olivine (Fo_{54-65}), and 4 to 23% clino- and orthopyroxene. Oxide minerals and biotite are minor constituents.

Granophyre associated with the anorthositic series rocks is rare in this area. Granophyre has been found as dikes, such as a granophyric dike 15 to 20 cm wide which cuts anorthositic gabbro. This occurrence is close (within 100 m) to a contact between anorthositic gabbro and troctolitic-gabbroic series rocks. Some small granophyric dikes have also been found that are associated with a hornfels inclusion exposed along the Erie Mining Company railroad. 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.

The above discussion was included since, although the bulk of the Cu-Ni mineralization in the Study Area and the Duluth Complex as a whole is in the Troctolitic-Gabbroic series rocks, an understanding of the anorthositic series rocks is necessary to understand the history of the Cu-Ni mineralization of the Duluth Complex.

The rocks of the Troctolitic-Gabbroic series are represented by several mappable units (Figure 14). A line can be drawn on Figure 14 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. This line would generally extend northeast from Hoyt Lakes. On the basis of interpretations of aeromagnetic maps, troctolitic rocks are inferred to underlie part of this largely covered area.

The South Kawishiwi intrusion was informally named by Green, Phinney, and Weiblen (1966) to designate troctolitic-gabbroic rock exposed in the Gabbro Lake quadrangle. It has been subdivided into 5 units:

1) Contact Zone Troctolite - a contact zone of troctolite with sulfide mineralization.

2) Contact Zone Gabbro - a contact zone of gabbro with sparse sulfide mineralization.

3) Troctolite - the troctolite unit.

4) Anorthosite - the anorthosite unit.

5) Low Augite Troctolite - troctolite with less than 5% augite.

Contact Zone Troctolite: The contact zone of troctolitic rocks in the Kawishiwi area is 0.5 to 1 km wide and outcrops on the north side of Birch Lake on the southwest end to a point near the BWCA boundary on the northeast where it appears to end due to faulting (Figure 14). It is characterized by sulfide mineralization and extreme heterogeneity of rock types. The Maturi shaft and Spruce Road pit of INCO are located in this contact zone unit (see map, Figure

16, showing sites of mineral processing samples). The various rock types include dunite, picrite, troctolite, anorthositic troctolite, troctolitic anorthosite, norite, gabbro pegmatite, and gabbro. Various types of hornfels and Biwabik-type iron formation commonly occur as inclusions in this unit. These inclusions were described in an earlier section.

Gossan, a brown-stained, pitted rock from the oxidation and dissolution of sulfide minerals, is fairly common in the contact zone and is indicative of sulfide mineralization. The sulfide minerals most commonly present are pyrrhotite, chalcopyrite, cubanite, and pentlandite. Minor sulfide phases include bornite, sphalerite and pyrite as well as other sulfide minerals present only in trace amounts. These mineral phases will 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.

Contact Zone Gabbro: Bonnichsen (1970) has mapped a unit of gabbro with sparse sulfide mineralization along the base of the Duluth Complex south of Birch Lake. It consists of fine-to medium-grained gabbro, norite and troctolite, with variable quantities of olivine and oxide minerals. Hornfels inclusions are common throughout the unit and are especially abundant in the subsurface. The Erie Mining Company's Dunka Pit is located adjacent to this unit. Both contact zones are shown on Figure 14 with the same pattern.

Troctolite: This is the most extensively exposed unit of the South Kawishiwi intrusion. It is bounded on the east and northeast 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. The troctolite has an average compositional range of 65 to 85% plagioclase (An_{57-60}), 8 to 30% olivine (Fo_{50-55}), and minor amounts of pyroxene (1 to 6%), oxides (1 to 8%), and biotite (1 to 3%). The troctolite is very homogeneous in appearance with plagioclase and olivine the only primary or cumulus minerals.

Anorthosite: Exposures of anorthosite are scattered throughout the troctolitic rocks in the Gabbro Lake quadrangle and the surrounding area. In general, they all have more than 90% plagioclase and are presumed to represent plagioclase-rich segregations within troctolite.

Low Augite Troctolite: Southeast of the troctolite 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 average range in composition of the layered troctolite is 65 to 85% plagioclase (An_{57-67}), 10 to 35% olivine (Fo_{55-62}), and minor amounts of pyroxene (0 to 2%), oxides (0 to 4%), and zero to trace amounts of biotite. 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.

The Railroad troctolite (Figure 14) 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 2 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 and gabbro located in the southeast quarter of the Gabbro Lake and in the northeast quarter of the Greenwood Lake quadrangle (Figure 14). Medium to coarse-grained foliated troctolite is either in direct contact with or separated by one to 10-m wide covered areas from anorthositic series rocks along the western, northern, and eastern sides of the intrusion. Olivine and plagioclase are the main cumulus minerals present. The average composition is 57% plagioclase (An_{62-81}) and 34% olivine (Fo_{71-74}) with clinopyroxene and opaques present in minor amounts.

The gabbro in the northern part of the Bald Eagle intrusion is completely surrounded by troctolite. The average composition is 42% plagioclase (An_{57-67}), 46% clinopyroxene, and 10% olivine (Fo_{61-61}). Orthopyroxene, oxides, and biotite are present in trace amounts. 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.

The Partridge River troctolite (Figure 14) was informally named by Bonnichsen (1974) to designate troctolitic rocks near Hoyt Lakes and south of the Reserve Mining Company operation. 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 and part of the South Kawishiwi intrusion. 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. The contact zone is also characterized by sulfide mineralization similar to that found in the contact unit of the South Kawishiwi intrusion, but the mineralization appears to be present over a wider stratigraphic interval. Both AMAX and U.S. Steel have holdings in this unit.

The Powerline gabbro (Figure 14) 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. It is a coarse-grained olivine gabbro containing abundant apatite. The magnetite content is relatively high and the augite is characterized by abundant opaque inclusions.

Cross-cutting diabasic rocks are found widely scattered throughout the Duluth Complex in the Hoyt Lakes-Kawishiwi area. They consist mainly of basalt or diabase dikes which vary in width from less than 30 cm up to a meter and appear to be vertical. They cut both the troctolitic-gabbroic and the anorthositic rock series. These dikes are relatively small in width and so are not shown on Figure 14.

The geologic relationships summarized above show that in broad terms the Duluth Complex consists of a central cap of anorthositic series rocks underlain and surrounded by troctolitic-gabbroic rocks. Minor peridotite bodies are found at the base of the complex and irregular masses of felsic rocks sporadically intrude the anorthositic and troctolitic-gabbroic rocks, particularly along a north-northeast-trending linear zone in the upper part of the complex. Weiblen and Morey's (1975) petrologic analysis of the Duluth Complex shows that it may be viewed as a series of older rocks (peridotite, anorthositic series, and granophyre) intruded by a series of younger (troctolitic-gabbroic series) rocks. These younger rocks are the ones in which the primary Cu-Ni mineralization occurs. The introduction of sulfur into the troctolitic-gabbroic series magma played a role in the origin of the Cu-Ni deposits as suggested by Weiblen and Perry (in preparation). The proposed origin for the sulfur is the footwall rocks (Virginia Formation and Biwabik Iron Formation). The Giants Range granite is considered to be a very minor source for sulfur.

1.4.2 Structure and Engineering Properties

The structural and engineering properties of importance in considerations of mining in the mineralized portion of the Duluth Complex are listed in Table 14.

Table 14

Table 14. Important structural and engineering properties.

Faults

Joints

Dip

Contact undulations

Rock competence

Density

Faults and joints are geologic features. Faults are a surface or zone of rock fracture along which there has been displacement whereas joints are a potential surface or zone of faulting.

Only a few faults (Figure 4, given earlier) have been inferred to be present in the Study Area previous to work by Morey and Cooper (1977) and Cooper (1978a). 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 the 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 main study concerning the structure of the Duluth Complex in the Study Area has been done by Cooper (1978a) who examined various structural features. The dominant features were foliation and/or modal layering, joints, and faults. From the joint data Cooper 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 foliation and the basal contacts of the bodies. Following this all of the Duluth Complex underwent a period of extensive faulting. During the faulting, joint sets developed parallel to the faults and a third set (commonly sheared) developed trending N.15-20 degrees W. It was also observed that the density of fractures or joints increases near the mapped and inferred faults. Cooper 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.

Faults and joints contribute to the permeability of the bedrock for water movement. Present data is scarce, but indicates that there is a relatively limited areal extent of fractures and other secondary permeability with a consequent minimal discharge from bedrock aquifers. Highly mineralized water has been encountered during exploration drilling in the Duluth Gabbro Complex, indicating that water locally is trapped in small, deep-seated fracture systems (see Volume 3-Chapter 4). A great deal of flow from such occurrences is not expected, but it must be realized that very limited data is available on such situations.

Directly related to faults and jointing is rock competence. Deere et al. (1967) originated the measurement of rock competence known as Rock Quality Designation (RQD). RQD is the percentage of unweathered core greater than 10 cm (4 in.) in length in a designated distance of drilling, usually the length of the core barrel, 150 cm (5 ft) or 305 cm (10 ft). The RQD varies between 0 and 100 with the larger number indicating more competent rock.

The data shown in Table 15 was calculated for AMAX drill holes by modifying Deere's system slightly. The resulting RQD's are lower than those obtained by an exact use of Deere's method, but the reduction is minor and can be ignored.

Table 15

Hole 229 has a down-hole extent of 681 m (2,235 ft) and the minimum and maximum RQD values are 72.90 and 86.00, respectively. This indicates that the down hole variation of RQD is small. The variation was similarly small for each of the 9 holes from the AMAX area. From Table 15, 82 can be considered the average RQD for the AMAX area. This RQD may be a little low and the rock may be slightly more competent than indicated, but rock with an RQD of 82 would be classified as

Table 15. Average RQD for 9 AMAX holes.

DRILL HOLE NUMBER[a]	MEAN	STANDARD DEVIATION
245	83.49	9.47
219	81.67	11.11
227	81.10	13.65
236	81.03	11.97
238	82.09	9.87
257	83.06	9.05
247	81.26	11.12
229	80.15	9.90
226	82.25	9.91
Total	81.78	1.07

[a] Holes are located in the AMAX area and are presented as generally representative of Duluth Complex material. Specific localized areas may vary significantly from the mean RQD given here.

good (Table 16). The implications of rock strength for the applicability of various types of mining methods is treated briefly in Volume 2-Chapter 2.

Table 16

It is expected that relatively minimal ground support will be required in underground mining because the RQD of the Duluth Complex is high. Correspondingly, rock of this high degree of competence is not likely to be amenable to underground mining by caving techniques.

Dip is a measure of the slope of a surface. If the dip of a contact, such as between the Duluth Complex and the underlying Virginia Formation, varies, then the contact is said to undulate. Estimates on the range and average of the dip of the contact between the Duluth Complex and the footwall rocks by the MDNR (Listerud and Meineke 1977) give a range of 20 to 35° and an average of 25°. The near-surface dip of the footwall contact does not generally exceed 30°. Thus, the dip will probably not limit the steepness of the footwall side of an open pit mine, since the Duluth Complex could probably hold a slope greater than 45°.

An example of the undulations of the base of the Duluth Complex is shown in Figure 15 (from Listerud and Meineke 1977). Also note in Figure 15 that the contact between the Virginia Formation and the Biwabik Iron Formation appears uniform and free of large undulations, but the contact between the Biwabik Iron Formation and the Duluth Complex is not. Undulations in the base or contact zone of the Duluth Complex will have an effect on mining procedures (see Volume 2-Chapter 2). Because the base of the Complex is mineralized and the underlying footwall rocks generally are not, the planning of the mining scheme has to take

Table 16. Modified core recovery as an index of rock quality.

RQD (%)	Description of Rock Quality
0-25	Very Poor
25-50	Poor
50-75	Fair
75-90	Good
90-100	Excellent

into account the local undulations of the footwall-gabbro contact. Thus, for example, blasthole open stoping methods may be used in areas where the contact dip is at its maximum, and room-and-pillar techniques might be used in the flatter areas.

Figure 15

The range of calculated rock densities (based on MGS values) is from 3.01 to 3.27gm/cc. The average for a set of 10 process samples (see the next section) is 3.11 gm/cc. Using this value, one metric ton of Duluth gabbro takes up a cube of 68.5 cm (27 in.) on a side. The density of the gabbro is relatively high and therefore the tailing material will have a relatively high density. This in turn will have to be considered when planning tailing disposal systems.

The gabbro material is relatively hard, comparable to taconite. For example, Bond Indices range from 15 to 20 kwH/mt of rock when ground sufficiently for concentration by flotation. The material may be of sufficient hardness and have suitable fracturing properties to allow autogenous grinding to be used (see Volume 2-Chapter 3 for more information on these properties).

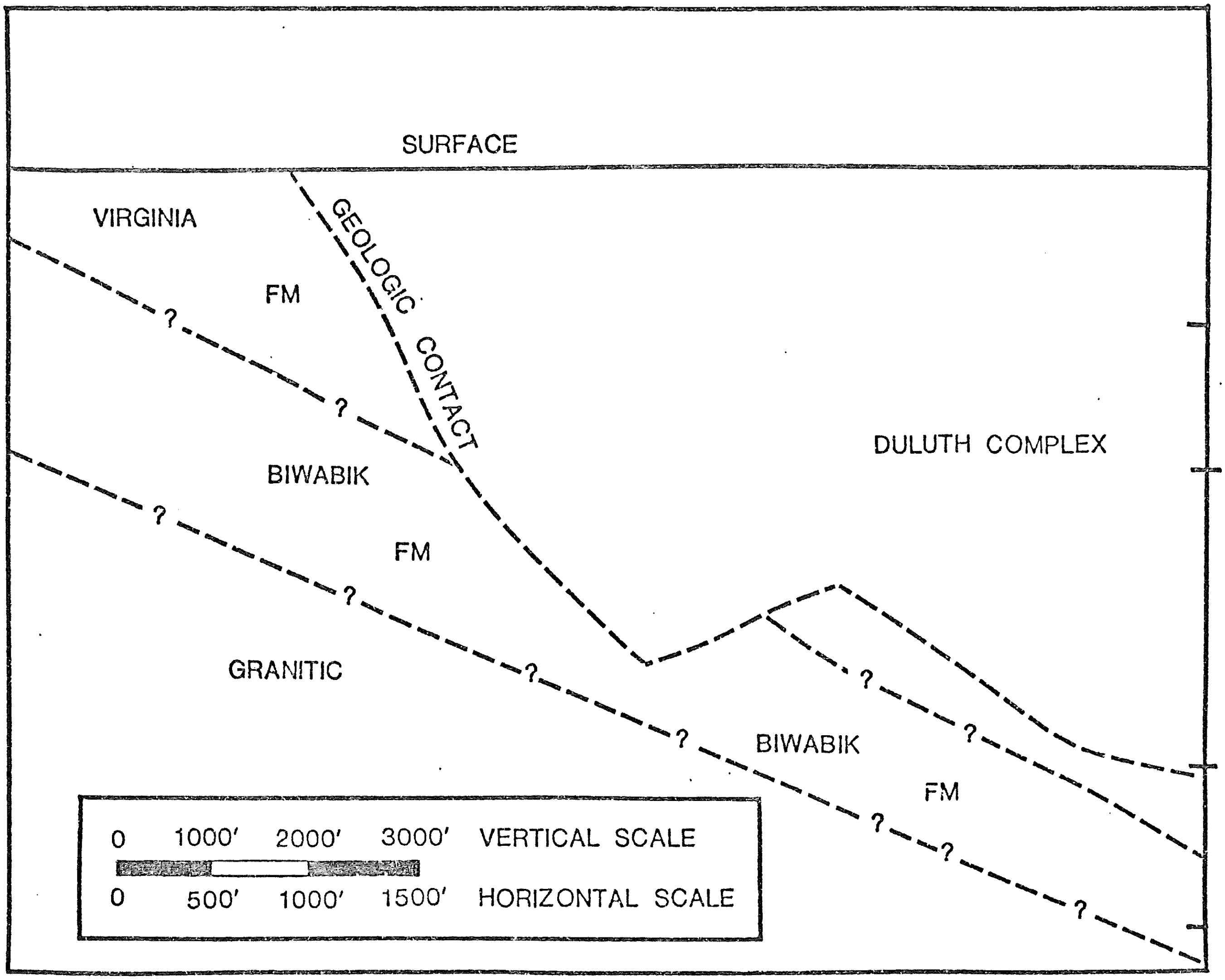
Although a large number of faults are present in the mineralization gabbro and surroundings rocks, only one earthquake out of a total of 7 in Minnesota recorded history has occurred in northeastern Minnesota.

1.4.3 Mineralogy and Chemistry

The mineralogy and the associated chemistry of the Duluth Complex, as presented here, is based on previous work (i.e. Weiblen and Morey, 1976), information available from mining companies and the literature, and work carried out under

FIGURE 15

GEOLOGICAL CROSS-SECTION OF THE DULUTH COMPLEX



SOURCE: LISTERUD AND MEIEKE, 1977

the direction of the Copper-Nickel Study. Work performed under the direction of the Copper-Nickel Study included data obtained from 91 samples selected from 9 drill cores located along the contact (discussed later), and a resource estimate study carried out by the Minerals Division of MDNR (Listerud and Meineke 1977). However, the bulk of the information to be presented here was obtained from a set of larger samples, typically several hundred pounds, collected from the Study Area for mineral processing tests at the MRRC (Iwasaki et al. 1978). Ten samples of rock from the base of the Duluth Complex were collected, 8 by the MDNR, and 2 by mining company staff. Two additional samples were taken from the archives of the MRRC at the University. The samples and their designations are given in Table 17, and their locations are shown in Figure 16 (refer to Figure 14 for geology of sample locations shown in Figure 16). All of the samples were collected with the permission and cooperation of the mining companies having interests in the various sample sites.

Table 17, Figure 16

Two samples shown in Table 17 came directly from AMAX (AX9006 and AX9007) and were not characterized by the MGS for mineralogy, as were the other samples. Sample DP9001 was not characterized chemically.

The mineralogy of the Study Area gabbroic rocks can be broken into 2 main constituent groups. The first group, sulfides, is split from the second group of minerals, nonsulfides or gangue, by the fact that the sulfides contain the Cu and Ni of potential commercial interest. For the purposes of the discussion here, the presence of sulfide minerals in the Duluth Gabbro is termed "mineralization".

1.4.3.1 Sulfide Mineralogy--Generally, gabbroic rocks can be classified for the purpose of examining mining potential, according to their sulfide mineral con-

Table 17. Description of Duluth Gabbro samples for mineral processing studies.

IP9002: A sample from INCO's Spruce Road test pit site

IP9003: A sample from INCO's Maturi shaft, from depths of 798 ft to 905 ft

DP9001: Unmineralized gabbro sample (from a stockpile) of gabbro outcroppings at Erie's Dunka Pit

DP9002: Mineralized gabbro sample (from a stockpile) of gabbro outcroppings at Erie's Dunka Pit

AX9001: Minnamax field leach test pad (FL-1) sample of lean ore

AX9002: AMAX shaft composite sample from depths of 1,249 ft and 1,312 ft below the surface

AX9003: AMAX shaft composite sample from depth of 1,338 ft and 1,343 ft below the surface

AX9004: AMAX semi-massive, mineralized rock sample from an underground exploration drift

AX9005: AMAX mineralized rock sample (from MRRC bulk sample No. 2) from an underground exploration drift

AX9006: AMAX semi-massive, mineralized rock sample from an underground exploration drift

AX9007: AMAX semi-massive, mineralized rock sample from an underground exploration drift

US9001: Mineralized gabbro sample from the U.S. Steel Research Center open pit bulk sample site

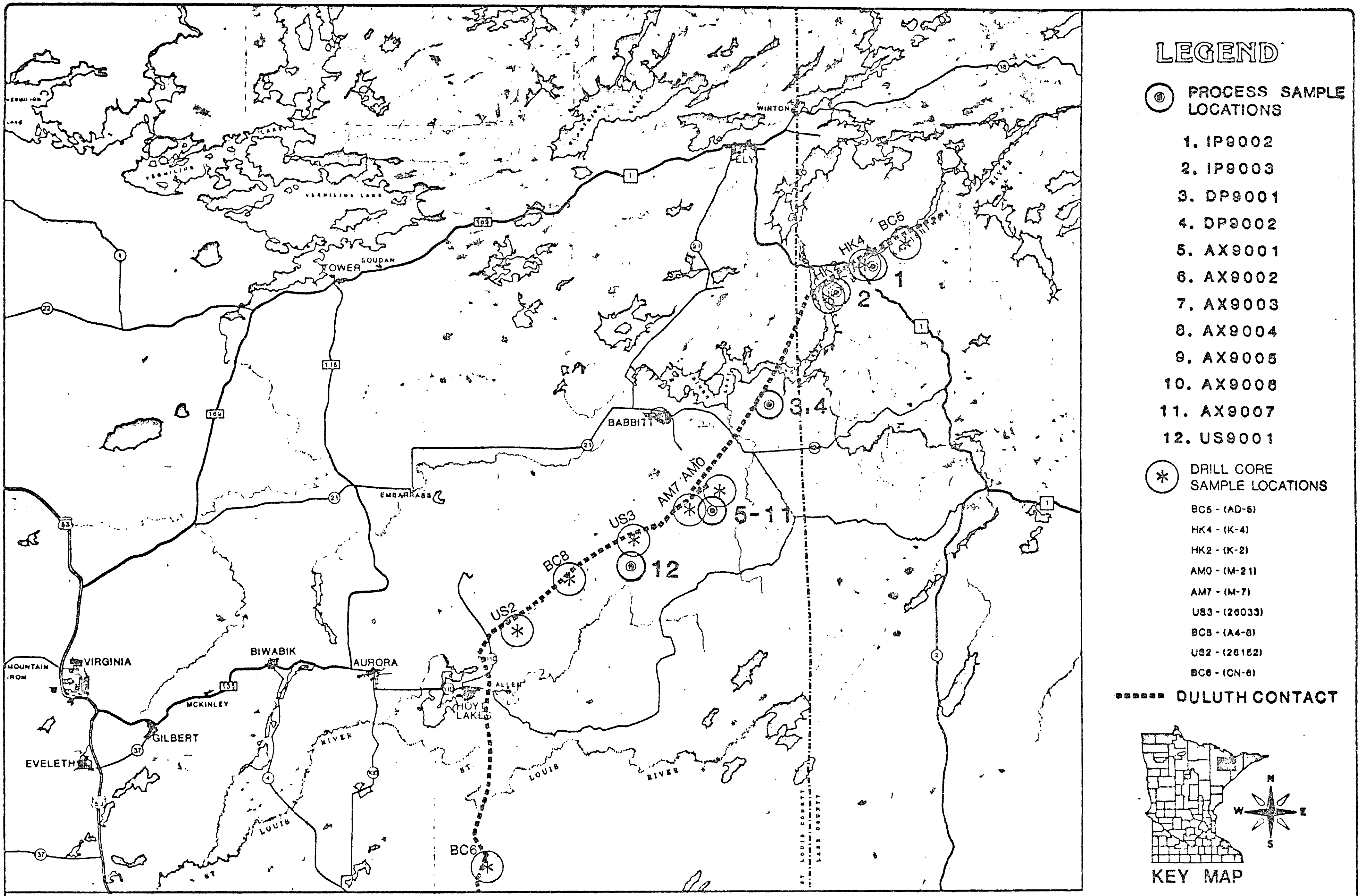


FIGURE 16

MEQB REGIONAL COPPER-NICKEL STUDY

MINERAL PROCESSING SAMPLE AND DRILL CORE LOCATIONS tent. Since the focus of interest on the part of the mining industry is not specifically on the sulfide mineral content per se, but rather on copper and nickel in the sulfide minerals of the gabbroic rocks, the most useful classification is based on the metal contents. The copper content typically exceeds the nickel content by a factor ranging from 1.5 to 4. Thus, the classification is simplified by referring to copper content alone. Table 18 indicates the general classifications into which a gabbroic rock can be placed, based solely on the copper content typifying each classification. The copper contents shown are based on mining company projected values and on Copper-Nickel Study projection work. The actual end points of the ranges shown or implied by the typical values given in Table 18 are dependent on other factors in addition to geology (e.g. economics, engineering, etc.).

Table 18

The classifications in Table 18 are those which would be used by a mining company to indicate whether or not a particular unit of rock can be mined for economic recovery of its metal content. Thus, the specific lower limits of grade for each classification depends on factors such as the size, shape, and depth of the material being considered. Nevertheless, the groupings shown in Table 18 reflect those of interest for the purposes of this study. It should be noted that since essentially all the copper and nickel contained in the gabbroic rocks are present in the form of sulfide minerals, there is a general correlation between content of these metals and sulfur content. However, sulfides can be present without the corresponding presence of copper or nickel, in the form of iron sulfides. Thus, the use of sulfur content alone does not assure a meaningful classification of gabbroic material for mining purposes. This will be discussed in more detail later in the report.

Table 18. Gabbro classifications in terms of copper content[a].

CLASSIFICATION	TYPICAL GRADES OF COPPER CONTENT (% by weight)
Waste rock	0.1
Lean ore	0.3
Disseminated ore	0.45--0.85
Semi-massive ore	greater than 1.0

[a] The specific values shown are examples of typical copper contents from data available to the Regional Study. In an actual operation, specific values may differ due to local conditions.

The origin of the copper-nickel sulfides is closely related to the emplacement and cooling history of the troctolitic-gabbroic rocks in the Duluth Complex. Troctolitic material containing copper and nickel is thought to have been emplaced around the periphery of the complex (Figure 14) in contact with pyrite-bearing, argillaceous country rock. As the magma cooled, plagioclase and olivine crystallized and formed a framework of cumulate grains. The remaining interstitial liquid was rich in copper and nickel but poor in sulfur. Weiblen and Perry (in preparation) suggest that sulfur was released from the country rock itself or from inclusions of the country rock by the reaction:

pyrite → pyrrhotite + sulfur

This sulfur reacted with the copper and nickel to form nickel-rich pentlandite and copper-rich cubanite and chalcopyrite. Local enrichments of copper- and nickel-bearing sulfides appear to have formed where rift-related faults facilitated passage of sulfurous emanations into the troctolitic magma and where inclusions of argillaceous material were particularly abundant. In the latter case, the sulfides occur as halos around the inclusions.

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. As part of the Regional Study, Listerud and Meineke (1977) compiled all data obtained by the MDNR from various mining companies and outlined all known areas with drill core with significant concentrations of copper-bearing sulfides (see section 2.2.1). Figure 17 shows the location of these areas, within a 6-mi wide band composed of a set of development zones. The development zones were defined for the convenience of the Regional Study to provide a framework to facilitate the discussion of possible environmental impacts (see section 2.1.1 of this report, as well as the terrestrial biology report, Volume 4-Chapter 2, for further discussion of these zones). The polygon areas are of economic interest because of the grade and the occurrence of the sulfides either near the present topographic surface or in bands of significant thickness. Areas with less than 0.25% Cu are shown as non-mineralized polygons as it was felt that at present they are not of economic interest.

Figure 17

Locally, thin semi-massive areas of copper-nickel mineralization are found. Because these areas are only present locally and their occurrence is sporadic, it is not expected that they will be able to support a mining operation. 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 (1972), Boucher (1975), and Weiblen and Morey (1976) have described in detail the texture and mineralogy of the sulfides. 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 include covellite, digenite, chalcocite, tenorite, cuprite, native copper, and galena. Table 19 is a list of these sulfides and their ideal formulas. The composition of the 4 main sulfide minerals are tabulated in Table 20 (Weiblen and Morey, 1976). It should be noted that these results are based on electron microprobe analyses with more than one analysis point per sample.

Tables 19 & 20

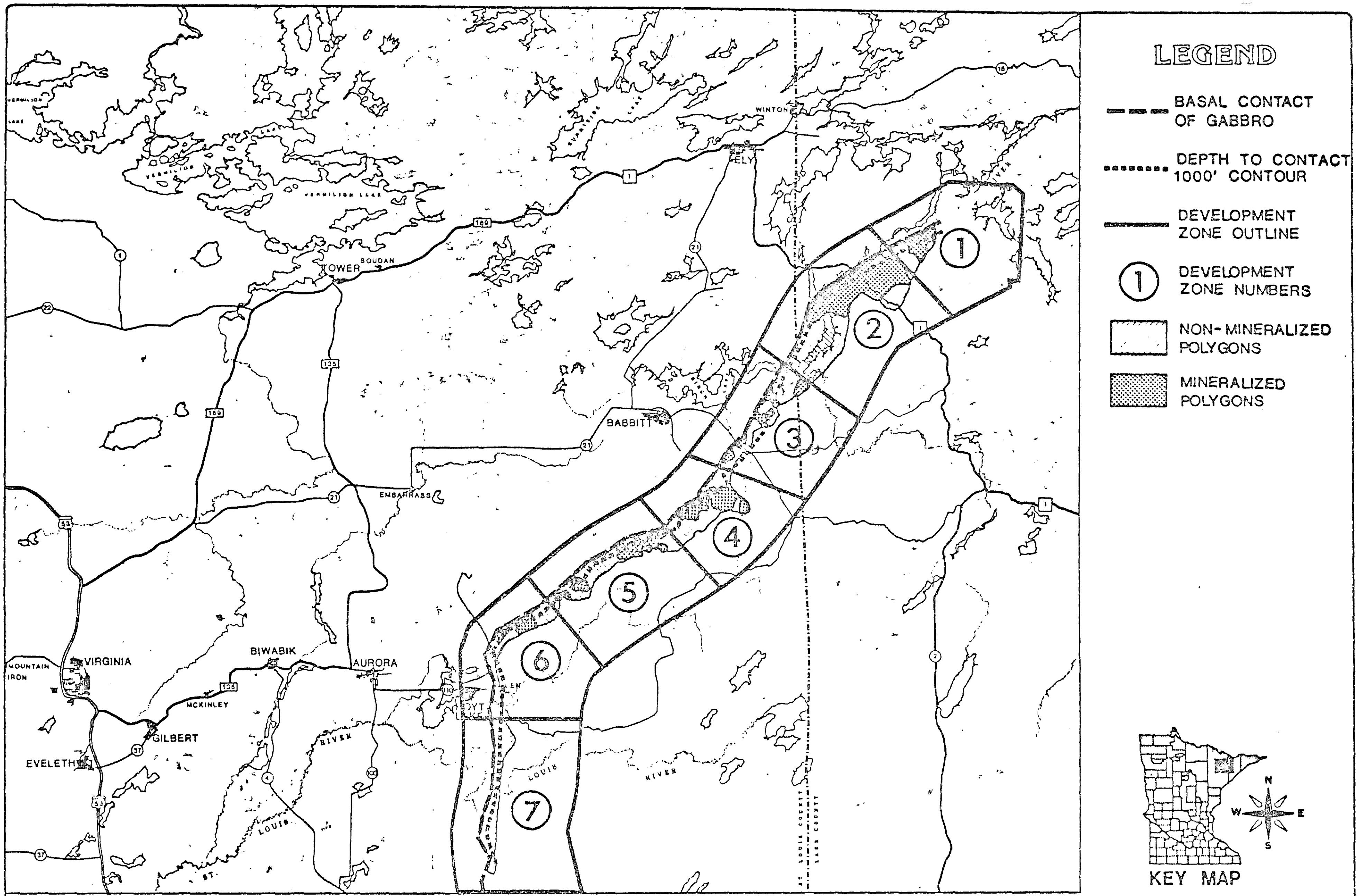


FIGURE 17

MEQB REGIONAL COPPER-NICKEL STUDY

MDNR MINERALIZED & NON-MINERALIZED POLYGON DISTRIBUTION

Table 19. Various sulfide minerals.

MINERAL	IDEAL FORMULA
Pyrrhotite	$Fe_{1-x}S$ (where X=0 to 0.2)
Chalcopyrite	$CuFeS_2$
Cubanite	$CuFe_2S_3$
Pentlandite	$(Fe,Ni)_9S_8$
Violarite	Ni_2FeS_4
Mackinawite	$(Fe,Ni)_{1.1}S$
Pyrite	FeS_2
Sphalerite	$(Zn,Fe)S$
Bornite	Cu_5FeS_4
Covellite	CuS
Digenite	Cu_9S_5
Chalcocite	Cu_2S
Tenorite	CuO
Cuprite	Cu_2O
Native Copper	Cu
Galena	PbS

SOURCE: Gary et al. 1974.

Table 20. Sulfide mineral composition (% by weight).

	Pentlandite	Pyrrhotite	Chalcopyrite	Cubanite
S	33.23	39.52	32.87	37.53
Cu	0	0.01	35.73	22.32
Ni	34.52	0.24	0.06	0.06
Fe	30.42	60.19	31.26	40.09
Co	1.82	0.03	0.08	0

SOURCE: Weiblen and Morey 1976.

The 10 mineral processing samples described earlier were selected to be representative of the material that might be mined in an operation based in the Duluth Gabbro. The samples were chosen with the help of the MDNR and were macroscopically and chemically (on the basis of elemental Cu, Ni, Fe, and S) similar to material that area mining companies have projected as mineable material. The samples are discussed in some detail below, as they may represent various classifications of mineralized material: waste rock, lean ore, disseminated ore, and semi-massive ore. Since the use of the term "ore" normally implies that the valuable metals contained in the rock can be recovered at a profit, it must be stressed that the term is used here assuming that future metal market prices will indicate that mining can proceed profitably. See section 2.1.2 for a further discussion of this point.

All samples, except IP9002 and IP9003 (taken from MRRC archives), were uniformally sampled from rock piles of over 90 mt. Sample DP9001 is representative of unmineralized gabbro (waste rock) from the Dunka Pit area (see Figure 16). AX90001 is an example of lean ore. Samples US9001, AX9002, AX9003, AX9005, IP9002, and IP9003 represent disseminated ore, whereas DP9002 and AX9004 represent semi-massive ore. The distinction between these last 2 types of ore will be shown in the following sections.

Table 21 is a summary of the mineralogy of the samples. The MGS determined the volume percent composition (as an arithmetic mean) from thin-section work. Figure 18 is a boxplot diagram of the results in Table 21. Boxplot diagrams show the distribution of values from specific thin sections, including the minimum, 25th percentile, median, 75th percentile, and maximum values. The box itself is drawn at the 25th and 75th percentile and the line inside the box is the median. In some instances, no line appears within the box, or no box appears, indicating that the median coincides with one or both of the quartile values, or one or both of the extremes, respectively. The minerals, their abbreviations and ideal chemical formulas are shown in Table 22.

Table 21, Figure 18, Table 22

Figure 19 is a boxplot of shows the volume percent distribution of total sulfides (cubanite, chalcopyrite, pyrrhotite, and pentlandite) for the 10 samples analyzed by MGS. The 10 sample numbers are shown on the bottom of the diagram with the number of thin sections analyzed given below them. The samples are arranged such that the unmineralized material (DP9001) is on the left and the semi-massive ores (DP9002 and AX9004) are on the right. The lean ore sample (AX9001) has more total sulfides than the unmineralized sample (DP9001) but generally less than the disseminated samples (US9001 thru IP9002). As can be seen from the diagram, the semi-massive samples (DP9002 and AX9004) do have a higher sulfide content. This is one of the criteria for calling a particular sample, "semi-massive". Other criteria will be discussed later.

Figure 19

Figure 20 shows the combined volume percent for chalcopyrite and cubanite, for the 10 MGS samples. Chalcopyrite and cubanite are the principal Cu-bearing sulfides in the Duluth Gabbro and so are the primary source of Cu in the rock. The low amount in DP9001 is expected for an unmineralized sample. While all 10 samples have at least one thin section with no chalcopyrite and cubanite present, some thin sections have over 12% (AX9005). This points out the local (within one meter) variability of the gabbro material.

Figure 20

Table 21. Mean mineralogical composition of test samples (volume percent).

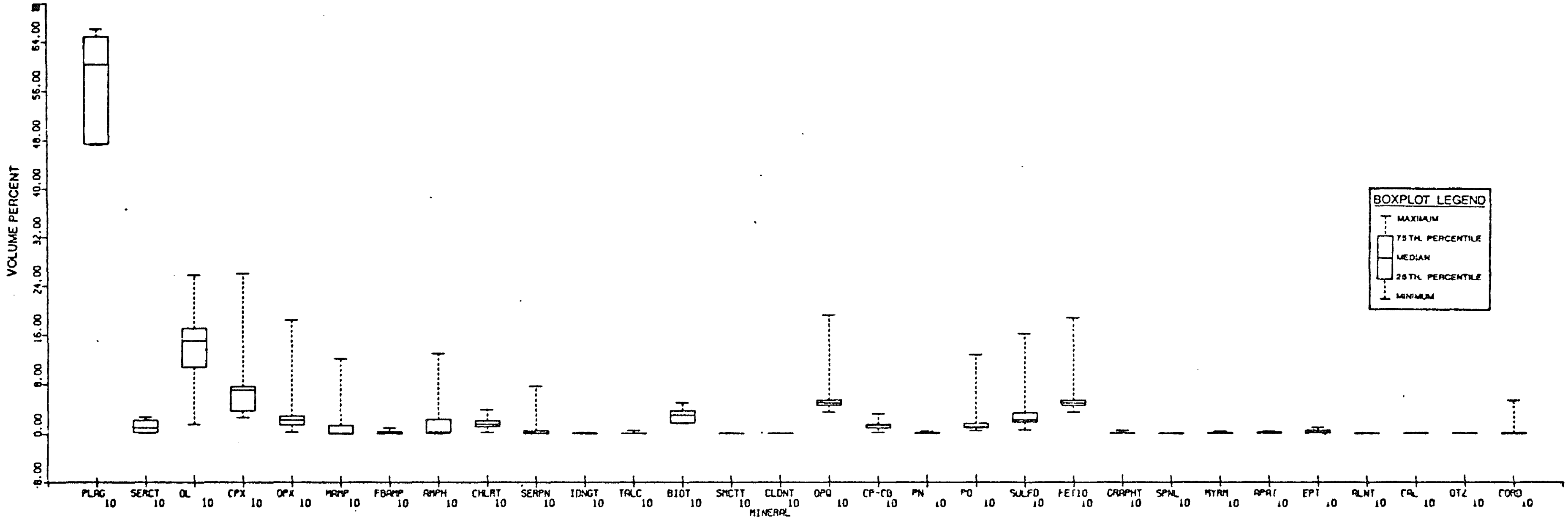
GABBRO CLASSIFICATION	"WASTE ROCK"	"LEAN ORE"	"DISSEMINATED ORE"							"SEMI-MASSIVE ORE"	
	DP9001	AX9001	US9001	AX9002	AX9003	AX9005	IP9002	IP9003	Average	DP9002	AX9004
Plagioclase	64.041	59.112	64.881	61.457	47.363	47.403	65.443	66.166	58.786	47.242	47.855
Sericite	1.569	2.176	0.188	2.518	1.911	0.245	2.683	0.373	1.320	0.069	0.091
Olivine	13.996	10.510	16.173	13.586	18.267	25.841	16.308	17.123	17.883	10.766	1.513
Clinopyroxene	7.604	11.185	7.237	6.809	5.024	7.622	3.723	3.717	5.689	26.102	2.656
Orthopyroxene	2.763	3.716	1.834	2.882	1.407	2.132	0.231	0.618	1.517	2.315	18.472
Monocrystalline amphibole	0.054	3.567	--[b]	0.095	12.225	0.066	1.387	1.055	2.471	--	0.025
Fibrous amphibole	0.005	0.288	--	0.335	0.850	--	0.934	0.077	0.366	--	0.024
Chlorite	1.696	1.136	1.349	1.950	3.887	1.337	2.078	2.612	2.202	0.403	0.145
Serpentine	0.016	0.257	0.097	0.441	0.033	7.659	0.731	0.026	1.498	0.014	--
Iddingsite	0.017	0.075	0.172	0.006	0.019	0.194	0.079	0.064	0.090	0.053	--
Talc	--	--	--	--	--	0.006	0.061	0.463	0.087	--	--
Biotite	3.284	1.738	3.785	3.037	3.010	2.431	1.696	1.788	2.624	5.031	4.475
Smectite	--	0.021	0.051	0.030	0.053	--	0.025	0.026	0.031	--	--
Celadonite	0.014	--	--	--	--	--	--	--	--	--	--
Opaques[a]	4.565	5.098	4.025	4.776	5.190	4.720	3.474	5.365	4.592	7.923	19.239
Chalcopyrite-cubanite	0.133	0.769	0.875	0.962	1.458	1.355	1.403	1.778	1.305	1.341	3.231
Pentlandite	0.032	0.037	0.102	0.012	0.113	0.043	0.117	0.025	0.069	0.341	0.161
Pyrrhotite	0.403	0.844	0.882	1.093	1.105	0.497	0.953	1.571	1.017	3.073	12.816
Ilmenite-magnetite	3.995	3.447	2.164	2.694	2.510	2.885	0.998	1.989	2.197	3.143	2.564
Graphite	--	--	--	0.015	0.004	--	--	--	0.003	0.025	0.467
Spinel	--	--	--	0.009	--	--	--	--	0.001	--	--
Myrmekite	--	--	0.106	0.042	--	--	0.288	0.065	0.084	--	--
Apatite	0.182	0.085	0.075	0.149	0.172	0.346	0.050	0.013	0.134	0.074	0.118
Epidote	0.167	0.953	0.017	0.203	0.470	--	0.698	0.322	0.285	--	--
Allanite	--	--	--	0.090	--	--	0.007	0.051	0.025	--	--
Calcite	0.026	0.056	0.007	0.065	0.017	--	0.089	0.077	0.042	0.006	--
Quartz	--	--	--	--	--	--	--	--	--	--	0.037
Cordierite	--	0.027	--	1.515	0.106	--	0.013	--	0.272	--	5.350

[a] The value shown for opaques is the sum of the 5 following values; see the note on minerals in Table 22.

[b] -- means not detected or not present (0%).

FIGURE 18

MINERAL COMPOSITION BOXPLOT OF THE 10 PROCESS SAMPLES



SEE TABLE 22 FOR DEFINITION OF MINERAL ABBREVIATIONS

Table 22. Mineral names, abbreviations, and formulas.

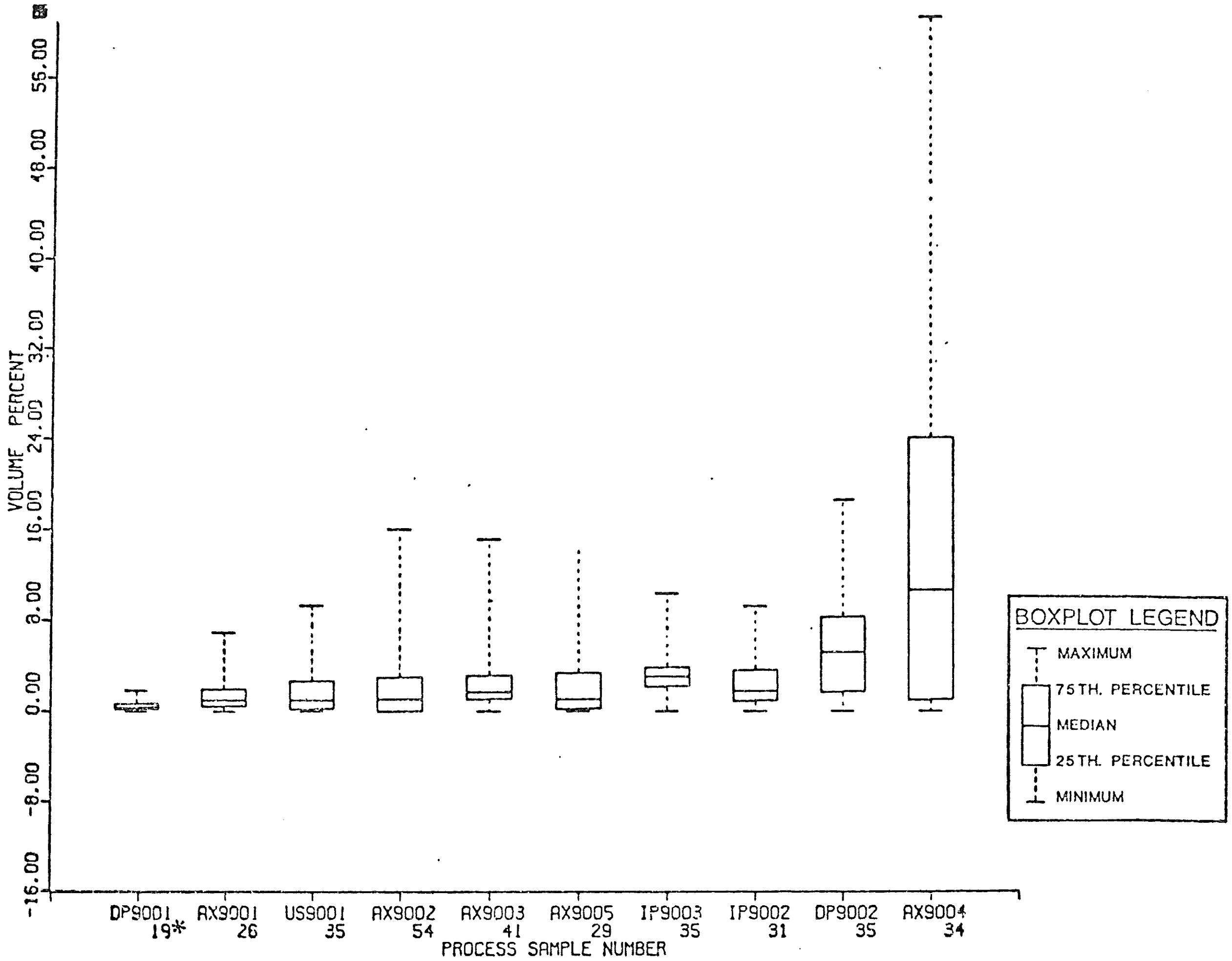
ABBREVIATION	MINERAL	CHEMICAL FORMULA	DESCRIPTION
PLAG	Plagioclase	$Na\ Al\ Si_3\ O_8 - Ca\ Al_2\ Si_2\ O_8$	a feldspar
SERCT	Sericite	$K_2\ Al_4\ Si_6\ Al_2\ O_{22}\ (OH, F)_4$	a mica, alters from feldspar
OL	Olivine	$(Fe, Mg)\ SiO_4$	Fe-Mg silicate
CPX	Clinopyroxene	$Ca\ (Fe, Mg)\ Si_2\ O_6$	a pyroxene, Fe-Mg silicate
OP	Orthopyroxene	$(Fe, Mg)_2\ Si_2\ O_6$	a pyroxene, Fe-Mg silicate
MAMP	Monocrystalline amphibole	$(Na, K)_{0-1}\ (Ca, Mg, Fe^{+2}, Fe^{+3}, Al)_7\ (Si_{6-8}\ Al_{2-0})\ O_{22}\ (OH, F, Cl)_2$	amphibole with non-acicular morphology
FBAMP	Fibrous amphibole	$(Na, K)_{0-1}\ (Ca, Mg, Fe^{+2}, Fe^{+3}, Al)_7\ (Si_{6-8}\ Al_{2-0})\ O_{22}\ (OH, F, Cl)_2$	amphibole with fibrous or acicular morphology
CHLRT	Chlorite	$(Mg, Fe, Al)_{12}\ (Si, Al)_8\ O_{20}\ (OH)_{16}$	alters from Fe-Mg silicates
SERPN	Serpentine	$Mg_3\ Si_2\ O_5\ (OH)_4$	alters from Fe-Mg silicates
IDNGT	Iddingsite	Serpentine + iron oxide phase	alters from olivine
TALC	Talc	$Mg_6\ Si_8\ O_{20}\ (OH)_4$	alters from Fe-Mg silicates
BIOT	Biotite	$K_2\ (Mg, Fe^{+2})_{6-4}\ (Fe^{+3}, Al, Ti)_{0-2}\ (Si_{6-5}\ Al_{2-3})\ O_{20}(OH, F)_4$	a mica
SMCTT	Smectite	$(1/2\ Ca, Na)_{0.7}\ (Al, Mg, Fe)_4\ (Si, Al)_8\ O_{20}\ (OH)_4 \cdot nH_2O$	a clay, alters from feldspar
CLDNT	Celadonite	$K\ Mg\ Fe^{+3}\ Si_4\ O_{10}\ (OH)_2$	a mica, similar to glauconite

Table 22 continued.

ABBREVIATION	MINERAL	CHEMICAL FORMULA	DESCRIPTION
OPQ	Opaque minerals, sum of following seven minerals*		
CP-CB	*Chalcopyrite *Cubanite	$Cu\ Fe\ S_2$ $Cu\ Fe_2\ S_3$	undifferentiated
PN	*Pentlandite	$(Fe, Ni)_9\ S_8$	
PO	*Pyrrhotite	$Fe_7\ S_8 - Fe\ S$	
FETIO	*Ilmenite	$Fe\ Ti\ O_3$	
	*Magnetite	$Fe_3\ O_4$	contains appreciable
GRPHT	*Graphite	C	present as flakes
SPNL	Spinel	$Mg\ Al_2\ O_4$	
MYRM	Myrmekitic intergrowths, generally between plagioclase and olivine		
APAT	Apatite	$Ca_5\ (PO_4\ )_3\ (OH, F, Cl)$	
EPI	Epidote	$Ca\ Fe^{+3}\ Al_2\ Si_3\ O_{12}\ (OH)$	(includes zeolites and prehnite $(Ca_2\ Al\ Al\ Si_3\ O_{10}\ (OH)_2)$
ALNT	Allanite	$(Ca, Ce)_2\ (Fe,^{+2}\ Fe^{+3}$ $Al_2\ Si_3\ O_{12}\ :OH$	borders radiating epidote
CAL	Calcite	$Ca\ CO_3$	
QTZ	Quartz	$Si\ O_2$	
CORD	Cordierite	$Al_3\ (Mg, Fe^{+2}\ )_2\ Si_5\ Al\ O_{18}$	associated with hornfels

FIGURE 19

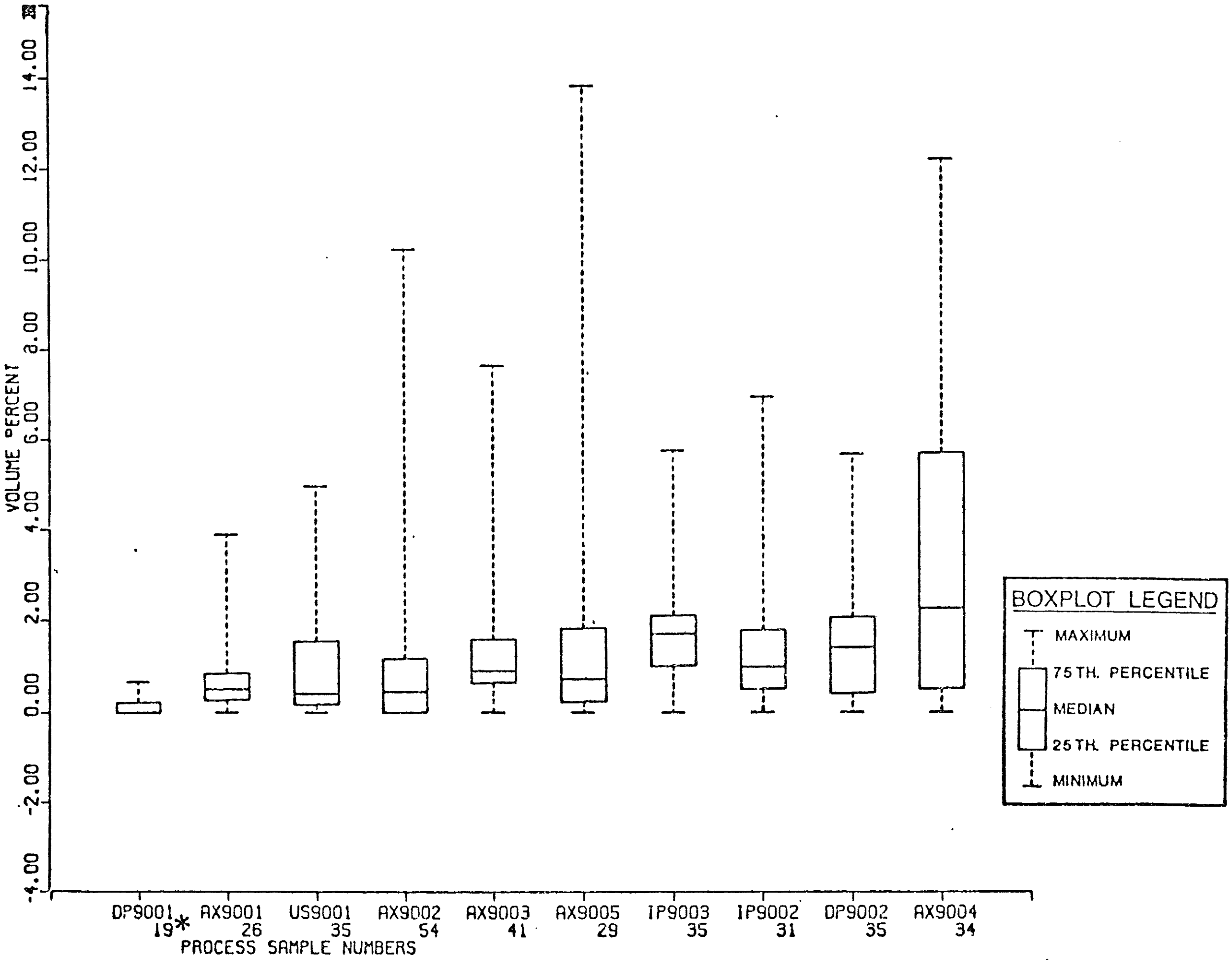
TOTAL SULFIDE MINERAL CONCENTRATION IN MINERAL PROCESSING SAMPLES



*NUMBER OF THIN SECTIONS ANALYZED

FIGURE 20

CHALCOPYRITE & CUBANITE : CONCENTRATION IN MINERAL PROCESSING SAMPLES



*NUMBER OF THIN SECTIONS ANALYZED

Of the 3 sulfide minerals, pentlandite (Figure 21) is present in the lowest amount. Pentlandite is the chief source of Ni in the rock. Cobalt is a minor element found in the pentlandite of the Duluth Complex rocks. Even though it is a minor element in the pentlandite, pentlandite is the major source of Co in the rock (Table 20). Drill hole sample DP9002 (a semi-massive sample) has the highest amount of pentlandite (5 times the disseminated average, Table 21) than any of the other samples.

Figure 21

Pyrrhotite volume percent is shown in Figure 22, pyrrhotite has no economic value. Samples DP9002 and AX9004 have the highest amount of pyrrhotite. Recall that these 2 samples also had elevated amounts of chalcopyrite-cubanite. The relatively high amounts of these 2 sulfide groups in the semi-massive material is what gives them the high total sulfide content (Figure 19).

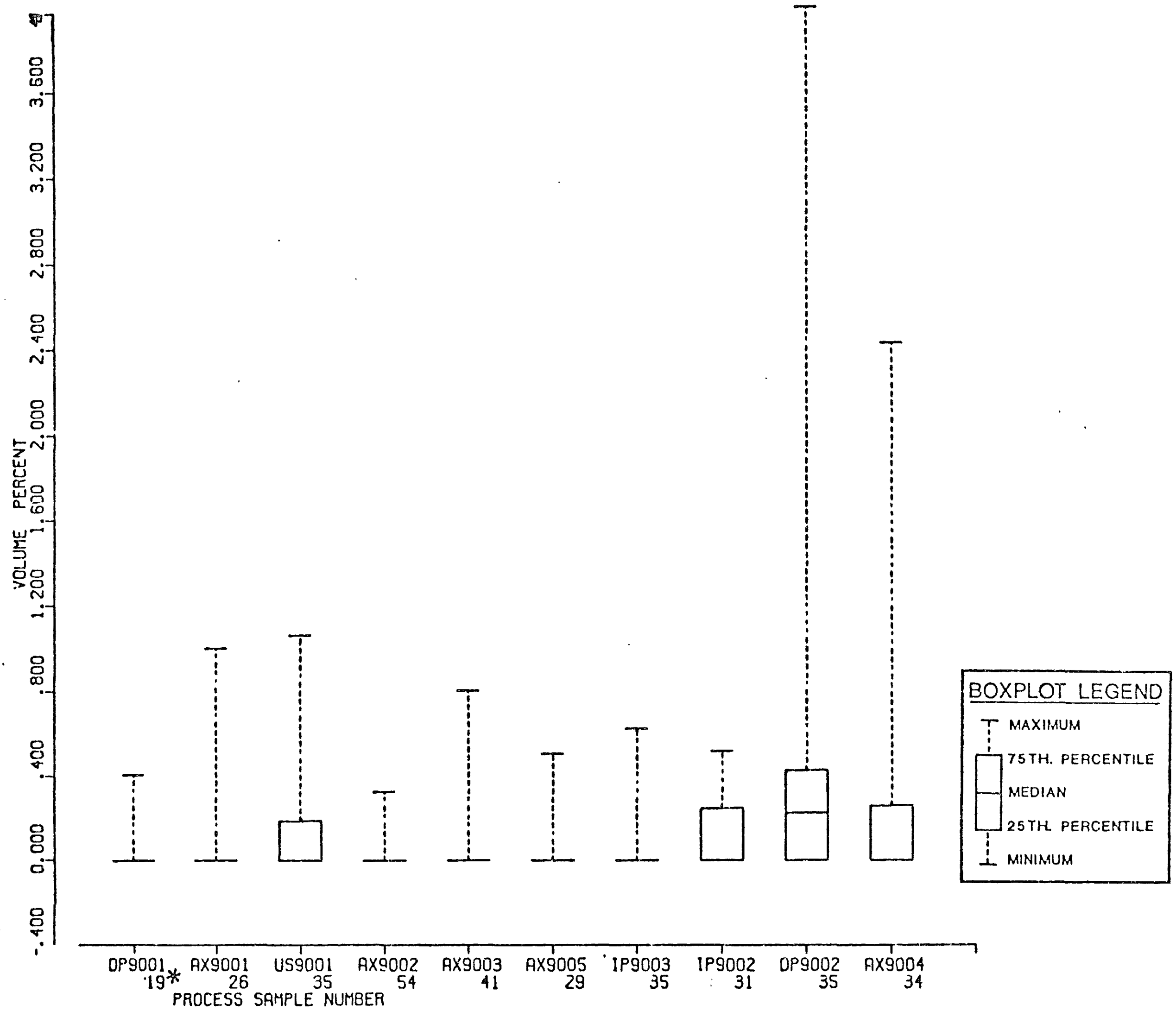
Figure 22

As was mentioned, semi-massive ore samples have a proportionally higher amount of sulfide than the other samples. This is of interest even though there is a relatively small amount of this type of ore present compared to the disseminated type. Processing of semi-massive ore will likely produce different proportions of elements that could be harmful to the environment as well as producing a greater amounts of Cu and Ni per unit of ore treated.

1.4.3.2 Sulfide Chemistry--The chemistry and elemental composition of a rock is a reflection of its mineral content. So for rocks high in sulfide minerals, the analysis shows a relatively high amount of sulfur. The sulfide chemistry of the

FIGURE 21

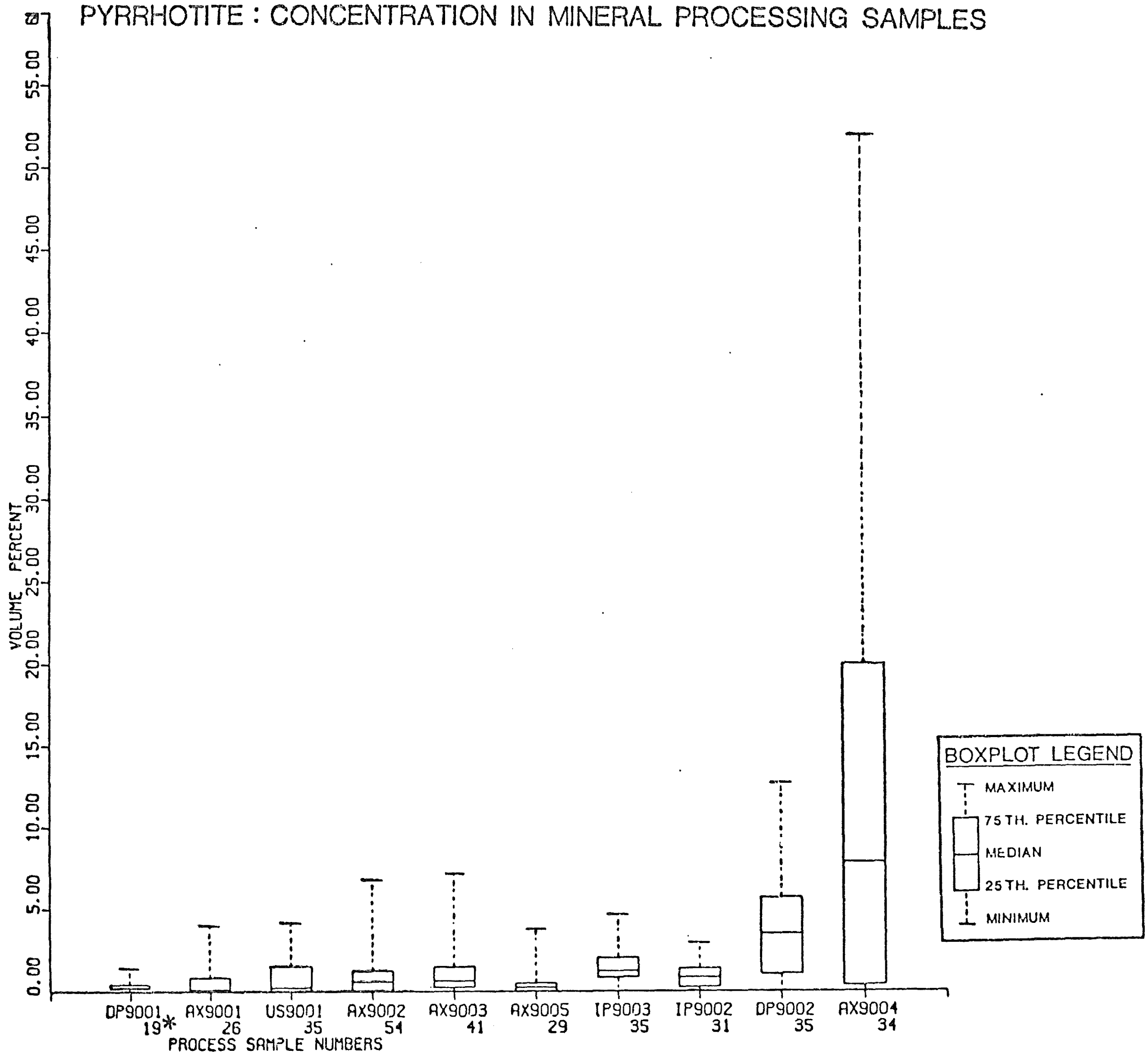
PENTLANDITE : CONCENTRATION IN MINERAL PROCESSING SAMPLES



*NUMBER OF THIN SECTIONS ANALYZED

FIGURE 22

PYRRHOTITE : CONCENTRATION IN MINERAL PROCESSING SAMPLES



*NUMBER OF THIN SECTIONS ANALYZED

rock is that portion of the chemistry that is related to sulfur and the sulfide minerals.

Table 23 is a compilation of the elemental and chemical analyses of the mineralized samples based on plasma emission spectrometry (Iwasaki et al. 1978), and thin section analysis. Elements with an affinity for sulfur, that is those which tend to combine with sulfur in minerals (i.e. iron and copper in chalcopyrite), are shown below sulfur (S) on Table 23. A table entry of -1 indicates that the particular element was not analyzed in that sample. Zero (0) indicates that the element was below the limit of detection for that element. The reported detection limits for the various elements in the analysis of a solid rock sample are shown in Table 24 (Iwasaki et al. 1978). The values in parentheses are the elemental amounts with their associated oxygen to balance the total weight to 100%.

Tables 23 & 24

Table 25 shows the disseminated average chemistry for the samples designated as disseminated (US9001 thru IP9002 of Table 23) and the semi-massive average chemistry for the samples designated as semi-massive (DP9002 thru AX9007 of Table 23). Also shown in Table 25 are the median values for 91 core analyses.

Table 25

The 91 core analyses were collected from 9 drill cores, taken from the locations shown on Figure 16. The 91 analyses are not considered to be accurate for P or Th so these elements are not shown in Figure 23. Figure 23 is a normalization plot of the core analysis data. The plotted numbers are the $\log_{10}$ of the ratio

Table 23. Mineralized sample chemistry.

SAMPLE	AX9001	US9001	AX9002	AX9003	AX9005	IP9003	UNITS[a]
ELEMENT							
Si(SiO_2)	22.80(48.81)	23.46(50.22)	22.37(47.90)	22.31(50.56)	22.31(47.77)	21.12(45.21)	PCT
Al(Al_2O_3)	8.98(16.96)	9.00(16.99)	8.99(16.98)	8.69(16.42)	7.88(14.89)	9.78(18.48)	PCT
Fe(Fe_0)	9.22(11.86)	7.83(10.07)	8.71(11.20)	8.64(11.11)	11.10(14.28)	8.57(11.02)	PCT
Mg(MgO)	4.31(7.15)	3.73(6.18)	4.65(7.70)	4.44(7.35)	4.11(6.81)	5.27(8.73)	PCT
Ca(CaO)	5.55(7.76)	5.84(8.17)	5.33(7.46)	4.77(6.67)	4.92(6.88)	5.73(8.02)	PCT
Na(Na_2O)	2.00(2.70)	2.20(2.97)	2.08(2.81)	1.77(2.39)	2.05(2.76)	2.50(3.37)	PCT
K(K_2O)	0.32(0.39)	0.31(0.37)	0.29(0.34)	0.38(0.45)	0.55(0.66)	0.44(0.49)	PCT
Ti(TiO_2)	1.41(2.35)	1.00(1.66)	1.21(2.02)	0.98(1.63)	1.19(1.99)	0.64(1.06)	PCT
P(P_2O_5)	0.02(0.05)	0.02(0.04)	0.04(0.08)	0.04(0.10)	0.08(0.19)	0.01(0.01)	PCT
Mn(MnO)	0.12(0.16)	0.11(0.14)	0.12(0.15)	0.11(0.14)	0.13(0.17)	0.16(0.20)	PCT
Cr(Cr_2O_3)	0.03(0.05)	0.03(0.05)	0.02(0.03)	0.03(0.04)	0.03(0.04)	0.05(0.08)	PCT
B	662.00	1030.00	157.00	218.00	0[b]	1278.00	PPM
Ba	1173.00	1003.00	253.00	310.00	1020.00	1234.00	PPM
Be	1.00	0.95	0	0.90	1.00	0.40	PPM
Sr	279.00	243.00	258.00	230.00	254.00	331.50	PPM
V	276.50	175.00	195.00	182.50	186.00	126.25	PPM
Th	6.40	1.50	14.00	0	3.90	2.55	PPM
Zr	80.00	118.25	78.00	70.75	130.00	149.50	PPM
S	0.655	1.160	0.990	1.145	1.340	1.215	PCT
Cu	0.306	0.330	0.583	0.592	0.723	0.625	PCT
Ni	0.073	0.086	0.124	0.122	0.140	0.174	PCT
Fe(S)	0.696	1.518	1.022	1.210	1.422	1.283	PCT
Co	0.009	0.010	0.012	0.011	0.014	0.012	PCT
Zn	157.00	133.00	169.00	194.50	111.00	84.75	PPM
Pb	0	0	31.00	0	0	0	PPM
Ag	1.35	0.63	2.75	2.25	3.60	1.80	PPM
As	0	0	0	0	0	0	PPM
Hg	-1[c]	0.060	0.090	-1	-1	-1	PPM
Mo	0.50	1.25	3.50	0	2.00	2.50	PPM
Cd	0	0	2.00	0	0	0	PPM

[a] PCT=weight percent
PPM=parts per million by weight

[b] 0 = below detection limits

[c] -1 = not analyzed

Table 23 continued.

SAMPLE	IP9002	DP9002	AX9004	AX9006	AX9007	UNITS[a]
ELEMENT						
SiO_2	21.40(45.81)	22.22(47.56)	18.15(38.85)	20.42(43.73)	23.31(49.90)	PCT
Al_2O_3	10.95(20.68)	7.15(13.51)	6.43(12.15)	7.71(14.56)	7.04(13.30)	PCT
Fe_O	7.30(9.38)	8.15(10.48)	7.71(9.92)	8.65(11.13)	10.12(13.02)	PCT
MgO	4.75(7.86)	3.47(5.74)	2.69(4.46)	3.24(5.37)	3.01(4.99)	PCT
CaO	6.56(9.18)	5.28(7.39)	3.44(4.81)	.75(1.05)	2.05(2.87)	PCT
Na_2O	2.48(3.34)	1.72(2.32)	1.18(1.59	.90(1.21)	1.26(1.70)	PCT
K_2O	0.17(0.20)	0.35(0.43)	0.73(0.88)	0.47(0.57)	0.55(0.66)	PCT
TiO_2	0.49(0.82)	1.56(2.61)	.65(1.08)	.63(1.04)	1.16(1.93)	PCT
P_2O_5	0.01(0.03)	0.02(0.04)	0.03(0.07)	0.03(0.07)	0.03(0.07)	PCT
MnO	0.11(0.14)	0.13(0.17)	0.11(0.14)	0.06(0.08)	0.11(0.14)	PCT
Cr_2O_3	0.03(0.04)	0.03(0.04)	0.04(0.06)	0.03(0.05)	0.03(0.04)	PCT
B	537.00	81.00	428.00	0[b]	0	PPM
Ba	426.00	231.00	310.00	480.00	547.00	PPM
Be	0	0.85	1.20	2.70	2.20	PPM
Sr	350.00	200.50	151.50	158.00	156.00	PPM
V	134.00	190.00	213.00	243.00	245.00	PPM
Th	11.00	0	0	5.90	7.70	PPM
Zr	30.00	122.00	59.50	47.10	87.80	PPM
S	0.925	3.880	10.500	7.480	4.250	PCT
Cu	0.413	0.782	1.155	6.030	3.430	PCT
Ni	0.105	0.178	0.418	0.462	0.214	PCT
Fe_S	1.038	4.848	13.885	7.133	3.472	PCT
Co	0.010	0.020	0.036	0.029	0.015	PCT
Zn	146.00	222.50	185.00	302.00	237.00	PPM
Pb	0	0	0	0	0	PPM
Ag	5.30	2.90	0	16.90	8.50	PPM
As	115.00	0	0	0	0	PPM
Hg	0.090	0.070	-1[c]	-1	-1	PPM
Mo	0	0	5.50	0	0	PPM
Cd	0	0	0	0	0	PPM

[a] PCT=percent by weight
PPM=parts per million by weight
[b] 0 = below detection limits
[c] -1 = not analyzed

Table 24. Reported detection limits for elemental analysis performed on mineral processing samples.[a]

Au	0.02	Ag	0.002	Mn	0.0005
Cd	0.07	Ti	0.001	Ba	0.034
Fe	0.004	As	0.14	Sr	0.0002
Ni	0.09	Co	0.016	Zr	0.0014
Si	0.006	Mg	0.008	Ca	0.025
Zn	0.019	K	1.0	B	0.006
Al	0.034	Na	1.3	Mo	0.03
Cr	0.007	Th	0.06	Se	4.0
Pb	0.16	Be	0.005	Te	3.3
P	0.7	Cu	0.002	V	0.0017

[a] SOURCE: Iwasaki et al. 1978: analysis is by plasma emission spectrometry, values are ppm by weight.

Table 25. Average chemical composition of various groups of Duluth Gabbro samples.[a]

SAMPLE	DISS. AV.	SEMI-MASS AV.	CORE MEDIAN	UNITS[b]
ELEMENT				
Si(SiO$_2$)	22.29(47.72)	20.68(44.28)	22.88(49.00)	PCT
Al(Al$_2$O$_3$)	9.21(17.41)	7.08(13.37)	8.71(16.45)	PCT
Fe(FeO)	8.69(11.18)	8.66(11.14)	8.55(10.99)	PCT
Mg(MgO)	4.54(7.52)	3.10(5.14)	3.53(5.85)	PCT
Ca(CaO)	5.53(7.74)	2.88(4.03)	5.62(7.87)	PCT
Na(Na$_2$O)	2.18(2.94)	1.26(1.70)	1.99(2.68)	PCT
K (K$_2$O)	0.35(0.42)	0.53(0.64)	0.40(0.48)	PCT
Ti(TiO$_2$)	0.92(1.53)	1.00(1.67)	0.92(1.53)	PCT
P (P$_2$O$_5$)	0.03(0.08)	0.03(0.07)	0 (0)[c]	PCT
Mn(MnO)	0.12(0.16)	0.10(0.13)	0.11 (0.15)	PCT
Cr(Cr$_2$O$_3$)	0.03(0.05)	0.03(0.04)	0.02 (0.03)	PCT
B	571.22	127.20	0	PPM
Ba	704.33	394.40	892.0	PPM
Be	0.54	1.74	0.6	PPM
Sr	277.67	181.90	254.00	PPM
V	166.21	222.60	160.00	PPM
Th	4.34	3.40	1.7	PPM
Zr	96.08	79.10	85.70	PPM
S	1.129	6.528	1.120	PCT
Cu	0.545	2.849	0.485	PCT
Ni	0.125	0.318	0.096	PCT
Fe(S)	1.249	7.335	1.239	PCT
Co	0.012	0.030	0.014	PCT
Zn	139.00	236.80	93.5	PPM
Pb	5.31	0	0	PPM
Ag	2.72	7.10	2.5	PPM
As	10.00	10.00	0	PPM
Hg	0.080	0.070	0	PPM
Mo	1.56	1.40	NA[d]	PPM
Cd	10.00	10.00	0	PPM

---

[a] See text for a discussion of the samples included in each of the groups.

[b] PCT = weight percent
PPM = parts per million by weight

[c] 0 = below detection limits

[d] NA = not analyzed

of the sample composition to the disseminated average composition. The disseminated average is shown as a straight line across the figure while the 75th and 25th percentiles of the 91 core analyses are shown as the jagged lines. Note the disseminated average is within the 75th and 25th quartile ranges except for Mg, Cr and Zn. Even these 3, however, are very close to the 75th percentile. This close agreement between core data chemistry and the disseminated average supports the contention that the disseminated samples can be considered to be reasonably representative of the mineralized gabbro.

Figure 23

In Figure 24, the disseminated samples are plotted against their average. As can be seen in this figure the values for the major sulfide elements [S, Cu, Ni, Fe(S), and Co] are not highly dispersed about their average, whereas the minor sulfide-related elements are more dispersed. This minor element dispersion is largely due to the small amounts present but general trends still do show up. The values for Cu and Ni tend to be either both below the average or both above the average, indicating a relatively constant Cu/Ni ratio and also a relatively constant chalcopyrite and cubanite/pentlandite ratio.

Figure 24

Figure 25 is a normalization plot of the lean ore sample (AX9001) and the semi-massive samples plotted against the disseminated sample average. The difference between the lean ore, disseminated sample average, and semi-massive samples shows up best in sulfur and the sulfur-related elements. Since the sulfide content of the lean ore sample is, by definition, lower than the disseminated average, its plot on Figure 25 is lower than the disseminated average in sulfur and sulfur-

FIGURE 23

DRILL CORE DATA VERSUS THE DISSEMINATED AVERAGE COMPOSITION

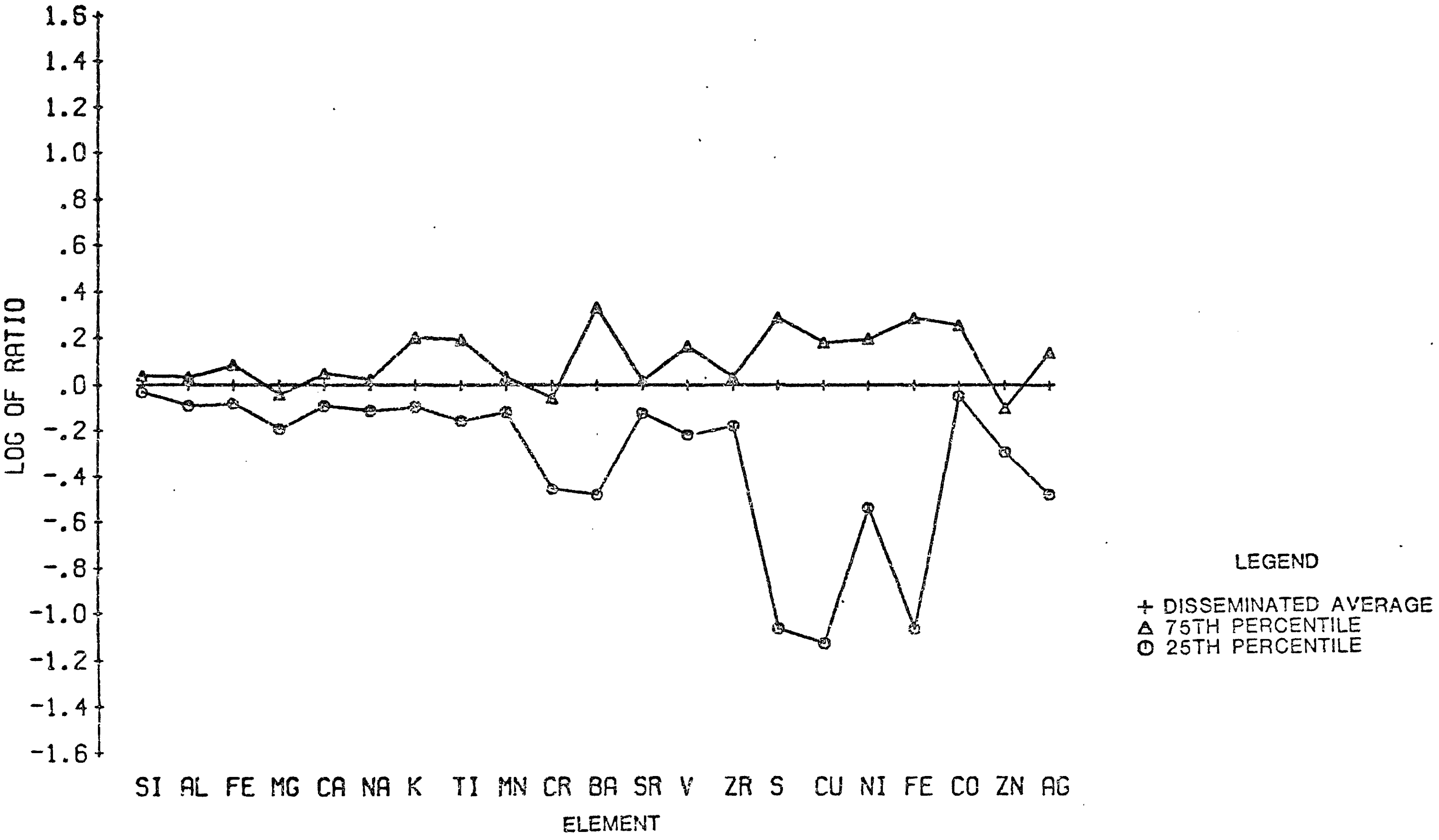
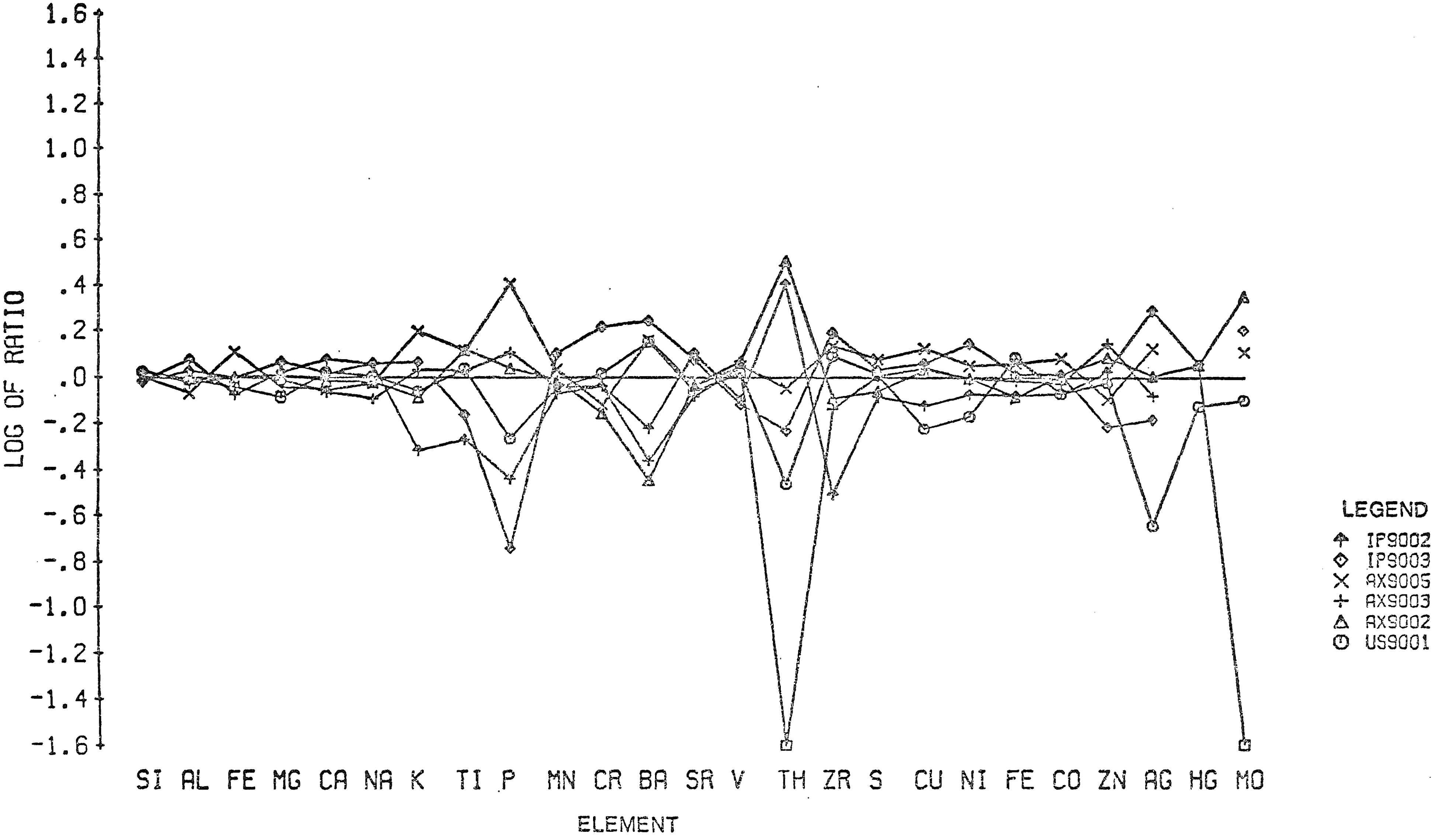


FIGURE 24

DISSEMINATED SAMPLES VERSUS THE DISSEMINATED AVERAGE COMPOSITION



related elements. Correspondingly, all of the semi-massive ore samples are above the disseminated average in sulfur and sulfur-related major and minor elements (Cu, Ni, Fe, Co, and Zn). Trace elements (Ag, Hg, and Mo) are at such low concentration levels that conclusions drawn from the amounts present would be speculative. The highest Fe value corresponds to the sample that has the highest amount of pyrrhotite (AX9004).

Figure 25

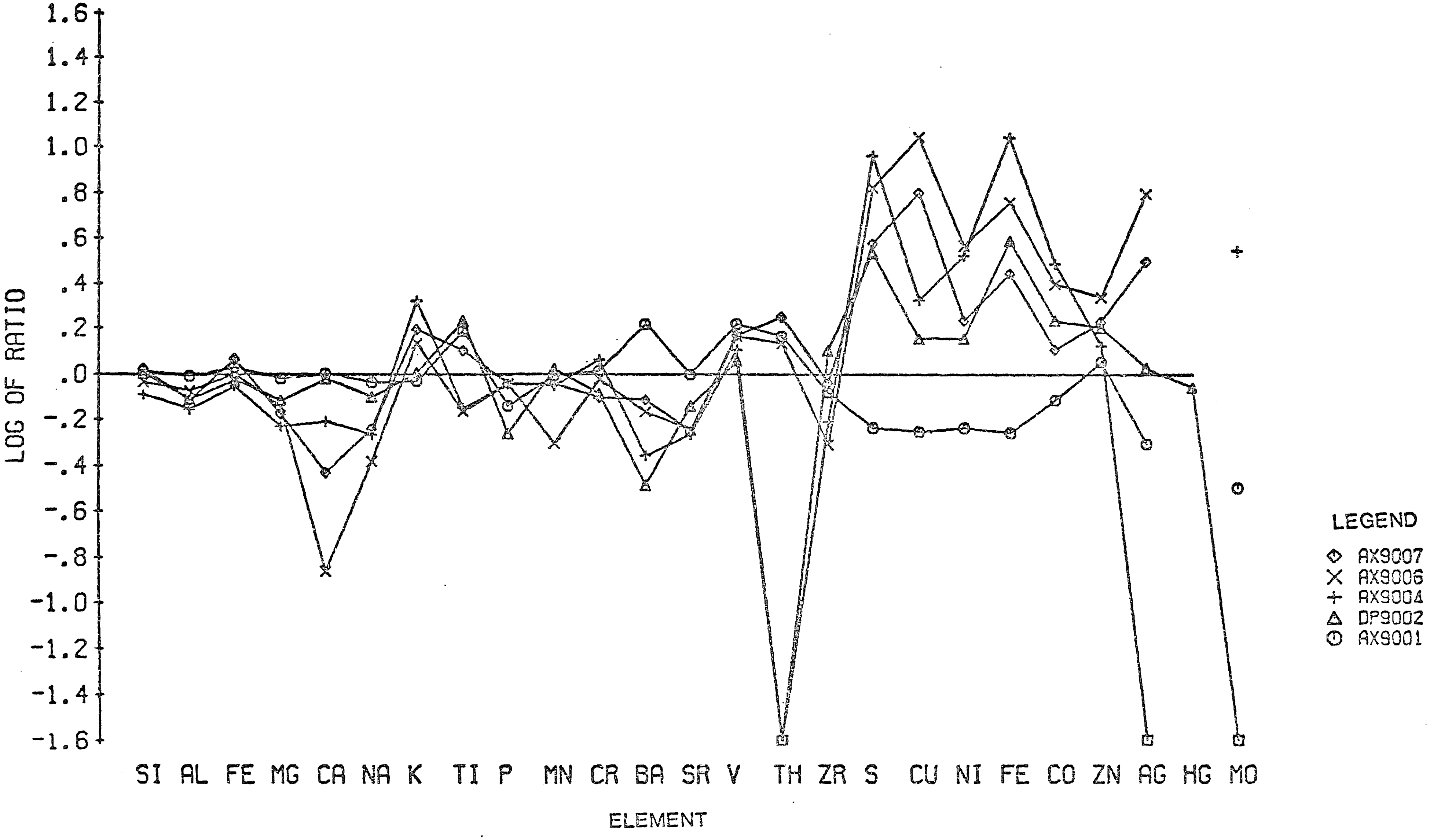
Unlike the Cu/Ni ratios of the disseminated samples, there is no consistent relationship for the ratios shown in the semi-massive ore. However, the lean ore (AX9001) sample does have a Cu/Ni ratio consistent with the disseminated average. This supports the thesis that lean ore is disseminated ore diluted by gangue minerals, as found by Listerud and Meineke (1977).

The Cu/Ni ratio is important because these are the 2 elements that are in the highest concentrations of the base metals present. By knowing the ratio and its variation with such variables as depth of an ore body, tonnages and grades of ore can be estimated and/or projected.

Listerud and Meineke (1977) summarized data concerning the Cu/Ni ratio and the sulfur content in mineralized areas. Although the 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 Listerud and Meineke (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% by weight and averaged (weighted)

FIGURE 25

SEMI-MASSIVE AND LEAN ORES VERSUS THE DISSEMINATED AVERAGE COMPOSITION



2.64% for zones containing 0.5% or greater. Because of the small amount of data available Listerud and Meineke (1977) made no conclusions concerning the variation in sulfur content.

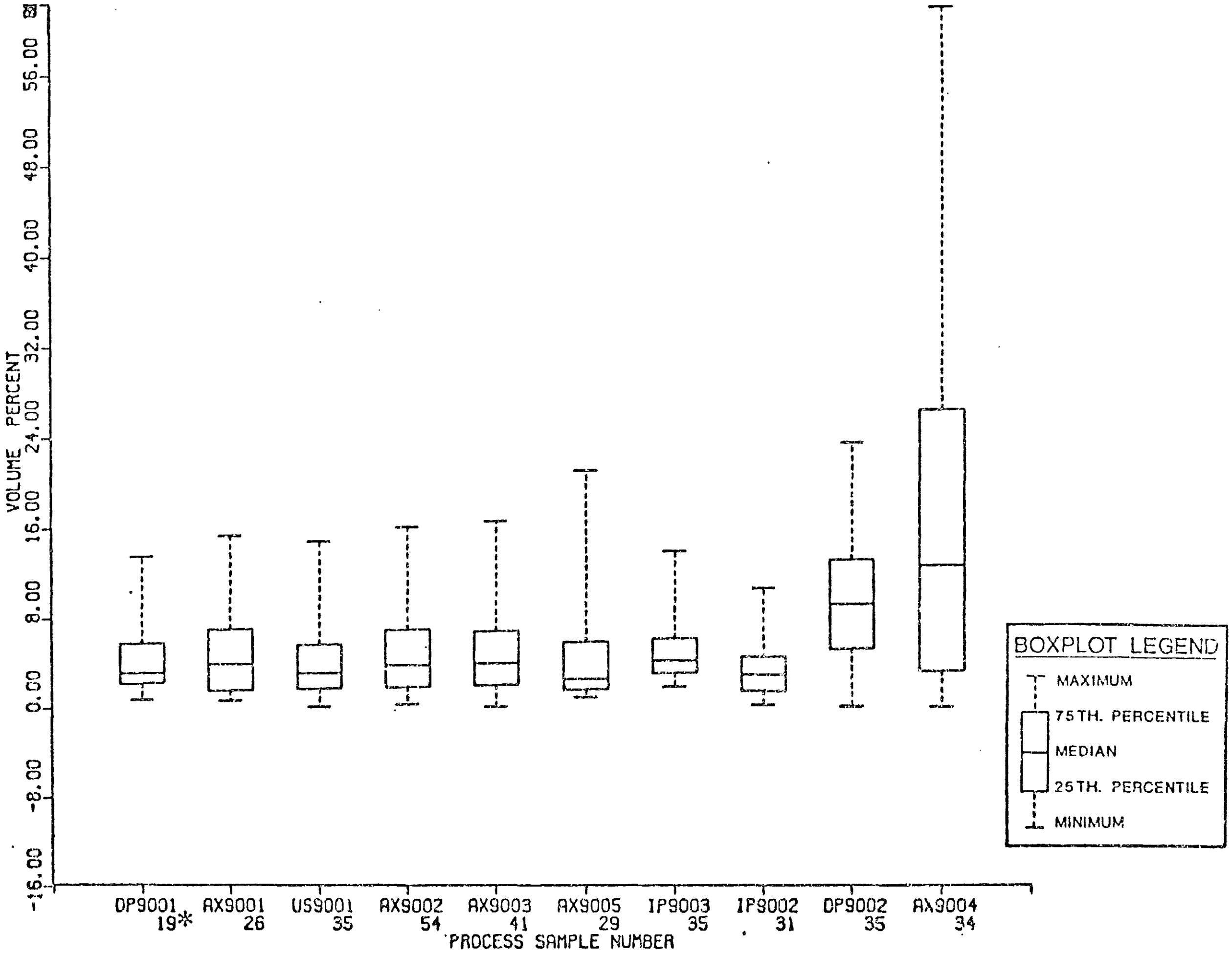
1.4.3.3 Non-Sulfide Mineralogy--The Fe-Ti oxide (illmenite plus magnetite) variation found by MGS is shown in Figure 26. In some areas along the base of the Duluth Complex the amount of titanium oxide (TiO_2) in the rock exceeds 10%, and are a possibly economic sources of titanium. The values shown in Figure 26 for the lean ore and disseminated samples are very similar. The semi-massive samples do have greater amounts of these oxides but since the Ti content (Figures 24 and 25) is similar in the disseminated and semi-massive samples, the difference appears to be the result of an increase in the amount of magnetite in the semi-massive samples.

Figure 26

The oxide, carbonate, and silicate minerals present in the samples are listed in Table 26 with their chemical compositions in weight percent, as used by MGS in determining approximate chemistries and elemental compositions of the process samples. The amounts of non-sulfide minerals present are important because they will be the main minerals present in tailing and waste rock. They are also the dominant minerals in the disseminated ore. Some of these minerals have a potential for economic development. Plagioclase is a possible source of alumina and olivine is a possible source of refractory material (see Volume 2, section 5.3.4 for a further discussion).

Table 26

FIGURE 26
ILMENITE PLUS MAGNETITE CONCENTRATION
IN MINERAL PROCESSING SAMPLES



*NUMBER OF THIN SECTIONS ANALYZED

Table 26. Non-sulfide mineral chemistries (volume percent).

MINERAL

Constitent	Plagioclase	Sericite	Olivine	Clinopyroxene	Orthopyroxene
SiO_2	52.851	48.781	34.490	51.382	53.263
Al_2O_3	29.012	27.362	0	2.371	0.569
FeO	0.220	5.770	42.889	11.219	24.212
MgO	0	0.050	21.565	12.540	19.727
CaO	12.085	0.050	0.040	20.359	1.217
Na_2O	4.852	0.353	0	0.777	0
K_2O	0.840	11.314	0	0	0
TiO_2	0.140	0.876	0.010	0.676	0.167
P_2O_5	0	0	0	0	0
MnO	0	0.050	0.895	0.504	0.785
Cr_2O_3	0	0	0.010	0.172	0.059
Cu	0	0	0	0	0
Ni	0	0	0.101	0	0
Fe	0	0	0	0	0
Co	0	0	0	0	0
S	0	0	0	0	0
C	0	0	0	0	0
H_2O	0	4.342	0	0	0
CO_2	0	0	0	0	0
Cl	0	0	0	0	0
F	0	0.050	0	0	0

Constitent	Amphibole	Chlorite	Serpentine	Talc	Biotite
SiO_2	45.070	27.224	42.220	62.566	36.507
Al_2O_3	10.262	17.493	0.099	0.050	13.893
FeO	23.038	33.742	19.029	2.458	14.197
MgO	6.439	9.791	29.633	30.199	19.673
CaO	12.575	0.211	0.099	0	0.051
Na_2O	0	0.010	0	0	0.051
K_2O	0	0.010	0	0	9.249
TiO_2	0.402	0.351	0	0	3.083
P_2O_5	0	0	0	0	0
MnO	0.201	0.050	0	0.010	0
Cr_2O_3	0	0	0	0	0
Cu	0	0	0	0	0
Ni	0	0	0	0	0
Fe	0	0	0	0	0
Co	0	0	0	0	0
S	0	0	0	0	0
C	0	0	0	0	0
H_2O	2.012	11.117	8.920	4.717	3.296
CO_2	0	0	0	0	0
Cl	0	0	0	0	0
F	0	0	0	0	0

Table 26 continued.

MINERALS

Consituent	Smectite	Celadonite	Ilmenite	Magnetite	Graphite
SiO_2	58.889	49.546	0	0.105	0
Al_2O_3	19.143	18.305	1.528	1.459	0
FeO	5.381	8.402	43.199	75.160	0
MgO	2.142	3.123	2.853	2.404	0
CaO	1.645	1.038	0	0.063	0
Na_2O	0.445	0.232	0	0	0
K_2O	5.277	5.662	0	0	0
TiO_2	0.838	0.212	51.961	20.388	0
P_2O_5	0.052	0	0	0	0
MnO	0	0	0.458	0.346	0
Cr_2O_3	0	0	0	0.073	0
Cu	0	0	0	0	0
Ni	0	0	0	0	0
Co	0	0	0	0	0
S	0	0	0	0	0
C	0	0	0	0	100.000
H_2O	6.188	13.570	0	0	0
CO_2	0	0	0	0	0
Cl	0	0	0	0	0
F	0	0	0	0	0

Constituent	Spinel	Myrmekite	Apatite	Epidote	Allanite
SiO_2	0	53.263	0	37.199	41.746
Al_2O_3	53.399	0.569	0	22.418	21.878
FeO	43.549	24.212	0.318	14.348	19.551
MgO	2.387	19.727	0.050	0	0.441
CaO	0	1.217	54.670	23.285	5.893
Na_2O	0	0	0.040	0	0
K_2O	0	0	0.010	0	0
TiO_2	0.645	0.167	0.020	0	0.055
P_2O_5	0	0	42.084	0	0
MnO	0.020	0.785	0.020	0.756	7.504
Cr_2O_3	0	0.059	0	0	0
Cu	0	0	0	0	0
Ni	0	0	0	0	0
Fe	0	0	0	0	0
Co	0	0	0	0	0
S	0	0	0	0	0
C	0	0	0	0	0
H_2O	0	0	0.973	1.995	2.933
CO_2	0	0	0	0	0
Cl	0	0	0.199	0	0
F	0	0	1.618	0	0

Table 26 continued.

	MINERAL		
Consituent	Calcite	Quartz	Cordierite
SiO_2	0	100.000	48.693
Al_2O_3	0	0	33.204
FeO	0	0	8.791
MgO	0.040	0	7.719
CaO	55.970	0	0.531
Na_2O	0	0	0.541
K_2O	0	0	0.429
TiO_2	0	0	0.051
P_2O_5	0	0	0
MnO	0	0	0.041
Cr_2O_3	0	0	0
Cu	0	0	0
Ni	0	0	0
Fe	0	0	0
Co	0	0	0
S	0	0	0
C	0	0	0
H_2O	0	0	0
CO_2	43.990	0	0
Cl	0	0	0
F	0	0	0

As can be seen in Figure 27, plagioclase is the dominant mineral in the samples. Although no obvious trend can be shown, both semi-massive samples shown have the lowest median volume percent value. It should also be pointed out that in some cases (i.e. AX9005) thin sections were observed with less than 10% by volume plagioclase. These low amounts correlated with a high degree of alteration and the presence of a large amount of other silicates, particularly olivine and pyroxene.

Figure 27

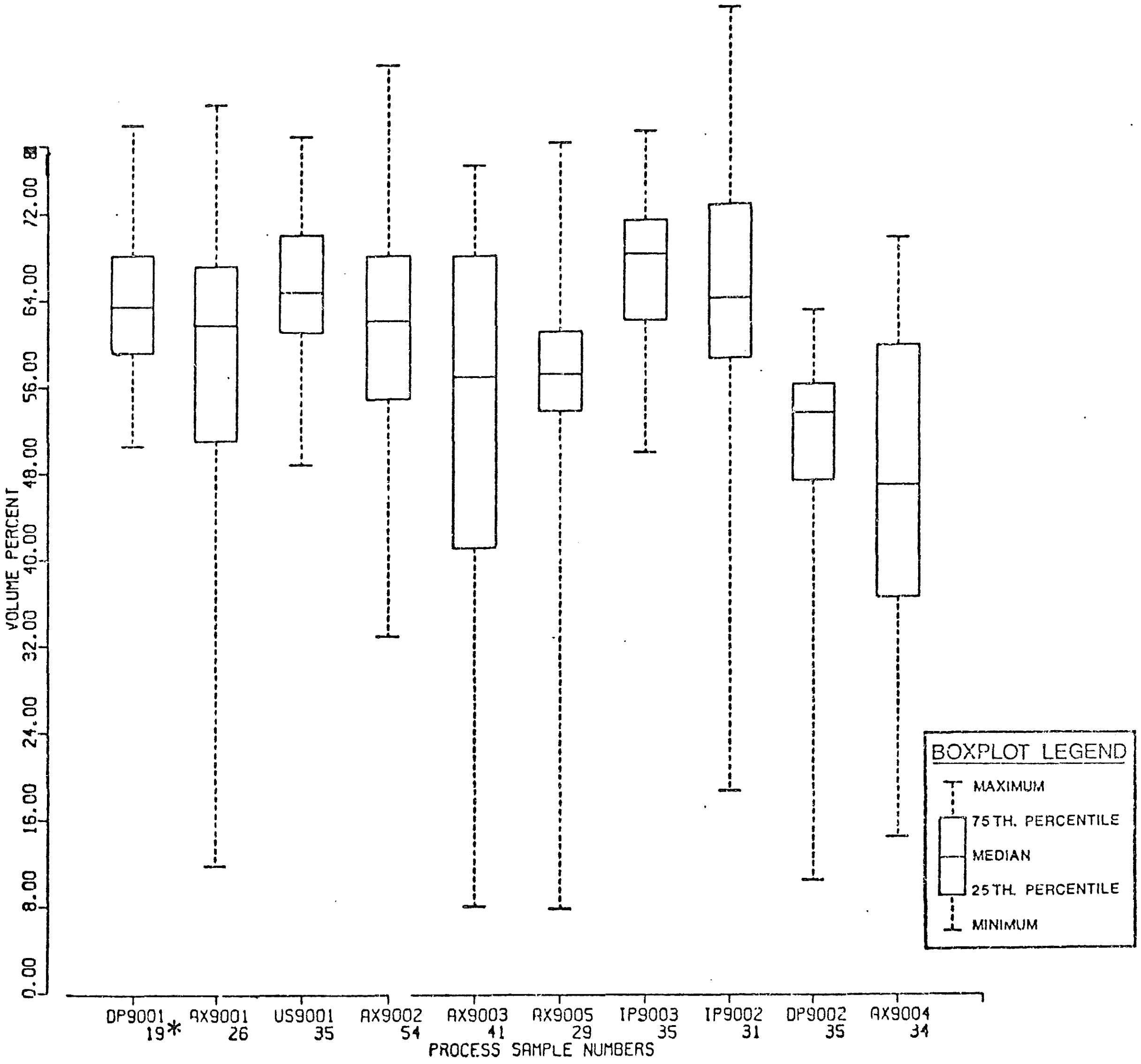
Figures 28 and 29 show the distribution of olivine and clinopyroxene. Again, as with plagioclase, both olivine and clinopyroxene show no obvious trend in the lean ore and disseminated samples, but the AX9004 sample is much lower. The lower amount of these Fe-Mg silicates is offset by an increase in the other similar silicate, orthopyroxene (Table 21). This increase in orthopyroxene is a function of the amount of Si and Ca available. With a relatively low abundance of Ca and a relatively high abundance of Si, orthopyroxene will form instead of olivine and clinopyroxene.

Figures 28 & 29

Alteration of the Fe-Mg silicates results in the formation of chlorite, serpentine, and amphibole. The amphibole distribution is shown in Figure 30. The amphibole content is a good measure of the degree to which the gabbro has been altered. This may be important in the context of health effects since one of the morphologic habits of amphibole is asbestiform, and certain varieties of asbestiform amphibole have been shown to be carcinogenic (see Volume 5-Chapter 2). Generally, the semi-massive samples are much less altered than the other

FIGURE 27

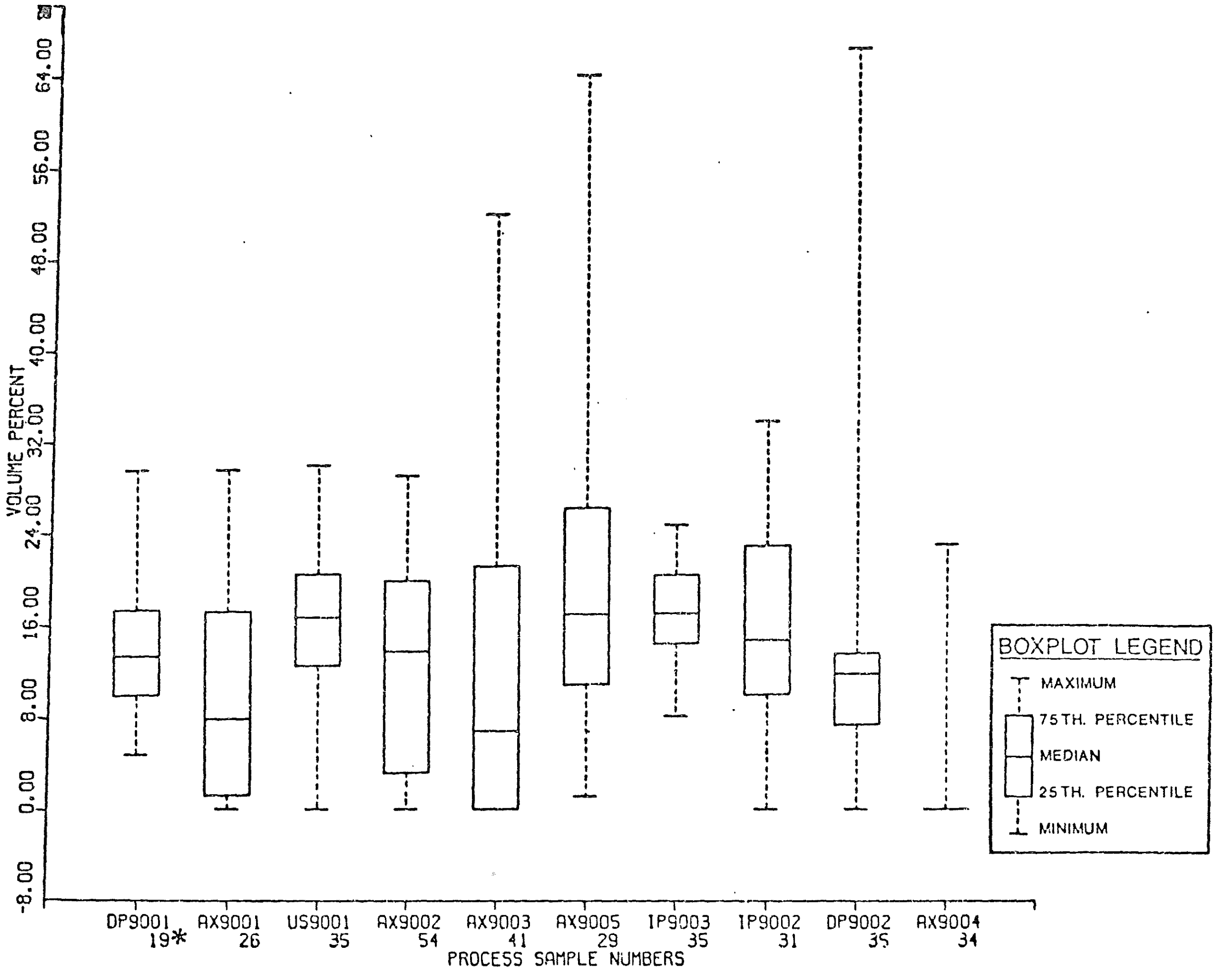
PLAGIOCLASE: CONCENTRATION IN MINERAL PROCESSING SAMPLES



*NUMBER OF THIN SECTIONS ANALYZED

FIGURE 28

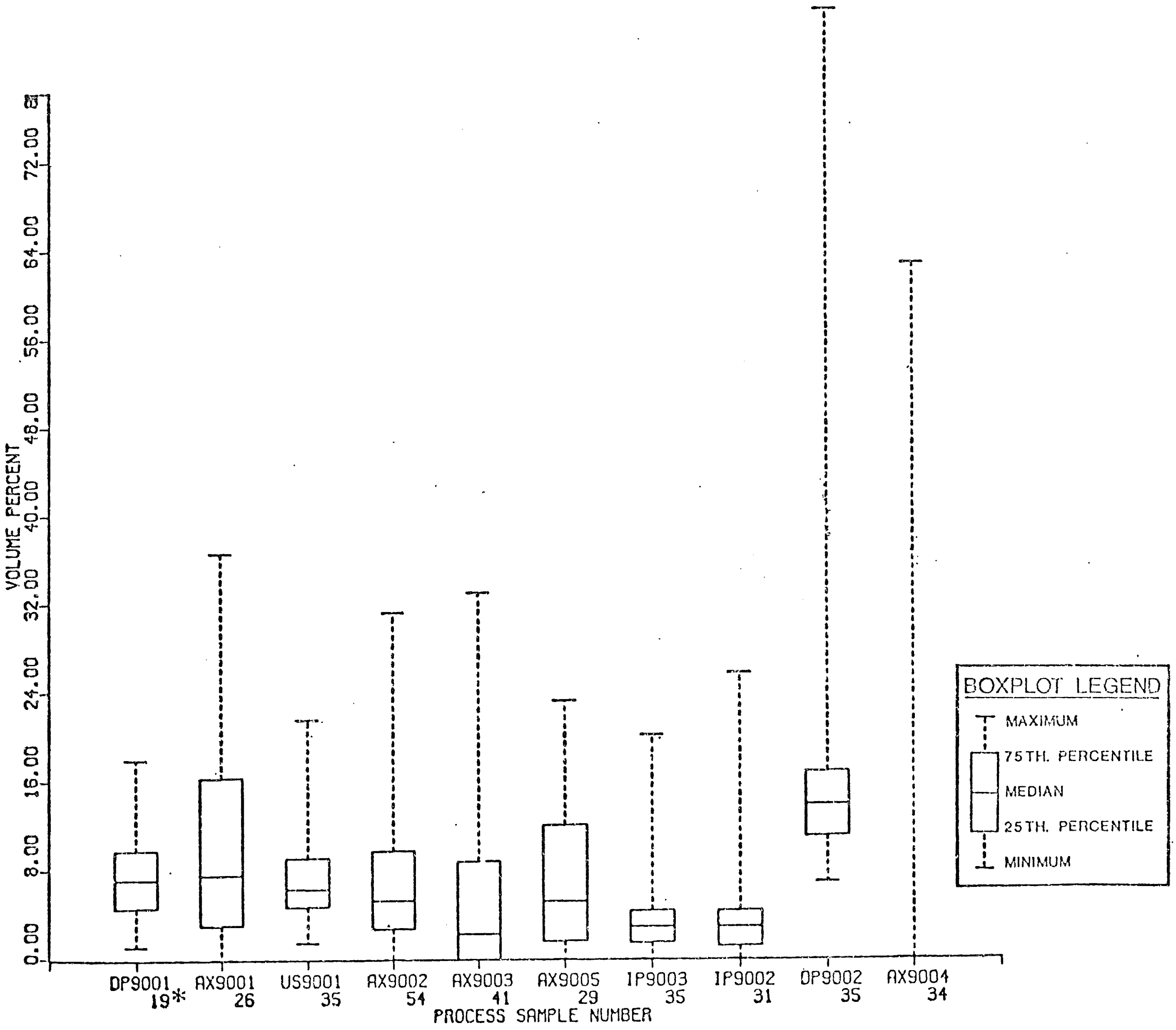
OLIVINE : CONCENTRATION IN MINERAL PROCESSING SAMPLES



*NUMBER OF THIN SECTIONS ANALYZED

FIGURE 29

CLINOPYROXENE: CONCENTRATION IN PROCESSING MINERAL SAMPLES



*NUMBER OF THIN SECTIONS ANALYZED

samples. One thin section in the group for AX9001 has over 60% by volume amphibole. This indicates how variable the degree of alteration can be in the non semi-massive samples.

Figure 30

1.4.3.4 Non-Sulfide Chemistry--The relevant data here was presented earlier under the section discussing the chemistry of the sulfide minerals (section 1.4.3.2). This information will now be discussed briefly.

Figure 23 shows that for the non-sulfide related elements (Si thru Zr) the disseminated average feed is between the 25th and 75th percentiles of the core data. The only exceptions are Mg and Cr, and these are very close to the 75th percentile.

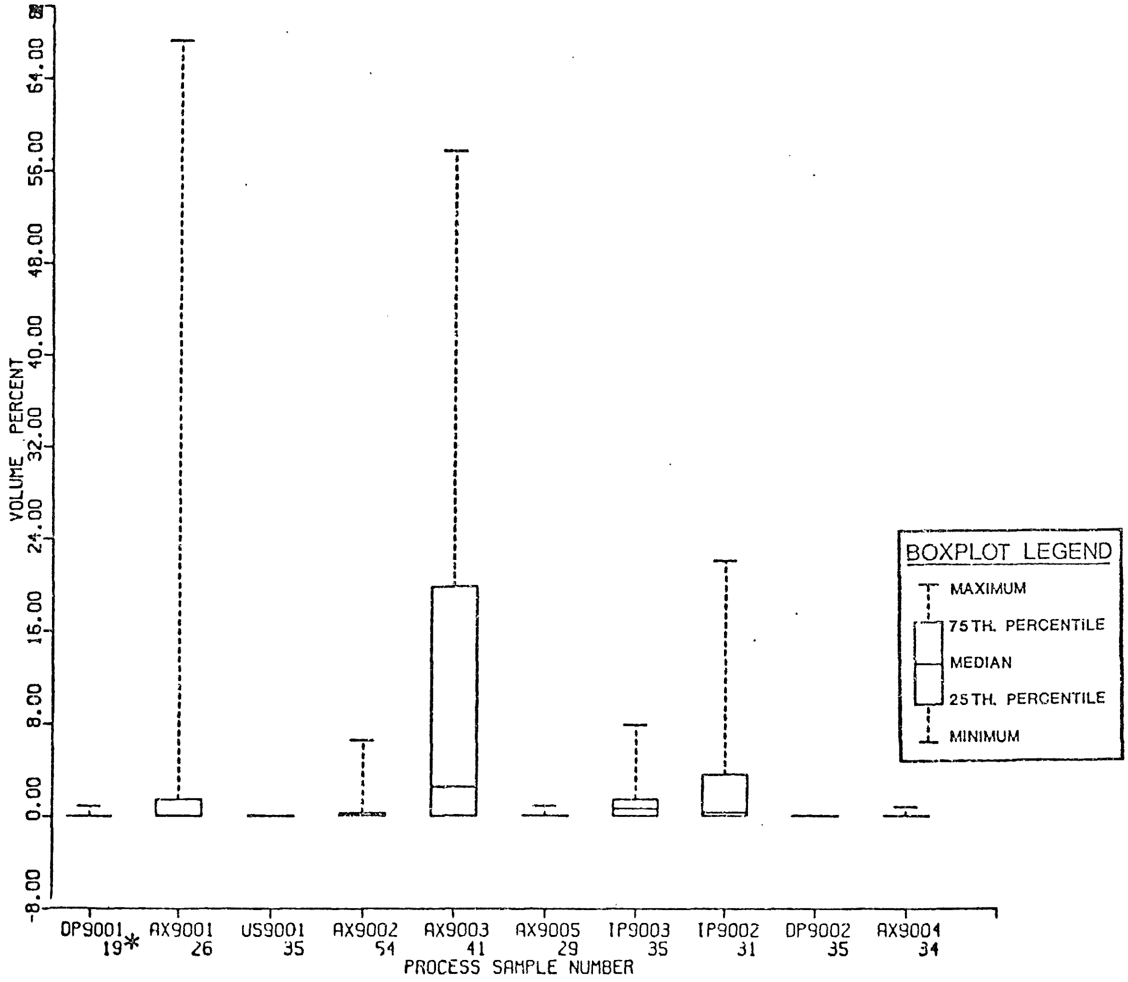
In Figure 24, the normalized chemical compositions of the 6 disseminated process samples are plotted against their average. The major departures from the average occur for K, Ti, P, Ba, Th, and Zr. The Ba, Th, and Zr variations are probably due to the fact that only small amounts of these elements are present, so when the values are normalized the fairly small differences in actual content cause the resultant points to be widely scattered about the average.

The K, Ti, and P variation among samples is due to the variation in the sample content of biotite, ilmenite, and apatite, respectively. The lower the amount of any of these 3 minerals, the lower the respective elemental amounts.

Figure 25 is a normalization plot of the lean ore sample and the semi-massive ore samples. The lean ore is very close to the disseminated average for non-sulfide elements. The semi-massive samples, in relation to the disseminted average, have

FIGURE 30

AMPHIBOLE : CONCENTRATION IN MINERAL PROCESSING SAMPLES



*NUMBER OF THIN SECTIONS ANALYZED

a lower amount of non-sulfide elements except for K, Ti, V, and Th. Again, the Th variations are probably due to the small amount present, but it can be said that the Th amount is close to that of the disseminated average. Vanadium is primarily found in the magnetite; Ti in the ilmenite, and K in the biotite. Therefore, for the semi-massive samples, the magnetite, ilmenite, and biotite contents are above the average disseminated values. The other elements in the non-sulfur group are close to or just below the disseminated average. This is primarily a function of the increased amount of sulfide minerals present which reduces the non-sulfur related element amount. A notable exception to this is the quite low amount of Ca in the semi-massive samples. No satisfactory explanation for this low Ca content has yet been put forth, although some connection to the high sulfur content of these samples seems probable.

1.4.3.5 Mineral Fibers--Because of the concern over the possible health hazards posed by the release of mineral fibers to the environment (Volume 5-Chapter 2), it is appropriate to discuss this topic here. Accordingly, this section deals with the question of the presence in Duluth Complex material of minerals which may result in the release of mineral fibers or fiber-like fragments to the environment. For the purpose of this study, a fiber is defined as an inorganic mineral with parallel sides and an aspect ratio (length/width) greater than 3. This definition includes asbestiform material as well as acicular crystals and cleavage fragments. The term "asbestos" is often used in the context of discussions of mineral fibers, and it is appropriate to clarify this term, as well as the terminology to be used here. Further information may be obtained from the reports "Concentrations of Mineral Fibers in Process Samples from Northeast Minnesota" (Stevenson 1978) and "Ambient Concentrations of Mineral Fibers in Air and Water in Northeast Minnesota" (Ashbrook 1978).

The word "asbestos" is used as a collective mineralogical term encompassing the asbestiform varieties of various silicate minerals and is applied to a commercial product obtained by mining primarily asbestiform minerals. Five minerals fit this definition: chrysotile (a member of the serpentine group), and the asbestiform varieties of actinolite-tremolite, anthophyllite, cummingtonite-grunerite, and riebeckite (members of the amphibole group). Chrysotile by definition occurs in the asbestiform habit, amphiboles usually occur in non-asbestiform habits, with the exception of riebeckite, which usually occurs in the asbestiform habit as crocidolite. Asbestiform minerals occur as fibers, which display some resemblances to organic fibers in terms of flexibility, silky surface luster, and other characteristics. Cleavage fragments, such as those produced from crushing and processing non-asbestiform minerals, do not satisfy this definition of fibers and should be considered "fiber-like". When asbestiform and non-asbestiform minerals are subjected to crushing and processing, the resulting fragments have minor differences in morphology and physical properties that are very difficult to distinguish under a transmission electron microscope. For this reason, when the transmission electron microscope is used, fibers are defined as fragments with aspect ratio of 3:1 or greater, even though many of these fragments may not meet the mineralogic definition of a fiber. In this discussion, the term "mineral fiber" will be used to denote both asbestos fibers and cleavage fragments of non-asbestiform minerals because ambient levels of mineral fibers were determined by transmission electron microscopy, which did not distinguish between these 2 classifications.

As discussed earlier, thin section work was conducted for the Regional Study by the Minnesota Geological Survey on 9 out of a series of 10 mineralized Duluth Gabbro samples. Part of the intent of the work was to determine the presence of asbestiform minerals, as well as the content of minerals likely to form fiberous, or fiber-like, cleavage fragments during the crushing and grinding operations involved in mineral processing. Table 21, given earlier, shows the results of the thin-section work. The amphibole present originated from the alteration of olivine and pyroxene. Notice that the MGS divided the amphibole into 2 categories. One is monocrystalline (i.e. amphibole that is blocky in outline), and the other one is fiberous, but is better described as being acicular amphibole. The distinction between these 2 categories is not always obvious, so they may be combined into a total amphibole category. The mean value for this total amphibole category is 2.3% by volume, whereas the median is 0.43% by volume. The observed range of volume percent of the amphibole is from below detectable limits, probably near 0.01%, up to a maximum of slightly less than 13% (sample AX9003).

It is important to note that the amphibole contained in the samples studied was not present in the asbestiform habit. No obvious asbestiform habit was found in the 9 samples examined in the thin-section study. The data on the content of non-asbestiform amphibole is of considerable interest, however, since it can be related to the fiber content of the concentrate and tailing materials produced by the grinding and flotation operations (see section 2.4.4). In terms of observations of minerals occurring naturally in the asbestiform habit, one sample containing an unusual actinolite with asbestiform habit was found in gabbroic rocks adjacent to one of the mineralized process samples, indicating that such minerals do occur naturally in the area. However, based on the total surface area of rock examined during the course of this study, it may be concluded that in the vicinity of the sites of the various process samples, the occurrence of visible asbestiform amphibole is rare (0.50 gm in 5 X 10^6 gm of gabbro) and is associated with rare centimeter-sized cavities in mineralized rock. Although this study was far too cursory to rule out major occurrences, if the samples examined are representative then asbestiform amphibole occurs at levels of less than 0.1 ppm by weight in mineralized areas of the Duluth Complex (Weiblen and Stevenson 1978).

The major issue here of potential environmental concern thus does not appear to be the possible release to the air and water of naturally-occurring asbestiform fibers as a result of mining, but rather the possible release of mineral fibers mechanically created as cleavage fragments from the non-asbestiform amphibole present in the mineralized Duluth Gabbro. The actual health implications of such releases remains unclear, but since the potential exists, it is important to attempt to understand and quantify the generation of mineral fibers during the mining process. This is discussed further in section 2.4.4.