GEOLOGY AND SULFIDE MINERALIZATION

OF THE

SKELETON LAKE PROSPECT,

ST. LOUIS COUNTY, MINNESOTA

A THESIS

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Frontpiece: View looking southwest across Skeleton Lake

ABSTRACT

Banded, semi-massive, and disseminated sulfide
mineralization was intersected in three drill holes
near Skeleton Lake, northern St. Louis County, Minnesota.
Pyrrhotite and pyrite are the dominant sulfides, commonly
associated with magnetite and minor amounts of chalcopy-
rite.

The sulfides occur within a sequence of Archean
metavolcanic rocks that were deposited subaqueously, and
consist primarily of basaltic and andesitic flows, mafic-
intermediate tuffs, and associated diabasic rocks. Algo-
man-type iron formation and porphyritic intrusive rocks
of varying composition are also present in lesser amounts.

The sulfides were deposited: 1) in a restricted
horizon within a fine-grained, bedded quartz host rock;
and more generally, 2) as hydrothermal stringers in fav-
orable sites below the sulfide horizon. The restricted
sulfide zone is interpreted as being the product of vol-
canic-exhalative processes occurring at the sea floor,
whereas the hydrothermal veinlets are considered to be
epigenetic infillings concentrated in fractures below
the seawater-rock interface.

The circulating hydrothermal fluids that were respon-
sible for the transport of metals through the volcanic
pile have pervasively altered the rocks below the sul-
fide horizon in an irregular alteration "pipe". Two pyro-

clastic sequences, originally more permeable than the massive flow units, have been more profoundly affected by the hydrothermal fluids, resulting in stratiform alteration zones extending from the alteration pipe. A third discordant, pipe-like alteration area occurs stratigraphically above the sulfide horizon. The stratigraphic position of this zone, and the observation of hydrothermal veins cross-cutting the sulfide horizon, indicate a second period of hydrothermal activity at Skeleton Lake. These altered rocks are distinctive in their unusually high amounts ($>$ 50%) of quartz, carbonate, epidote, chlorite and other hydrothermal minerals, that occur in veins and in envelopes around amygdules and fractures. These altered rocks are further distinguishable by anomalous depletion of MgO, and enrichment of K_2O, SiO_2, and Na_2O.

The exhalative sulfide horizon and altered pyroclastic sequences were observed to be spatially related to andesitic rocks and iron formation.

Although a geologic environment that was conducive to massive sulfide deposition existed at Skeleton Lake, base and precious metal contents are not sufficient to make the prospect economically exploitable at this time.

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INTRODUCTION

Purpose of Study

Copper-zinc massive sulfide deposits are often associated with Archean greenstone belts throughout the Canadian Shield (Sangster, 1972). Since the mid-1960's several mineral companies have initiated exploration programs for massive sulfides in the western Vermilion district, an Archean greenstone belt that is exposed in northeastern Minnesota. Based on geophysical anomalies in the Skeleton Lake area northern St. Louis County, Minnesota, Exxon Corporation drilled three exploratory holes in late 1973 and early 1974 on State of Minnesota land. Two of these holes intersected a 5-to 7-meter horizon of pyrite-pyrrhotite-chalcopyrite mineralization. Exxon subsequently released its control and submitted these cores and logs to the State.

This study seeks to provide a better understanding of the sulfide mineralization and general geology of the area. Specific objectives of such an investigation include determination of rock types, general stratigraphic relationships, sulfide mineralogy and genesis, ore indicators, and hydrothermal alteration.

Location and Physiographic Setting

The Skeleton Lake prospect lies in the Vermilion district, a western extension of the Shebandowan volcanic-plutonic belt of the southern Superior province of the

Canadian Shield. The rocks of the Vermilion district form a supracrustal belt 10 to 30 kilometers wide and approximately 160 kilometers long, extending from Tower northeastward into Ontario (Figures 2, Table I). The study area is approximately 6 square kilometers in size and is located 5.6 kilometers southeast of Soudan, Minnesota, northern St. Louis County, (T61N, R14W) in Section 8 and portions of adjoining sections. It is easily accessible via a logging road 4/10 kilometers east of mile marker 268 on Minnesota Highway 169 (Figure 1).

The topography is typified by low hills and ridges with intermittent areas of swampy lowlands, the higher areas having a maximum relief of approximately 30 meters. Skeleton Lake is located in the north-central part of the area and is part of a northeast-southwest trending series of small, glacial lakes. Outcrops (roughly 15% of the total area) are almost exclusively confined to the higher land, and tend to be scattered and discontinuous, the main exception being a sharp westfacing bluff, exposed for nearly 400 meters, in the central portion of the study area.

Methods of Study

Geological mapping was conducted for five weeks during the summer of 1979. The outcrop geology was mapped on a scale of 1"=500' on an enlarged USGS 7-1/2 minute topographic base map (Soudan Quadrangle). Dips and plunges were taken with a Brunton compass while most other field measurements were obtained with a sun compass, as
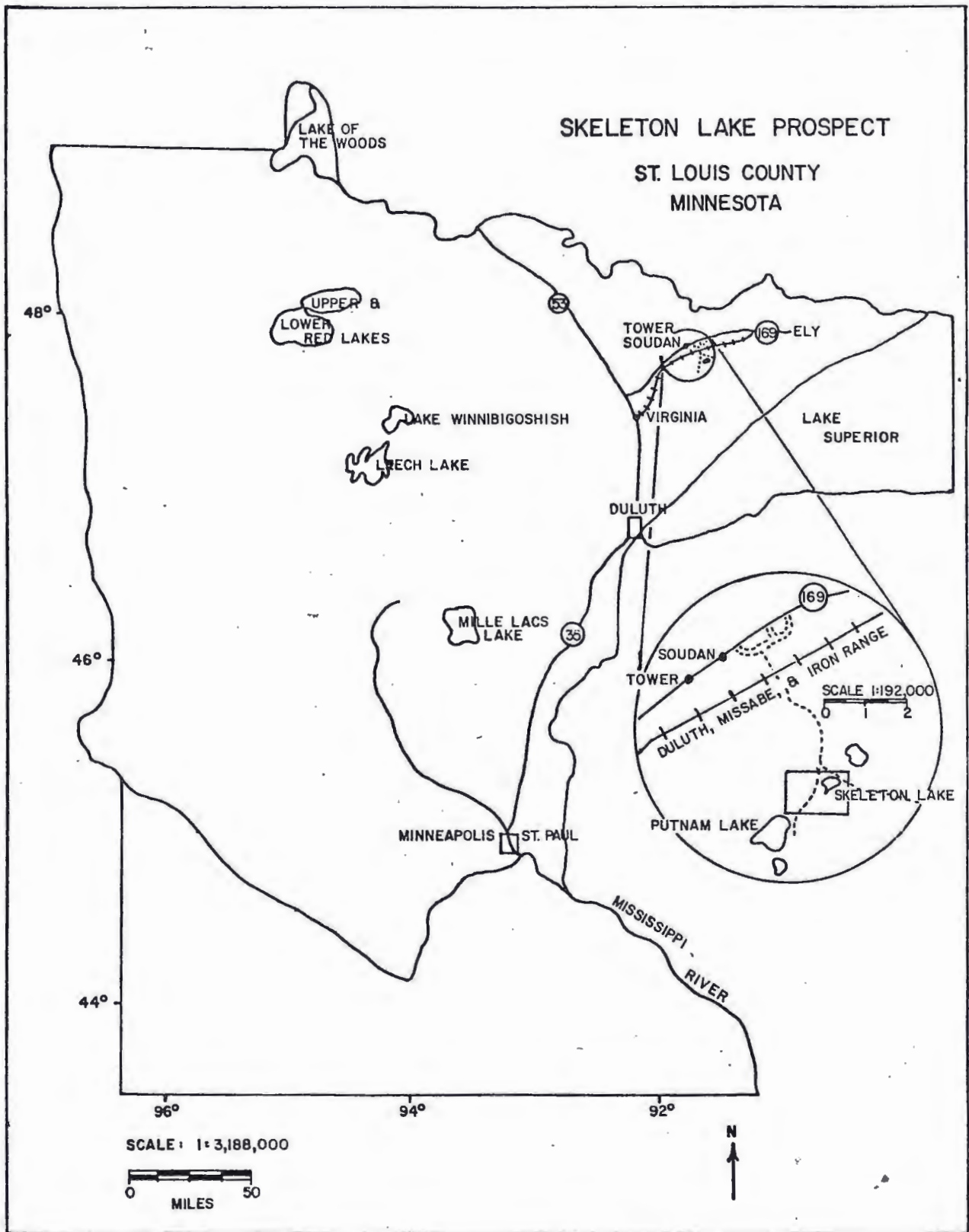
Fig. I : LOCATION MAP — SKELETON LAKE PROSPECT

many outcrops were close to iron formation.

One hundred ninety-two samples were collected from 84 outcrops and 1286 feet of drill core. One hundred seventy-five thin sections and 17 polished sections were prepared from these samples for study of relict textures, structures, and mineralogy of the metavolcanic rocks, and opaque mineralogy and ore paragenesis of the sulfide minerals. Selected thin section heels and cut samples were etched in hydrofluoric acid and stained for potassium after the method described by Chayes (1952) and Rosenblum (1956). Selected samples were also stained for calcic feldspar using a method described by Laniz, Stevens, and Norman (1964).

Study and sampling of the drill core from the Exxon exploratory holes was completed in the fall and winter of 1979. The cores were logged on a scale of 1"=10', and described with respect to mineralogy, alteration, and petrographic fabric. The drill core is presently stored at the MDNR drill core library in Hibbing, Minnesota.

Forty-four rock samples were analysed by atomic absorption methods by Albert Klaysmat of the MDNR in Hibbing. Twenty of these samples were analysed for the major oxides SiO_2, Al_2O_3, TiO_2, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O for aid in the determination of original rock composition. All samples were also analysed for the trace elements Ag, Au, Co, Cu, Ni, Pb, and Zn for determination of possible ore indicators.

Geophysical data were provided by the public file records of the MDNR. The information included a magnetic contour map; the results of airborne magnetic, ground magnetic, and electromagnetic surveys conducted by Geoterrex LTD, for Exxon Corporation in 1973; and, the MDNR's own geophysical survey of the area in 1975 and 1976. The results of these surveys aided in defining strike and lateral extent of unexposed iron formation.

Previous Work

Although specific studies of the Skeleton Lake prospect are lacking, references pertaining to the western Vermilion district are extensive and were recorded as early as 1852. In his somewhat optimistic report on the occurrences of gold and silver in the "talcose slates" around Vermilion Lake, Henry H. Eames (1866) aroused the public and started a short-lived "gold-mining fever" in the area. The less colorful, but more substantial, discovery of hematitic iron in 1865, led to an increasing interest in the Vermilion district. Many prominent geologists of the time, including R. D. Irving, U. S. Grant, A. Winchell, N. H. Winchell, and C. H. Van Hise made important studies of the region. N. H. Winchell (1882) and J. H. Clements (1903) both give excellent summaries of these and other early works.

The mining of iron ore began at Tower in 1884 and near Ely in 1888. N. H. Winchell and A. Winchell (1891) stated that the iron ore was found in massive and schistose greenstones of "Keewatin" age. The greenstones were

interpreted as being "eruptive rocks", while the iron and associated jasper were regarded as a direct chemical precipitate formed under high pressures from an ocean of hot, alkalic water. Since then, the iron ores were determined to be products of hydrothermal enrichment of the chemical precipitates at Tower-Soudan (Gruner, 1926 and Klinger, 1956) and Ely (Machamer, 1968). Sims (1972) synthesized the major studies on the Soudan Iron Formation--the thickest iron formation in the Vermilion district.

In his monumental study of the Vermilion district, J. M. Clements (1903) provided detailed descriptions of the greenstones, iron formation, clastic sediments, and granitic rocks, with an early statement of their stratigraphic and structural relationships. Proceeding from oldest to youngest, the Archean rocks were separated into three stratigraphic divisions: Ely Greenstone, Soudan Iron Formation and granitic rocks. The Ely Greenstone was shown to be of subaqueous, volcanic origin, forming the Archean basement and serving as the source rock for the infolded sediments. Tuffaceous members in the volcanic pile were described, and discordant mafic intrusives were suggested to be connecting conduits between the eruptive material and the source magma. Coarse-grained clastic deposits of various lithologies, collectively named the "Ogishke conglomerate", were considered to occur between the older mafic volcanic succession and a younger sedimentary succession, consisting primarily of

"Knife Lake slate". The pervasive metamorphism and deformation of the Ely Greenstone, Soudan Formation and related sediments was attributed to the intrusion of the flanking granitic batholiths with metamorphic grade increasing toward the granite contacts.

The stratigraphic framework established by Clements in the Vermilion district was extended to all older Precambrian terranes in northern Minnesota by Grout (1926). Grout, et al. (1951) incorporated many studies in their extensive review of Precambrian geology. Most notable among this was Gruner's (1941) detailed mapping of the Knife Lake "series" (later changed to "group" by Grout, et al. 1951) which firmly established the volcanic affinity of the Knife Lake group, and showed that the "Ogishke conglomerate" was not just a basal clastic deposit of wide extent, but rather was several coarse clastic deposits that were interbedded within strata dominated by graywacke, slate, and tuff.

After detailed regional mapping by Green, et al. (1966), Sims, et al. (1968), Griffin and Morey (1969), and Green (1970); Morey, et al. (1970) revised the stratigraphic nomenclature used in the Vermilion district. The terms "Ely Greenstone" was restricted to the lithologies continuous with those exposed at the type locality near Ely. The Soudan Iron Formation was given formational status and restricted to rocks continuous with those exposed on Soudan Hill. The name "Lake Vermilion Formation" was given to the epiclastic and volcaniclastic rocks that

overlie the Ely Greenstone and Soudan Formation in the
western Vermilion district, while the metasediments of
the Knife Lake group were restricted to the continuous
exposures at the type locality near the Canadian border.
In the central portion of the district, the mafic and
felsic metavolcanic rocks overlying the Knife Lake group
were separated into a new unit, the Newton Lake Forma-
tion (see also Green, 1970). Recently, Sims and South-
wick (1980) demonstrated that the Soudan Iron Formation
continued southeast of the Tower-Soudan area and included
substantial amounts of mafic volcanic rocks.

H. L. Smyth and J. R. Finley (1895) first discussed
the complex eastward plunging anticlinal and synclinal
folding of the slates and jaspers near Lake Vermilion.
The steeply plunging, east-west trending synclinorium
near Tower, described by Clements (1903), has been rein-
terpreted as an inverted anticline (Hooper and Ojakangas,
1971). The presence of graded beds facing opposite dir-
ections within the same limb of a fold, the distribution
of rock units near Tower, and early foliations folded
around later folds all indicate at least two generations
of deformation in the Tower area (Hooper and Ojakangas,
1971; Sims,1976; and Ojakangas, et al. (1978). A third
deformation, first recognized by Van Hise (1911), is
characterized by faults, joints, and kink-bands which dis-
place earlier foliations (Hooper and Ojakangas, 1971).
The folding is attributed to compression caused by the
upwelling and convergence of buoyant granitic bodies of

the surrounding batholithic intrusions (Sims, 1976).
Huddleston (1976) has suggested that at least some of
the first episode of folding is due to slumping and soft-
sediment deformation of the well-layered rocks. Sims
(1976) has described three steep fault sets which post-
date the folding.

In a review and analysis of previous Minnesota geo-
chronological studies, Goldich (1972) suggested that all
Early Precambrian events, including the emplacement of
the Saganaga, Vermilion, and Giants Range batholiths
took place between 2700 and 2750 million years (m.y.)
ago. These refined measurements did not permit differ-
entiation between the Laurentian and Algoman orogenies,
or setting close limits on the duration of the Algoman
orogeny. Jahn and Murthy (1971) reached similar conclu-
sions, reporting ages of 2725 ± 50 m.y. for the Ely Green-
stone and 2720 ± 70 m.y. for the Newton Lake Formation.

Specific studies of the Skeleton Lake prospect were
initiated by airborne magnetic surveys of Exxon Corpora-
tion, which led to their leasing of the area in 1973.
Ground magnetic and electromagnetic survey lines were
placed at 400-foot intervals running at right angles to
a N 80° W baseline. Exxon completed three drill holes
in late 1973 and early 1974, intersecting a 5-to 7-meter
zone of sulfide mineralization in two of the holes. In
the summer of 1974, at the request of Exxon Corporation,
R. W. Ojakangas mapped the prospect area. All the informa-
tion compiled by Exxon is available for public inspection

as part of the permanent files of the MDNR in Hibbing.

In 1975 and 1976, the MDNR conducted ground magnetic and electromagnetic surveys on the pre-existing Exxon grid in the study area and on parallel traverses in the near vicinity. Gyttja lake sediment samples were taken from Skeleton, Little Skeleton, and Putnam Lakes as part of a regional geochemical survey of Northeastern Minnesota.

David Drapela, under the auspices of the MDNR, mapped and sampled the Skeleton Lake prospect during the summer of 1977. His map, samples, and report were made available to the author by the MDNR and Mr. Drapela.

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Special thanks must be extended to my field partner, Lloyd Johnson, who hauled many pounds of samples, took innumerable measurements, and untangled my fishing line, all with exemplary patience and diligence.

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Finally, I would like to acknowledge the constant encouragement of my parents, Ann and Joseph, whose limitless understanding is always a continuing education.

REGIONAL GEOLOGY

The Archean greenstone-granite terrane of the western Vermilion district is typical of other such complexes found throughout the Canadian Shield. These complexes consist of low-grade metamorphic assemblages of volcanic and associated sedimentary rocks usually lying in basin-shaped, parallel linear belts, between gneissic domes and granitoid plutons (Windley, 1977). The rocks are called "greenstones" because of the pervasive greenschist grade metamorphism characterized by secondary chlorite, epidote, and green amphibole. Theories of greenstone belt formation include plate tectonic, vertical tectonic, and meteor impact models (West, 1980).

The steeply-dipping, metavolcanic and metasedimentary rocks of the Vermilion district lie in a northeasterly-trending belt, 10-30 kilometers wide and more than 160 kilometers long. The supracrustal rocks of the district consist of four formational units (Morey, 1970) that are bordered by three, more or less contemporaneous, granitic batholiths (Figure 2, Table I):

1) the Vermilion batholith in the north,

2) the Giants Range batholith in the south; and

3) the Saganaga batholith in the east.

The Keweenawan (1100 m.y.) Duluth Complex truncates the Giants Range batholith and the volcanic-sedimentary rocks in the eastern part of the district.
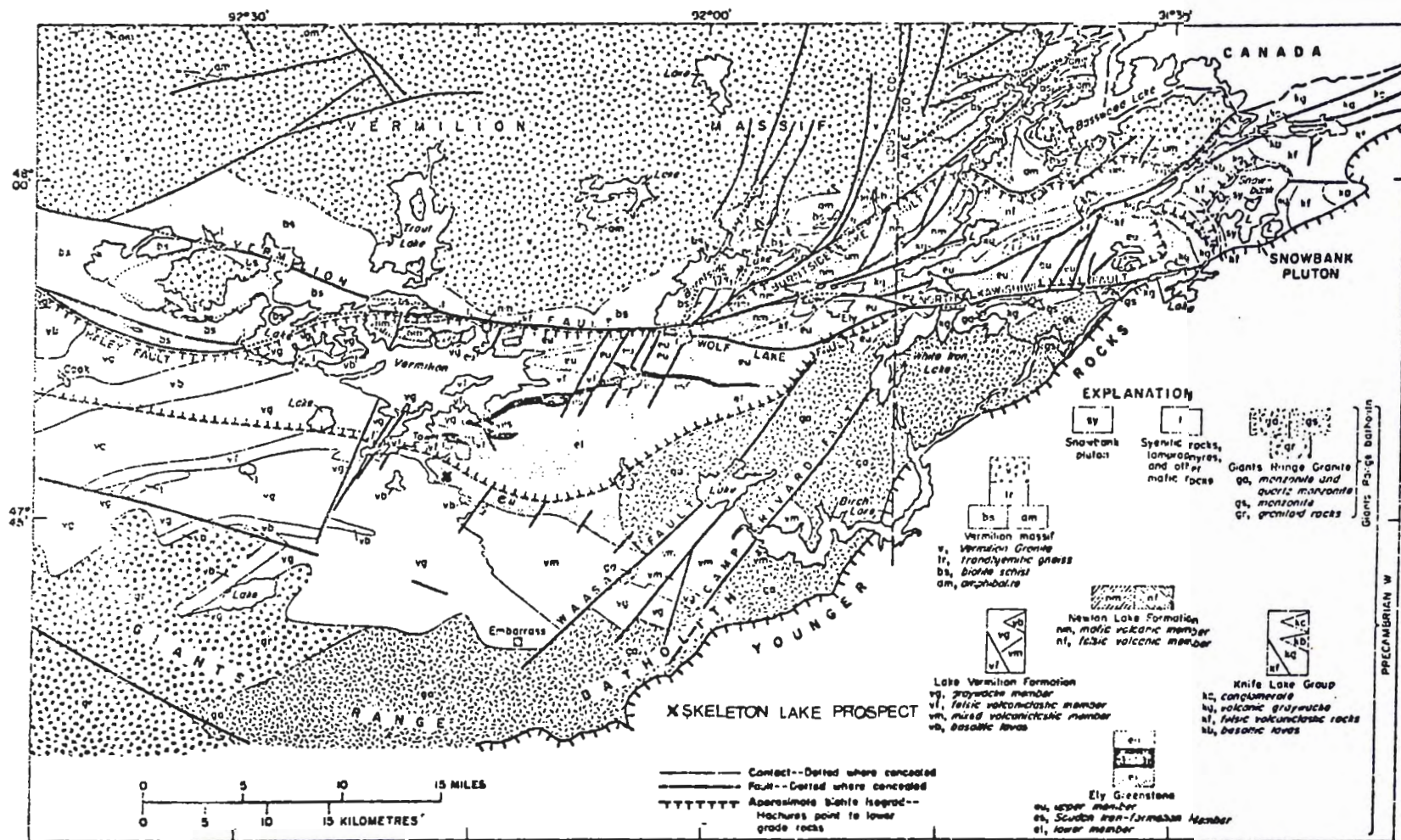
Figure 2 Geologic map for the western Vermilion district (after Sims, 1976).

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TABLE I Supracrustal Rock Units in the
Vermilion District (after Sims, 1976).

Rock Unit	Lithology in order of approximate decreasing abundance	Estimated maximum thickness (m)
Newton Lake Formation		
Mafic Member..........	Pillowed to massive Mafic lava	>1,350
	Diabasic gabbro	
	Differentiated mafic-ultramafic sills	
	Intermediate-mafic pyroclastic rocks	
	Siliceous, impure marble	
Felsic Member.........	Felsic intermediate pyroclastic rocks	>1,000
	Felsic lavas	
Knife Lake Group..........	Felsic-intermediate pyroclastic rocks	4,500
	Graywacke	
	Slate	
	Conglomerate with mixed epiclastic and pyroclastic clasts	
	Iron formation	
	Mafic lavas	
Lake Vermilion Formation		>3,000
Graywacke Member......	Graywacke	
	Felsic-intermediate pyroclastic rocks	
Felsic Volcani-........ clastic Member	Dacite tuff and agglomerate, in part reworked	
Mixed Volcani-........ clastic Member	Felsic-intermediate tuff breccia	
	Volcanic sandstone	
Basaltic Lavas		
Ely Greenstone		
Upper Member..........	Mafic lava, mainly pillowed	3,600
	Intermediate-mafic pyroclastic rocks	
	Diabasic gabbro	
	Iron formation	
Soudan Iron-.......... Formation Member	Iron formation	150
	Intermediate-mafic pyroclastic rocks	
Lower Member..........	Mafic to intermediate amygdaloidal, dominantly pillowed lava	3,000
	Diabasic gabbro	
	Mafic to felsic pyroclastic rocks	

Ely Greenstone Formation

Van Hise and Clements (1901) named the Ely Green-
stone from exposures near the town of Ely, where a
variety of green-colored extrusive, intrusive, and
fragmental rocks occur. Originally all greenstone
bodies in the Vermilion district were considered Ely
Greenstone. Morey, et al. (1970) restricted the term
"Ely Greenstone" to the body of metavolcanic and related
rocks that is continuous with the rocks exposed in the
town of Ely. As redefined, the Ely Greenstone extends
from the vicinity of Tower northeastward for about 65
kilometers and has an outcrop width of 4-10 kilometers.

The Ely Greenstone is divided into three members,
the laterally persistent Soudan Iron member separating
a lower and upper volcanic member. The mafic, mainly
subaqueous volcanism which produced the lower member is
the earliest recognized event in the region. This lower
member is dominantly made up of pillowed and massive
flows, accompanied by pyroclastic material, synvolcanic
hypabyssal intrusions, and lesser amounts of intercalated
sedimentary rocks and iron formation. Although rocks
of basaltic composition predominate, andesitic flows
have been described by Schulz (1978) from a few locali-
ties.

The Soudan Iron Formation forms the thickest and
most continuous banded iron formation in the Vermilion
district. It extends for a distance of about 25 kilometers
from Tower, and consists of several types of ferruginous

cherts that are interbedded with fine-grained carbona-
eous and sericitic tuff and lesser agglomerates and
basalt (Klinger, 1956; Morey, 1979). Locally, the iron
formation has been brecciated and recemented by hematite
or quartz. Massive "blue hematite", which has hydro-
thermally replaced the iron formation, was the source of
high-grade ores mined at Soudan (Gruner, 1926).

The Soudan Iron Formation overlies the lower Ely
member in the western part of the district and was prob-
ably deposited during a quiescent period in the volcan
ism (Sims, 1972). The Soudan Iron Formation is overlain
by the Lake Vermilion member near Tower and by the upper
Ely member at its eastern extent. Because of complex
and repeated folding within this unit, the true thickness
of the member is unknown.

The upper member of the Ely Greenstone lies strati-
graphically above the Soudan Iron Formation, interfing-
ering with the Knife Lake group (to the east) and the
Lake Vermilion Formation (to the west). Morey, (1979)
indicates that the upper member was, at least in part,
contemporaneous with the clastic sedimentation of those
units. The Knife Lake group unconformably overlies the
Ely Greenstone in the Gabbro Lake quadrangle (Green, 1970).
Rocks of basaltic composition comprise the largest part of
the upper Ely member with felsic volcanic rocks, chert,
banded iron formation, and clastic rocks constituting the
remainder.

Generally, the thickness of the Ely Greenstone is difficult to determine because of uncertainties in structure and because the base is transected by granite and the North Kawishiwi fault. However, at Twin Lakes (Griffin, 1967) this unit is estimated to be at least 20,000 feet thick. Green (1970) has determined a minimum thickness of 12,000 feet for the Ely Greenstone in the Gabbro Lake quadrangle.

Knife Lake Group and Lake Vermilion Formation

The Ely Greenstone is overlain by the Knife Lake group (in the east) and the Lake Vermilion Formation (in the west). Both units consist of felsic volcaniclastic and turbiditic rocks, that are mainly of volcanogenic origin (Ojakangas, 1972 and 1979) and were originally mapped together as the Knife Lake group (Gruner, 1941; Grout, et al., 1951). Field work by Morey, et al. (1970) suggested that the strata of the two areas were not demonstrably continuous and established the Lake Vermilion Formation in the west.

Both the Lake Vermilion Formation and Knife Lake group are interpreted as being felsic volcanic centers that were constructed on the mafic volcanic platform and partly buried in their erosional debris, with clast size of the volcaniclastics increasing toward the probable vent centers (Ojakangas, 1979).

Newton Lake Formation

The Newton Lake Formation was originally mapped as Ely Greenstone by Clements (1903) and was later referred

to as the "unnamed" formation by Green (1966) in the Gabbro Lake quadrangle. Green (1970) later showed that the rocks of the "unnamed" formation overlie the Ely Greenstone and are in apparent depositional contact with the Knife Lake group in the area. Morey, et al. (1970) formally designated these younger metavolcanic rocks as the Newton Lake Formation, dividing it into two informal members that intertongue in the vicinity of Newton Lake:

1) a mafic volcanic member occurring west of Newton Lake; and,

2) a felsic to intermediate volcanic member to the east.

The Newton Lake Formation probably represents renewed mafic-intermediate volcanism in the central part of the Vermilion district, while sporadic mafic volcanism and clastic sedimentation (Lake Vermilion Formation) continued in the western part of the district (Sims, 1972).

Intrusive Rocks

Three varieties of hypabyssal intrusive rocks have been recognized in the volcanic-sedimentary pile (Sims, 1972). See also Green (1970) for other minor types. These consist of:

1) diabasic dikes and sills in the Ely Greenstone and Newton Lake Formation,

2) differentiated mafic-ultramafic sills in the mafic portion of the Newton Lake Formation; and,

3) dikes and small bodies of quartz-plagioclase porphyry found locally throughout the volcanic-sedimentary pile.

Several types of plutonic rocks occur in the western part of the district. The oldest recognized are the syntectonic rocks of granitoid composition that constitute the western part of the Giants Range and Vermilion batholiths (Southwick, 1972). Younger post-tectonic rocks of monzonite-quartz monzonite composition compose the eastern end of the Giants Range batholith and also occur as small, isolated plutons along the length of the supracrustal belt (Sims, 1976). The youngest plutonic rocks in the region are post-tectonic alkalic syenites and associated lamprophyres (Sims, 1976).

Structure

The supracrustal rocks in the district are steeply inclined and complexly folded. Geologic evidence indicates that major faulting post-dated the folding and superimposed a steep shingling effect to the original fold pattern (Sims, 1976). The variety of folds that have developed is a function of the physical characteristics of the original rock types. In general, the layered rocks have responded to deformation more plastically, resulting in steep isoclinal folds with short wavelengths. The more massive volcanic rocks have yielded mainly by brittle fracture and now form steeply-dipping homoclines of wide regional extent (Sims, 1976).

Although evidence for superimposed folds is widespread, the pattern of multiple folding has only been examined in the Tower area (Hooper and Ojakangas, 1971; Sims, 1976). Hooper and Ojakangas (1971) assigned a F_1

and F_2 notation to the first and second generation of folding, respectively. Subsequently, Sims (1972, 1976) gave the geographical names Embarrass-Lake Vermilion (F_1) and Tower (F_2) to these deformational episodes.

In the Tower area vertical structures such as faults, joints, and kink bands displace the F_2 folds, and represent a still younger event (Hooper and Ojakangas, 1971). Such structures are also present in the Ely-Moose Lake area to the east (Green, 1970).

Three steep fault sets post-date the folding (Sims, 1976):

1) vertical dip-slip faults,

2) right-lateral, steep strike-slip faults, longitudinal to the Vermilion district; and,

3) transverse (northeast-trending) left-lateral strike-slip faults.

The transverse faults generally have lesser displacements, both horizontally and vertically, than the longitudinal faults. The longitudinal Vermilion fault is the most laterally continuous fault in the district and separates granites and associated high-grade schists from green-schist facies rocks (Sims, 1972). From his study of the structure in the Vermilion district, Sims (1976) interpreted both sets of strike-slip faults as forming at approximately the same time.

Metamorphism

All the supracrustal rocks in the western Vermilion district have been subjected to metamorphism, usually to

at least the greenschist facies (Sims, 1972). Quartzo-feldspathic rocks contain chlorite, muscovite, albite, quartz, and epidote; whereas, mafic rocks contain chlorite, calcite, tremolite or actinolite, epidote, and quartz. Generally, recrystallization is incomplete as evidenced by well-preserved bedding features and primary textures. In addition, zoned plagioclase crystals and relict horn-blende grains are widespread in the felsic volcanogenic and volcanoclastic rocks as are relict augite and labra-dorite in the mafic rocks (Green, 1970).

Metamorphic intensity increases toward bounding granite masses or major faults, reaching middle-upper amphibolite facies grade metamorphism near contacts. The metamorphic aureoles associated with the plutons vary in width and maximum grade attained, depending on the tectonic setting in which they were emplaced (Griffin, 1967). All of the metamorphic assemblages in the district appear to be similar to the Abukuma-type facies series of Miyashiro (1961), which is characteristic of regions with steep thermal gradients at low to moderate pressures.

THE GEOLOGY AND PETROGRAPHY

OF THE

SKELETON LAKE PROSPECT

Introduction

Over eighty percent of the exposures near Skeleton
Lake are extrusive flows. The volcanics have been
assigned to the Soudan Iron Formation (Sims and South-
wick, 1980) because they contain considerably more iron
formation than either the lower or upper Ely Greenstone,
and are demonstrably continuous with the more character-
istic Soudan Iron Foramtion at the type locality (Figure 2).

The orientation of the Skeleton Lake rocks is related
to an overturned plunging anticline originally described
as a syncline by Clements (1903). The hinge of this major
fold is located just west of Tower, with a northern and
southern limb extending eastward until they are truncated
by the Giants Range batholith. The mapping area is located
on the southern limb of the synform, five and one-half km.
southeast of Tower. The structural trends of pillowed
flows and banded iron formation indicate that the rocks
strike northwest-southeast, dip to the northeast, and have
a stratigraphic younging direction to the southwest.

The majority of outcrops at Skeleton Lake are basaltic-
andesitic flows (see Chapter 4), diabase, and pyroclastic
rocks. Smaller amounts of iron formation, intrusive por-
phyries of varying composition, and post-Algoman mafic
dikes also occur throughout the volcanic pile (Plate I).

EXPLANATION

ARCHEAN

A_v Lake Vermilion Formation

A_{ue} Upper Ely Member Ely Formation

A_s Soudan Iron Member Ely Formation

A_{le} Lower Ely Member Ely Formation

—————— Inferred Lithologic Contact

Overturned Fold Axis (Anticlinal)

Minn

N

Scale 1:9050

0   1   2
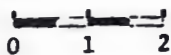
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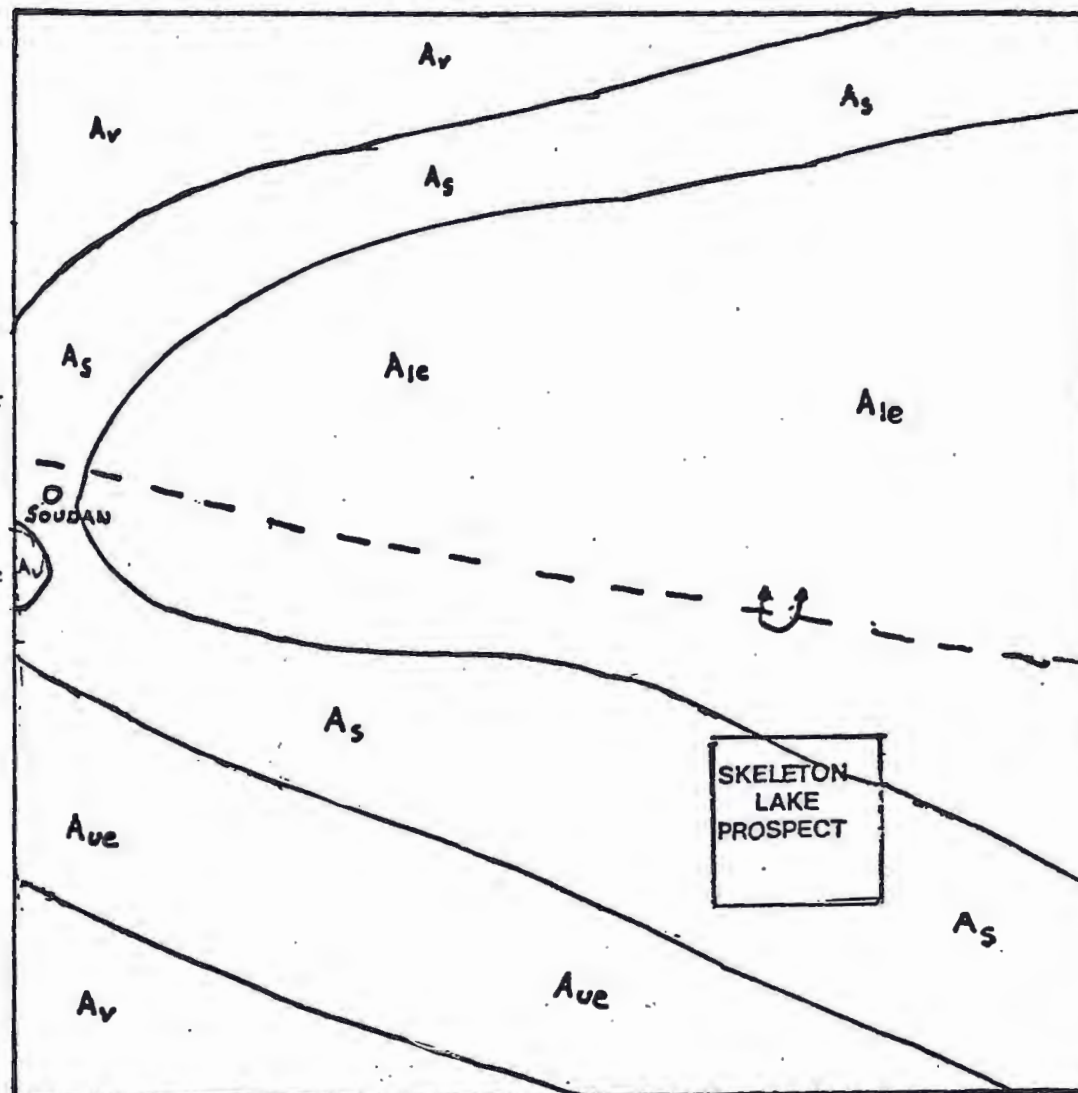
Figure 3 Generalized Regional Geology
Skeleton Lake Prospect Area

Extrusive Rocks

. At Skeleton Lake, the flows alternate between basaltic and andesitic compositions from north to south across the study area (Plate II). Regionally, the basalts are much more important volumetrically, as the andesites tend to pinch out along strike to the northwest and southeast of Skeleton Lake (Aesm unit of Sims and Southwick, 1980), P. K. Sims (1980) visited the area while compiling data for the USGS Soudan Quadrangle Map 1:24,000 (Sims and Southwick, 1980). Sims and the author both mapped similar lithologic boundaries in the volcanic pile, but Sims based these contacts on the relative abundance of iron formation rather than a primary difference in composition between the flow units. It would seem that at least in the immediate area of Skeleton Lake, there is a correlation between the relative abundance of iron formation and the composition of the flows, the more intermediate flows being more frequently associated with iron formation.

Basaltic Flows
(Unit B, Plate II)

The thickness of the basaltic flow sequences varied from 200 to 300 meters. As determined by actual outcrops, this unit has a strike length of 1150 meters. On the basis of interpretative or inferred contacts, the strike could be extended for more than 2 kilometers across the study area.

Approximately 60% of the basalt outcrops are pillowed. Generally, the pillows are bulbous, more or less equidimensional, and range in size from about 15cm. to over a meter,

Elongated pillows were found along the western margin of
the ridge in Section 8 (Locations 5, 7, and 8). The pil-
lows consistently trend northwest-southeast and top toward
the southwest. The pillow rims are thin (< 2cm.) and gray
to medium green, the darker colored rims having higher
percentages of epidote and chlorite. The pillow rims are
usually more altered than the interior portion of the pil-
low as evidenced by numerous quartz, epidote, and chlorite
veinlets.

Approximately one-fourth of the exposures of basalts
were amygdaloidal. The amygdules were generally round or
ovoid, .3-1.5mm. in diameter, and rarely made up more
than 5-10% of the rock. The fillings were most commonly
quartz and/or recrystallized actinolite, with or without
chlorite, epidote, carbonate, and pyrite. In well-foliated
rocks, the amygdules were stretched to some degree, the
elongated dimension in places approaching 4-5 times the
length of the shorter dimension. The volume percent and
diameter of the amygdules suggests extrusion at moderate
depths between 500-1000m. below sea level (Moore, 1965;
Jones, 1969).

The basaltic flows are dark to medium-green and aph-
anitic. Non-pillowed flows, representing either the mas-
sive interior of flows or hypabyssal dikes and sills, are
generally coarser-grained than pillowed flows and have
diabasic textures.

In this unit, the pillowed flows are typically
equigranular, hypidiomorphic, and fine-grained, with
amygdules concentrated in the pillow rims. In some

samples the pillow rims are porphyritic, with phenocrysts
(up to 15%) of augite (now actinolite) in a granoblastic
fine-grained matrix of sodic plagioclase. In both the
rims and the interior of the pillows, the primary minerals
have been replaced by greenschist facies mineral assem-
blages. Actinolite (30-60%) and albitic plagioclase (15-
30%) are the major constituents with epidote ($<$ 1-15%),
chlorite ($<$ 1-10%), quartz (0-10%), magnetite (0-7%),
calcite (0-5%), and rarely biotite (0-4%), usually com-
prising the remainder of the rock. Sphene (0-3%) and
pyrite (0-2%) are common accessory minerals (Figure 4 and
Table II).

Massive and pillowed flows that contain less actino-
lite (25-35%) are commonly porphyritic. These rocks con-
sist of microphenocrysts or glomeroporphyritic clusters
(up to7%) of plagioclase and actinolite set in a fine-
grained matrix of plagioclase microlites, actinolite,
chlorite, and epidote. The plagioclase microphenocrysts
are up to .5mm. long, lathlike or tabular in shape, are
largely replaced by albite, and commonly are altered to
saussurite and/or sericite. The chlorite, calcite, and
epidote are often in fine-grained ($<$ .3mm.) aggregates
throughout the groundmass and are typical of rocks with
hyalopilitic or pilotaxitic textures.

The coarser-grained basalts commonly exhibit dia-
basic textures, tend to have more actinolite (45-60%), and
typically are less altered than the finer-grained basalts.
Many workers (i.e., Schulz, 1978) believe that these dia-
basic rocks represent near-surface feeder systems below

TABLE II

MODAL ANALYSIS OF MAJOR LITHOLOGIC UNITS

	S-17 Basalt	S-32 Andesite	S-25-F Iron Fm.	S-1 Dacite Porphyry	S-18 Andesite Porphyry	SL-50 Volcani- clastic
ACTINOLITE	48	15	2	--	7	7
PLAGIOCLASE (ALBITE)	22	52	--	50	50	18
ORTHOCLASE	--	--	--	5	4	--
CHLORITE	7	5	--	2	1	1
EPIDOTE	5	5	--	3	1	2
CALCITE	3	5	3	1	1	7
QUARTZ	6	10	75	37	27	53
IRON OXIDES	4	<1	20	--	--	--
BIOTITE	--	--	--	--	6	7
SPHENE	<1	1	--	--	--	--
SAUSSERITE- SERICITE	5	3	--	2	3	5
APATITE	--	--	--	<1	<1	--
PYRITE	<1	<1	<1	<1	--	--

Albite was An_{0-10} as determined by the Michel-Levy Method.
Calcite was differentiated from other carbonate minerals by
x-ray analyses.
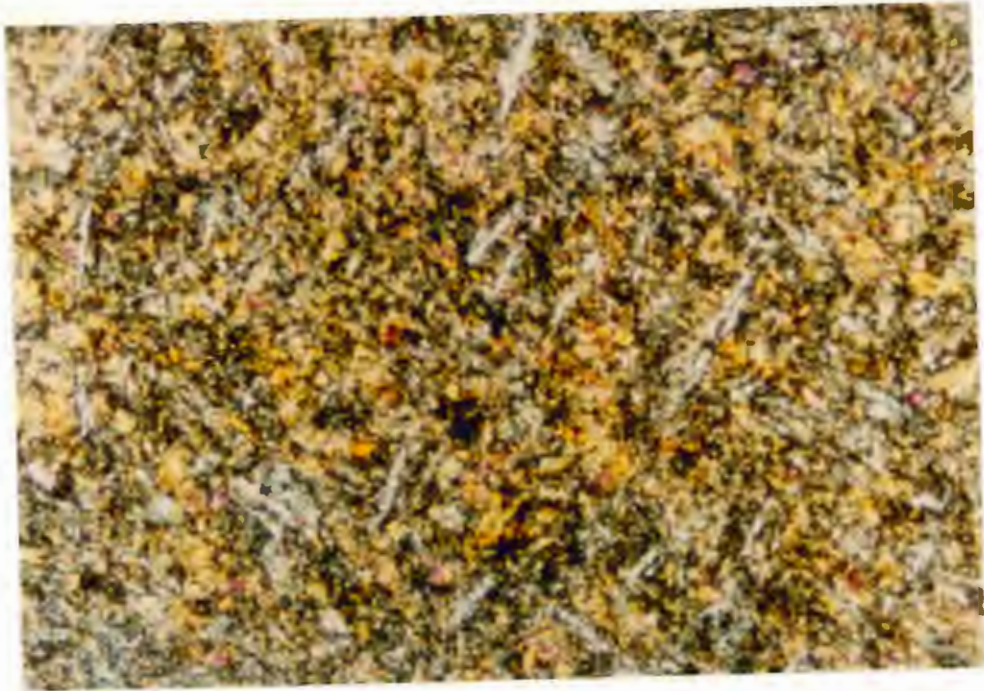
Figure 4 Typical Basalt. Note abundance of actino-
lite. Field of view: 5mm
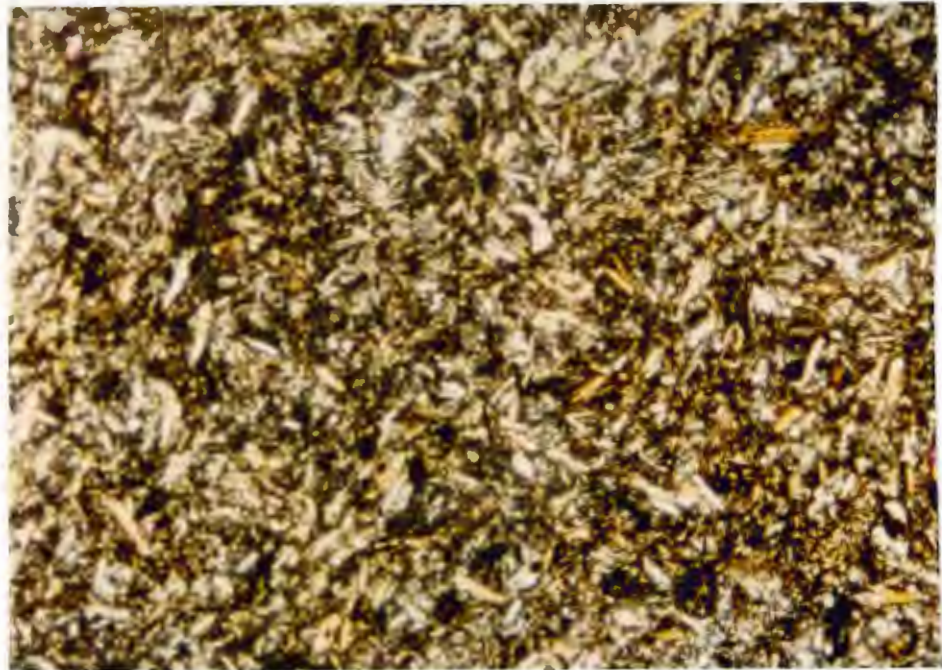
Figure 5 Typical Andesite with <10% actinolite.
Field of view: 5mm

associated pillowed flows.

Andesitic Flows, (Unit A, Plate II)

The andesitic flow sequences have similar strike
lengths but are not quite as thick (75 to 250 meters)
as the basaltic flows. The andesitic flows occur near
the various alteration zones (Chapter 4) and are more
commonly associated with outcrops of volcaniclastic rocks
and iron formation (Plate II).

The andesites are aphanitic to fine-grained and
tend to be gray or black as opposed to the dark chloritic
green which is more characteristic of the basaltic flows
(Figure 6). The andesites are less commonly pillowed
($\approx$ 30%) than the basaltic outcrops, but the pillows are
similar in shape, size, and texture. The pillow rims in
the andesitic flows tend to be lighter in color than the
basaltic pillow rims, due to greater amounts of quartz
and carbonate. Two of the pillowed andesites (Locations
46 and 47) were coarser grained than the typical pillowed
flows. The amygdules observed in the andesites were in
all ways similar to those found in the basalts.

Mineralogically, the andesites have conspicuously
lower percentages of actinolite (10-25%) and a greater
abundance of plagioclase (40-75%), calcite (0-15%), and
quartz (10-25%) (Figure 5). Biotite (0-5%) is an occa-
sional accessory mineral (Table II).

Most of the andesites are porphyritic, with micro-
phenocrysts and glomeroporphyritic crystals (up to 1.5mm.)
of plagioclase (2-5%) set in a groundmass of quartz,
plagioclase microlites, fine-grained epidote, and actino-

Figure 6 Hand samples of dark green basalt (left) and gray-black andesite (right), illustrating the color difference between flow units.

lite, with or without magnetite-ilmenite, carbonate, chlorite, and biotite. The plagioclase in both the phenocrysts and groundmass is frequently altered to sericite and/or saussurite. Less commonly, the andesites are comprised of an equigranular fine-grained mosaic of quartz and plagioclase with minor amounts of the previously mentioned accompanying minerals.

Volcaniclastic Rocks
(Unit T, Plate II)

Thin interbeds of volcaniclastic rocks, ranging from a few centimeters to a meter in thickness are found interlayered with both the flow units. Although these interlayers are widely distributed, they comprise less than 5% of the exposed volcanic succession. Relatively large (up to 3 x 7m.) isolated outcrops of volcaniclastic rocks occur along two northwest-trending zones (see Chapter 4) within the volcanic pile (Plate II). The three diamond drill holes were located in one such zone and intersected extensive volcaniclastic sequences (up to 40m. thick).

Due to their lower competence, the volcaniclastic rocks are characterized by a much stronger cleavage than the surrounding flows. The effects of alteration and metamorphism coupled with the pervasive cleavage obscures any bedding that may have been originally present.

The weathered outcrop surfaces are pale green and typically well foliated. Fresh surfaces are dark to medium green or gray, fine-grained to aphanitic and commonly have patches of quartz and/or carbonate concentrated along the cleavage planes. In hand sample, rock

fragments (2-10%) up to 6mm. long are the only other readily visible component of these rocks.

In thin section, the rock fragments are composed of heavily saussuritized plagioclase (20%), actinolite (30%), chlorite (5-10%), and various minor nondescript, micro-crystalline alteration products that give these fragments a brownish semi-opaque appearance (Figure 7). The ground-mass is dominantly a fine-grained (< 2mm.) mixture of quartz and minor plagioclase (10-25%) with or without varying amounts of biotite, chlorite, sericite, epidote, carbonate, and recrystallized needlelike amphibole. Locally subhedral to euhedral plagioclase crystals and crystal fragments (< .1-.3mm.) comprise up to 15% of a particular sample.

Because of the basic composition of the rock frag-ments and the presence of plagioclase crystals, the high percentage of quartz in the groundmass is probably, at least in part, due to secondary silicification of origi-nally more mafic rocks. Although recrystallization, metamorphism, and alteration have made it difficult to determine the origin of these rocks, the presence of fragmental, subhedral-euhedral crystals, their more common association with intermediate rather than basic volcanic rocks (see Andesite, this chapter, and Plate II), and their occurrence with exhalative sulfides (see Chapter 5) would suggest that these volcaniclastic units are pyro-clastic sequences within the volcanic pile.

A small outcrop (1 x 2m.) of what appears to be either an agglomerate or conglomerate is exposed at Loca-
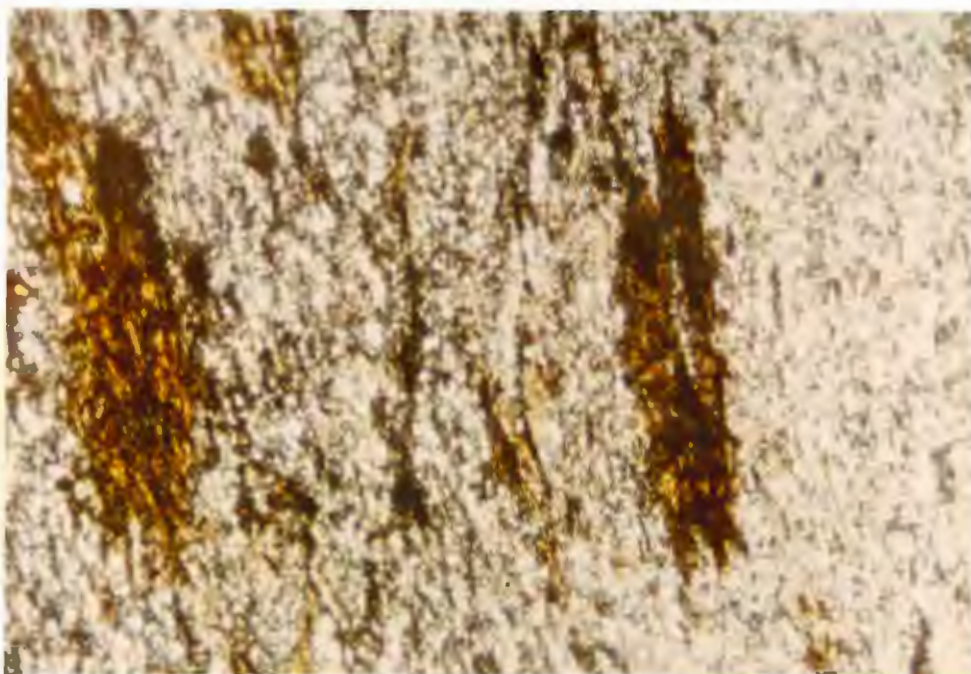
Figure 7   Altered mafic rock fragment in a silicified
tuff.   Field of view: 5mm

tion 58. Large (10-14cm.) gray-white clasts are set in a dark green, aphanitic to fine-grained matrix. The clasts are crudely aligned parallel to their long axes and make up about 40% of the outcrop.

As seen in thin section, the minerals within the clasts have been completely altered to epidote, chlorite, and quartz. The matrix is primarily chlorite (70%) with minor amounts of quartz, carbonate, and iron oxide. Veinlets of sericite with minor potassium feldspar and quartz are present in both the clasts and matrix. Due to the extremely limited exposure and complete alteration of original mineralogy, the relationship of this outcrop with the other volcanic units at Skeleton Lake is unknown.

Three outcrops of brecciated basalts occur at Locations 24, 58, and 76, in the vicinity of the two northwest-trending pyroclastic-alteration zones (Plate II). In all of these outcrops the fragments are angular, up to 8cm. in size, and have very little matrix ($<30\%$). The fragments are still in place or only slightly rotated and thus have not been transported. Outcrop 76 is clearly a pillow breccia as many of the fragments are pillow rinds. The other two outcrops are massive basalts, but were probably brecciated as the result of volcanic processes also. The mineralogy of the fragments is in all ways similar to the previously described basalts, while the matrix is dominantly made up of chlorite and epidote with minor amounts of quartz and carbonate. Similar brecciated zones occur over limited footages throughout the drill core.

Iron Formation (Unit I, Plate II)

Discontinuous outcrops of iron formation and associated volcaniclastic material are found between the extrusive rocks throughout the study area, but are especially prevalent near the andesitic flows (Plate II). The overall outcrop width of these sedimentary sequences average from 10 to 80 cm., but attain thicknesses up to a meter or more. In two of the larger exposures the iron formation had a considerable outcrop expression (3m. x 3m. x 7m.). Generally the outcrops persist along strike for less than 200m. but one iron formation in the north could be traced for approximately 1000m. across the area.

Although many of the outcrops exhibit well-developed bedding, a number of outcrops are only crudely bedded and at four locations are completely massive. Where bedding is evident, it is defined by rhythmically-layered black-gray ferruginous chert and barren white or red chert.

The cherts consist of a fine-grained ($<.2mm.$) aggregate of magnetite and quartz in variable amounts, with minor sericite, carbonate, chlorite, actinolite, and pyrite. Veinlets of almandine garnet were observed in one sample from outcrop Location 74. Slender crystals and radial clusters of cummingtonite-grunerite were frequently concentrated on foliation surfaces in minor shear zones within iron formation. Two samples of the massive iron formation revealed an assemblage of cummingtonite-grunerite (65%), and magnetite (30%) with minor sericite, carbonate and quartz. The abundance of amphibole, and the

lack of quartz, suggests that these massive units may be iron-enriched mafic flows intimately associated with iron formation.

In the far southwest area of the study site (Outcrop 90), a thick sequence (15') of bedded, iron poor chert was observed. Sericite and cummingtonite-grunerite has crystallized along the bedding planes. Locally, these beds are brecciated and have been infilled by sulfides between the fragments.

Intrusive Rocks

Porphyritic Dacite and Andesite
(Unit DP-Plate II)

Felsic to intermediate porphyritic intrusive rocks (Figure 8) occur in a series of outcrops concentrated along the eastern and northern margins of the study area and as isolated outcrops throughout the volcanic succession (Plate II). Porphyritic dikes generally have sharp contacts with the volcanic rocks and consistently strike within 10-20° of east-west. At one location a xenolith of volcanic material was enclosed within a dacite dike. The porphyritic rocks typically have uniform, buff-brown weathering surfaces. On freshly broken surface, phenocrysts (.5-3mm.) are readily apparent in comparison to the fine-grained to aphanitic groundmass. The more intermediate varieties usually have a darker colored groundmass due to higher percentages of chlorite and amphibole.

Tabular, or blocky phenocrysts (0-3mm.) of plagioclase are the most abundant constituent (30-45%) of the dacites.
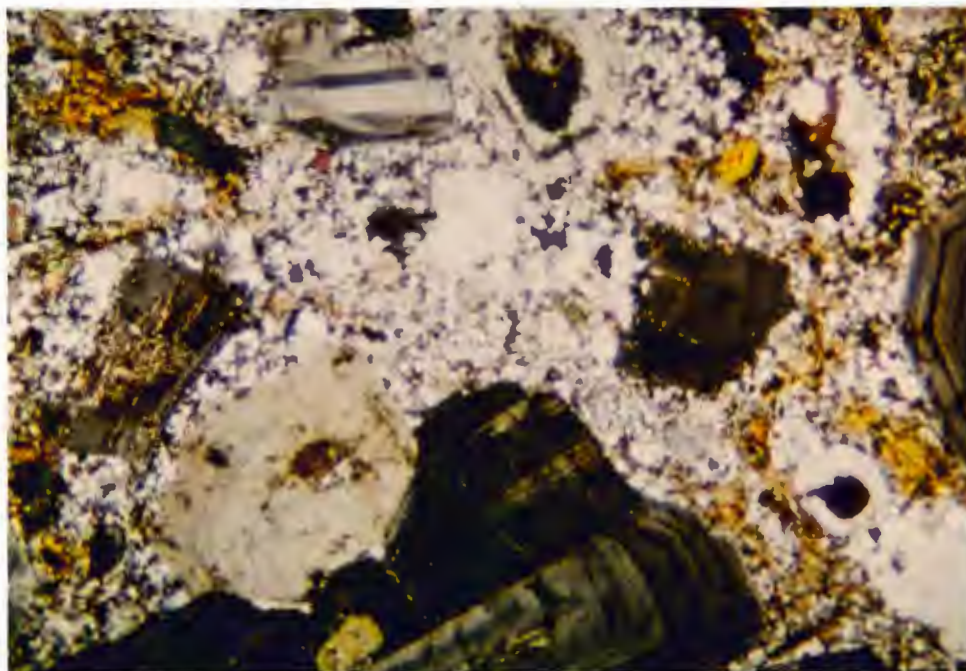
Figure 8 Typical Dacitic Porphyry. Field of view: 5mm

Oscillatory zoning is strongly developed in many of them. Unzoned crystals are albitic (An_{5-10}). The plagioclase has generally been altered in some degree to saussurite, sericite, or carbonate. Tabular orthoclase crystals (4-10%) with a similar size and form to the plagioclase, were noted in stained sections of several samples. Quartz phenocrysts (1-3mm.) are also ubiquitous in these rocks (5-15%) as equant, subhedral to anhedral rounded crystals that are frequently embayed. Actinolite is present as prismatic crystals or elongate feathery masses and is commonly altered to carbonate, chlorite, and epidote. The groundmass is principally composed of fine-grained (<.3mm.) quartz and plagioclase. Apatite is generally present as microphenocrysts in amounts less than 1%, while sphene and pyrite are less common constitutents of the groundmass. Biotite (1-5%) is especially prevalent in the porphyritic dacite in the northwest part of the mapped area.

The porphyritic andesites differ from the dacites mainly in their lack of quartz phenocrysts and their higher percentages of hornblende, biotite, and associated alteration products.

Quartz Diorite (Unit O, Plate II)

At Location 15, a 6 x 16m. outcrop of quartz diorite was observed lying above porphyritic dacite. In hand sample large, elongate (5-10mm.) clots of biotite contrast with a medium-grained "salt and pepper" groundmass of quartz, plagioclase, and finer-grained biotite. In thin section, the quartz (15-20%) is observed to be interstitial to a

hypidomorphic-granular accumulation of kaolinized sodic plagioclase (65-70%), biotite (3%), and hornblende (2-3%). Both the biotite and hornblende have begun to alter to chlorite and sericite. Patchy carbonate and iron oxides are also present in minor amounts (1-2%).

Mafic Intrusive Rocks
(Unit MP, Plate II)

Porphyritic basalts occur sporadically with the mafic flow units. These intrusive bodies are exposed in small discontinuous outcrops, the largest outcrop being only 5 x 25m. The mafic phenocrysts give both fresh and weathered surfaces a black to dark-green, grainy appearance. Prismatic uralitized pyroxene phenocrysts (1-3mm.) make up about 35% of these rocks. Although the pyroxene has been almost completely replaced by actinolite, euhedral pyroxene crystal shapes and relict grains are still observable (Figure 9). Many of these crystals have altered in a large degree to sericite, chlorite, and carbonate. Clots of needlelike actinolite and chlorite may represent altered olivine. The groundmass is a fine-grained, granular assemblage of plagioclase (15-20%), epidote (5-10%), carbonate (2%), chlorite (8-12%), quartz (0-2%), magnetite (3-5%), and biotite (1-2%). Pyrite (2-4%) and sphene (1-3%) are also commonly present.

A gabbro with a similar mineral assemblage was found at Locations 12 and 14. In hand sample, the mafic crystals tend to stand out prominently against a dull green background. Thus, in the field, these rocks appear identical to porphyritic basalts.
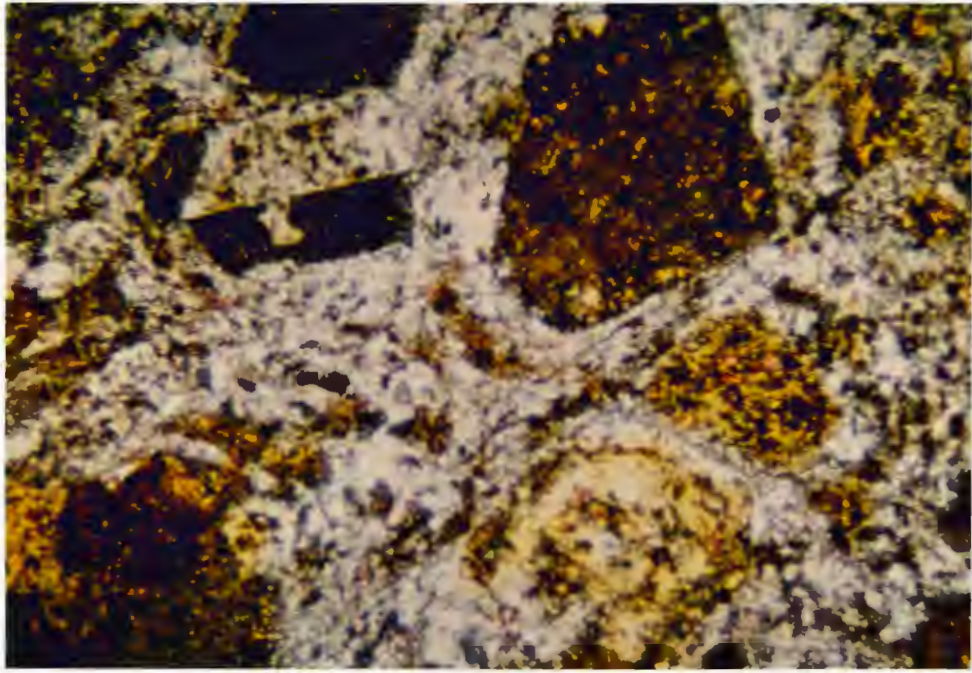
Figure 9   Mafic Porphyry.   Field of view: 5mm
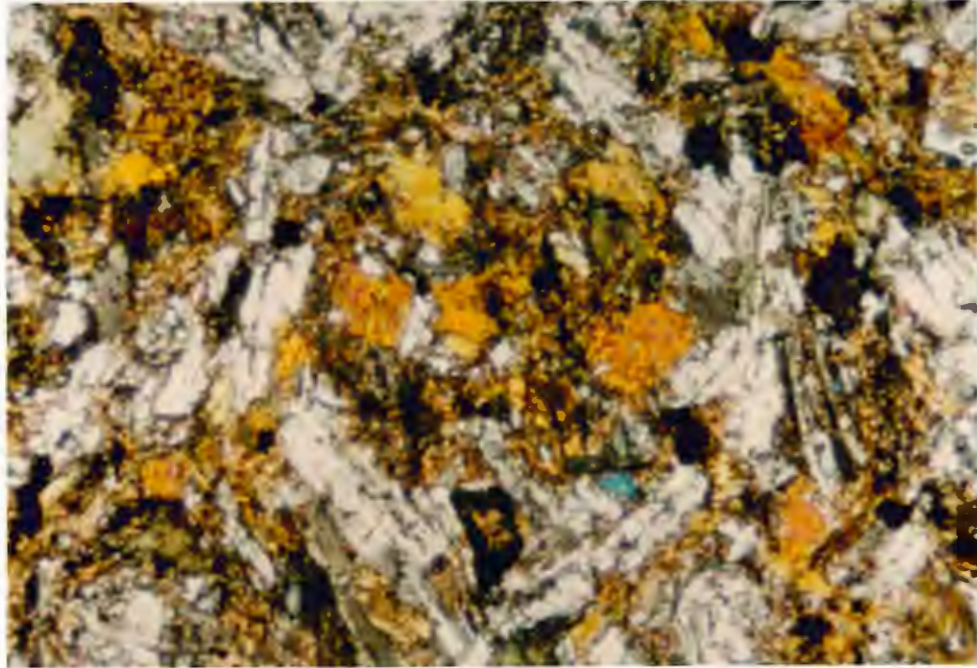
Figure 10   Late Diabase.   Original clinopyroxene
is preserved.   Field of view: 5mm

In addition to the diabasic rocks that are considered to be contemporaneous with the basaltic and andesitic flows (see Basalts, this chapter), much fresher diabasic dikes of similar composition have also intruded the volcanic pile (Locations 45 and 50). These rocks do not seem to have undergone regional metamorphism. Clinopyroxene and andesine are the major mineralogical constituents rather than the typical greenschist assemblage of actinolite and albite (Figure 10).

Several small dikes of diabasic gabbro were mapped in the Tower Quadrangle (Ojakangas et al., 1978). Samples from these dikes yielded a range of age dates between 1.5 and 1.7 billion years (Hanson and Malhotra, 1971). The less altered mafic diabase from the Skeleton Lake prospect may be related to this younger set of dikes.

<div align="center">STRUCTURE</div>

The orientation of the lithologies at Skeleton Lake is controlled by an overturned east-west trending anticline of regional extent. Pillowed flows have northwest-westerly strikes and south-southwesterly younging directions. Bedded iron formations strike northwest and are overturned steeply to the north. Folding within the iron formation and the orientation of penetrative structures in the volcanic rocks reflect the position and direction of this major fold.

Folding

Small-scale internal folding was evident only in the well-stratified iron formation, as the more massive mafic

volcanic rocks yielded to deformation homogeneously. The folds were generally small (5-15cm. in amplitude), moderately tight, and symmetrical, although a large, broad fold with an amplitude of 1m. was observed at Location 74. These small-scale folds consistently parallel the regional synform, having northwesterly-westerly trends and moderate plunges (50-70$^{\text{o}}$) to the northwest. At Outcrop 80 a second period of deformation refolded the limbs of the folds along northeast-trending axial planes (Figure 11).

Faults

A linear, northeast-trending topographically low area crosscuts the regional strike of various stratified units in the northwest corner of the mapping area. In thin section, a greater abundance of fine-grained ($<$.1mm.) epidote, carbonate, and more strongly sausseritized plagioclase was noted in many samples from this zone. The exposures generally have a strong foliation parallel to the trend of the zone and are commonly cut by minor shear zones. Because of the discontinuity of the outcrops and lack of good marker beds, a displacement along this zone could not be mapped with confidence. However, the shearing, parallel foliation, and more pervasive alteration in otherwise relatively impermeable rocks, would suggest at least a zone of movement or shearing.

Figure 11   Refolded Iron Formation.   Arrows denote
the trends of the two fold axis.

Penetrative Structures

Foliations

Foliation planes within chlorite, biotite, or sericite-bearing flows and the pyroclastic units in general, are well defined by the orientation of platy minerals. Poles to foliation were plotted on a Schmitt equal-area net and then contoured on a Kalbrek counting grid (after Reagan, 1973). The results (Figure 12) are in good agreement with measurements by Sims (1972) for the western Vermilion district. The general pattern appears to be nearly homoclinal with average strikes of N 45-50° W and dips of 75-85° to the northeast. The high concentration of readings near N 90° E were in part due to foliation associated with the intrusive contacts of the porphyries which were always within 15° of N 90° W. This subsidiary concentration of points in the southeat quadrant may be due to the northeast-southwest trending shear fault zone discussed in the previous section.

Lineations

Lineations were defined by actinolite prisms in the more mafic rocks and by mineral streaking on the foliation surfaces of various other units. The lineations generally plunge to the northwest (Plate II) at moderate (40°) to vertical angles.

Metamorphism of the Volcanic Rocks

At Tower, the volcanic succession has been metamorphosed to lower greenschist facies (Sims, 1976). Near the Giants Range batholith, approximately 12-18 kilometers to

NUMBER OF COUNTS
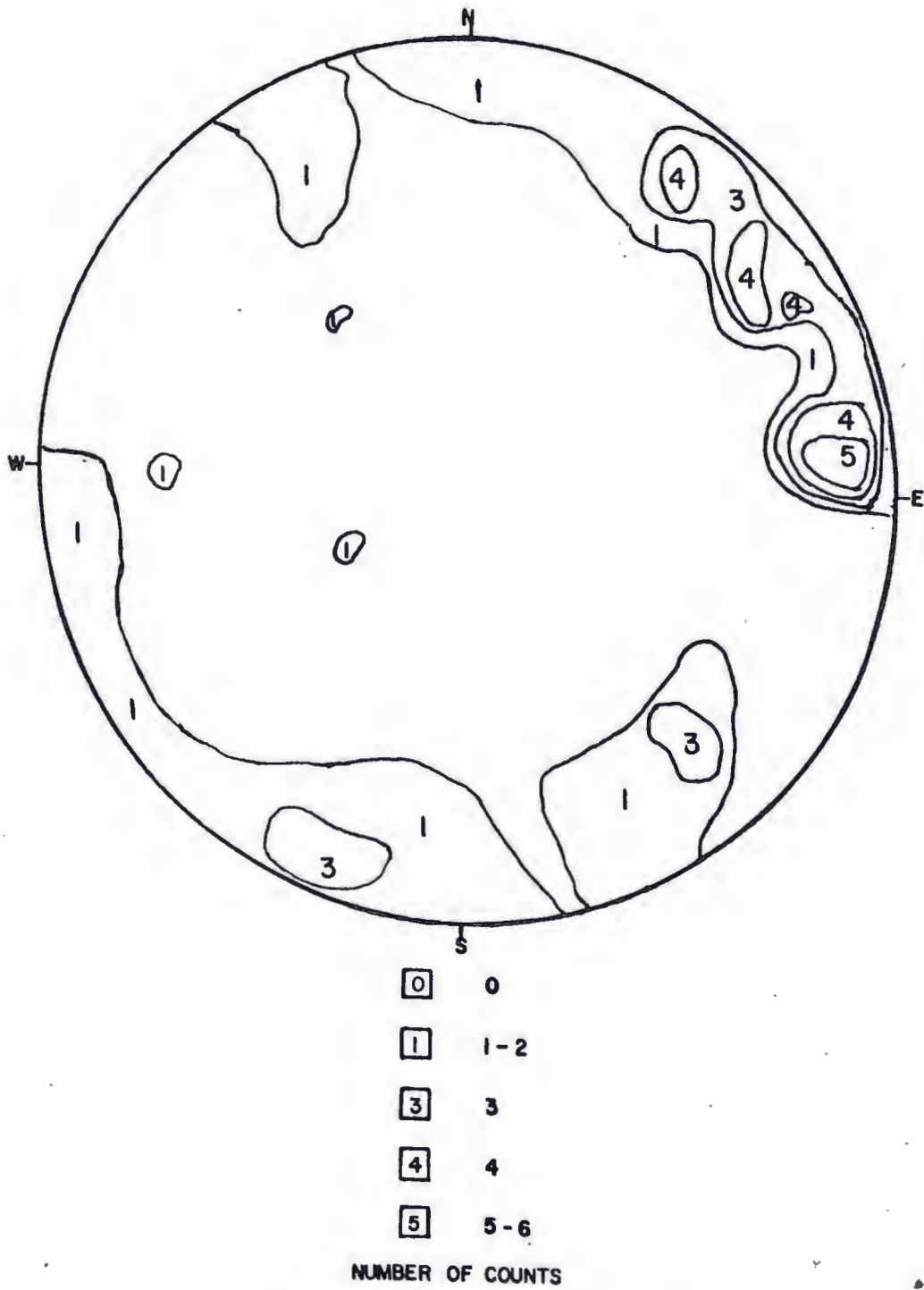
Figure 12: Contoured Poles to Foliation Diagram

the east, amphibolite assemblages are developed locally
in metamorphic aureoles (Griffin, 1967). Thus, rocks of the
Skeleton Lake area lie in a transitional zone between
epidote-amphibolite facies rocks to the west and lower
greenschist facies rocks to the east. The metamorphism
of the supracrustal rocks is interpreted as being contemp-
oraneous with the granitic massifs that now constitute
the Vermilion batholith and the western part of the
Giants Range batholith (Sims, 1976).

The mineral assemblages at Skeleton Lake reflect
both the regional greenschist grade metamorphism of the
Vermilion district, and the more local effects of hydro-
thermal activity (discussed in a later section) associated
with sulfide deposition. The pervasive low-grade meta-
morphism of the mafic and intermediate volcanic rocks has
produced the typical greenschist assemblage of actinolite-
albite-epidote-magnetite, with or without chlorite, quartz,
carbonate, sphene, and biotite. This assemblage is compar-
able to the low-intermediate pressure group or Abukuma-
type facies series of Miyashiro (1961, 1968), which is
characteristic of regions with steep thermal gradients at
low to moderate pressures.

GEOCHEMISTRY AND HYDROTHERMAL ALTERATION

OF THE SKELETON LAKE ROCKS

Geochemistry of the Skeleton Lake Rocks

Any geochemical interpretation of Archean volcanic
rocks has inherent difficulties due to the complex history
of greenstone terranes. Beside chemical variations attrib-
utable to the genetic evolution of the source magma, these
rocks may have experienced any or all of the processes of
deuteric alteration, diagenesis, spilitization, hydro-
thermal alteration, or regional metamorphism.

Twenty samples were analysed for major elements to
determine the chemical nature of the Skeleton Lake rocks,
and to permit a comparison with other greenstone terranes
from the Superior province of the Canadian Shield. Five
samples of various intrusive porphyries and one sample from
a post-Algoman diabasic dike were analysed for comparison
with similar units found throughout the Vermilion district.
Twelve samples from the flow unit and one sample from the
volcaniclastic unit were analysed in an attempt to chemi-
cally define the compositional variance of the volcanic
rocks, which was initially assumed from differences in
outcrop color and texture, noted in the field. Eleven
additional analyses of Skeleton Lake flow units (also pre-
pared by the MDNR) were made available to the author by
David Drapela (personal communication, 1977).

Jensen Cation Plot (Figure 13)

The Jensen Cation Plot (Jensen, 1976) was used in an
attempt to chemically classify the volcanic rocks of the
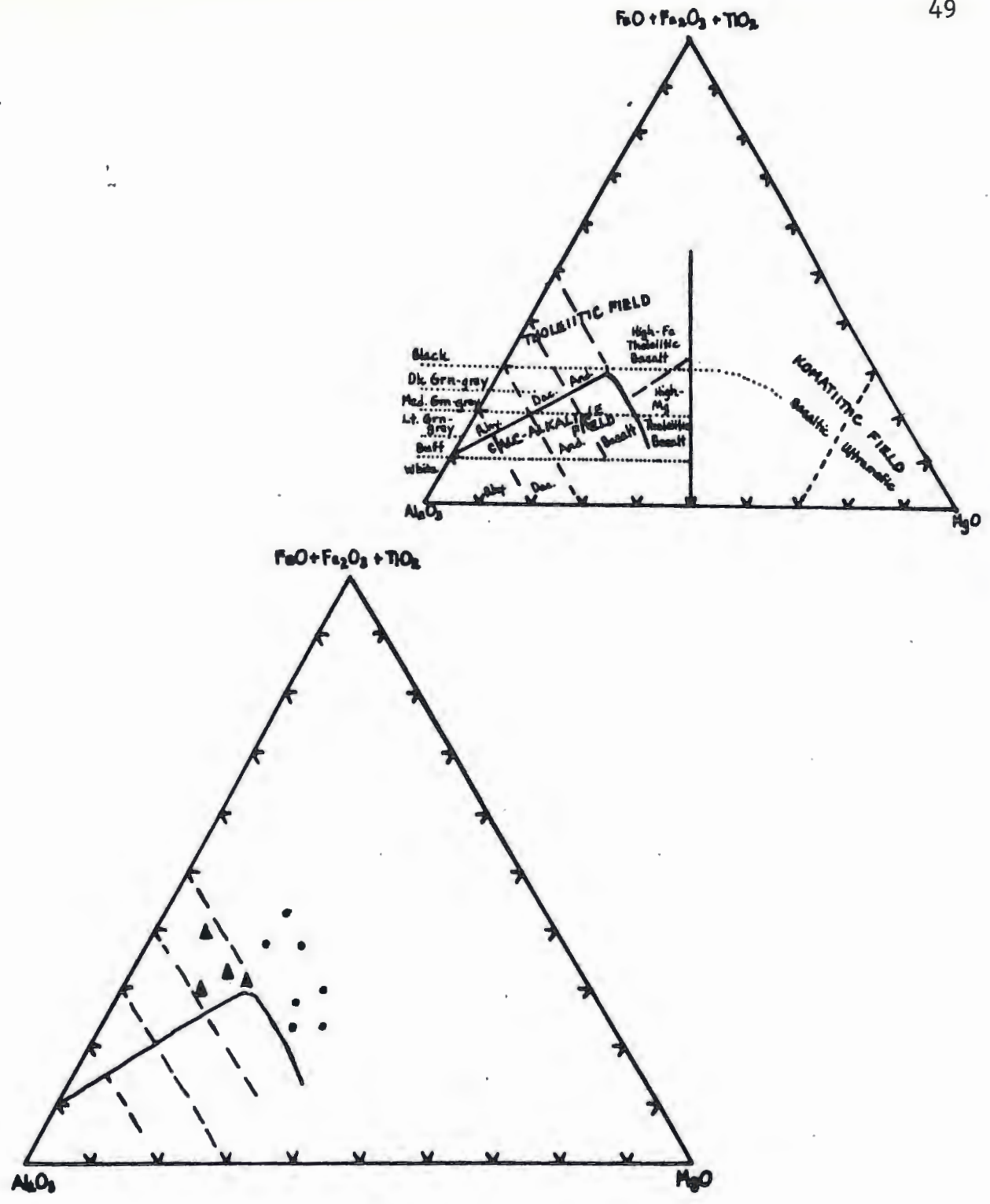
Figure 13   Jensen-Cation Plot(after Jensen, 1976).
For all chemical plots, triangles denote
andesitic rocks and circles denote basalt-
ic rocks.

Skeleton Lake area. To minimize the effects of alteration, the samples were chosen for their lack of conspicuous veining, fracturing, amygdules, or any other feature that could indicate the introduction of secondary components. All the samples were plotted on a K_2O + Na_2O vs. $\left(\frac{K_2O}{(Na_2O+K_2O)}\right)$ X 100 graph, after Hughes (1972), to eliminate samples that may have been spilitized or altered in a similar manner. Two samples were rejected on this basis. For basaltic rocks ($S_2O < 56\%$), a chemical screen modified by Manson (1967) after Green and Poldervaart (1955) was used to eliminate inferior analysis or those representative of highly altered rocks. The discussion that follows concerns only the remaining 12 unaltered analyses (Table III) felt to be dependable indicators of primary composition.

The Jensen Plot gives a good correlation between observed field and petrographic characteristics of the Skeleton Lake volcanics and their respective chemical classification. All four samples within the tholeiitic andesite field were gray to gray-black in color and had less mafic minerals in comparison to the basaltic flows. The andesites have an average of 23% normative quartz; whereas, the basalts had an average quartz normative value of 4.4 or were olivine normative (Table III). The andesites also had a lower MgO content, averaging 2.8% in comparison to 8.42% for the basalts. The basaltic rocks plot in both the iron-enriched and magnesium-rich tholeiite fields. Three of the magnesium-rich basalts had normative olivine (average 15%); whereas, none of the iron-rich basalts were olivine-normative.

TABLE III WHOLE ROCK ANALYSIS AND QUARTZ NORMATIVE VALUES OF SKELETON LAKE SAMPLES

Whole Rock Elements	QN(L*)	MnO	TiO_2	Na_2O	K_2O	CaO	MgO	FeO*	Al_2O_3	SiO_2	LOI	Total
UNALTERED BASALTS												
S - 26B	NA	0.12	0.99	3.77	1.74	8.78	9.85	10.55	12.62	50.91	1.02	99.41
S - 6	21.2 L	0.15	0.93	2.39	0.87	11.14	8.65	15.95	12.43	47.02	0.60	99.38
S - 8	10.3 L	0.09	0.87	3.86	0.49	8.06	7.26	10.29	16.32	50.91	0.07	98.13
S - 29	6.34	0.15	0.94	1.47	0.17	9.06	7.99	14.02	11.37	50.22	0.83	96.58
S - 81	5.12	0.13	0.91	3.10	0.33	7.39	8.16	9.70	14.05	54.20	2.03	100.06
S - 25	1.67	0.09	0.87	3.05	0.53	8.84	7.43	11.32	12.24	51.92	0.50	96.70
S - 19	9.5 L	0.14	1.11	2.36	0.93	10.41	9.15	12.99	11.83	49.63	0.01	98.41
ALTERED BASALTS												
S - 70	12.59	0.08	0.67	3.64	1.97	6.21	3.48	10.55	12.50	56.34	2.25	97.61
S - 46	NA	0.21	2.68	3.24	0.98	9.29	2.85	20.07	11.56	47.78	0.09	99.27
SL- 17B	23.28	NA	1.14	2.91	1.23	5.74	0.37	9.15	17.21	61.10	NA	98.85
SL- 52	15.34	NA	0.78	1.83	0.39	10.07	4.44	11.01	13.31	56.77	NA	98.40
S - 78	NA	0.29	1.83	2.56	0.63	7.89	3.71	15.78	11.37	54.92	0.77	98.19
S - 66	NA	0.07	0.61	3.05	1.06	5.79	8.62	10.03	11.49	54.92	1.00	96.67
UNALTERED ANDESITES												
SL- 80	24.56	NA	0.91	3.24	0.99	4.56	2.42	8.72	15.28	64.40	NA	100.50
SL- 26	25.75	NA	0.54	2.62	1.28	6.16	2.82	8.24	13.86	65.52	NA	101.04
SL- 59	14.46	NA	0.65	3.26	0.89	7.67	2.16	9.64	16.41	59.16	NA	99.84
SL- 61B	22.53	NA	0.65	2.64	0.96	6.91	2.49	9.35	13.47	62.10	NA	98.57

TABLE III (Cont'd.)

Whole Rock Elements	QN(L*)	MnO	TiO$_2$	Na$_2$O	K$_2$O	CaO	MgO	FeO*	Al$_2$O$_3$	SiO$_2$	LOI	Total
ALTERED ANDESITES												
S - 77	26.95	0.05	0.60	4.07	1.04	4.59	1.92	7.07	11.41	67.47	0.99	98.74
S - 74	26.24	0.93	0.53	3.77	0.97	4.98	2.19	8.10	10.13	65.03	1.00	97.90
SL- 44	NA	NA	0.27	3.24	1.28	4.76	0.33	8.98	13.58	67.77	NA	100.18
SL- 46	NA	NA	0.33	3.24	2.41	4.65	0.46	6.06	14.80	65.28	NA	99.26
ALTERED PYROCLASTIC												
SL- 50	20.94	NA	0.49	3.42	3.01	2.24	2.29	7.78	16.15	64.00	NA	99.18
POST-ALGOMAN DIKE												
S - 50	2.88	0.14	1.11	2.36	0.93	10.41	9.15	12.99	11.83	49.63	0.33	98.18
DACITE-ANDESITES												
S - 71	NA	0.03	0.24	6.66	1.56	1.01	1.53	3.99	11.60	71.18	0.39	98.16
S - 18	NA	0.02	0.44	5.45	1.77	3.30	1.82	2.83	12.39	71.47	0.28	99.56
S - 1	NA	0.04	0.26	7.63	1.31	1.84	0.99	5.79	13.22	68.45	0.68	99.43
S - 33	NA	0.10	0.23	6.47	0.98	1.84	1.39	5.02	10.96	71.02	0.41	98.32
MAFIC PORPHYRY												
S - 12	NA	0.13	0.49	0.88	1.44	16.44	16.25	9.99	5.48	54.20	2.03	99.08

*Fe reported as total iron
NA Analysis-not available
L - Olivine Normative

Because the magnesium-rich basalts had field characteristics
(such as color and texture) intermediate between the iron-
rich basalts and andesites, field differentiation was diffi-
cult and sampling not adequate to define any lithologic
boundary for this rock type.

Chemical Plots defining Tholeiitic and Calc-Alkaline Trends

Magheenan (1978) reported that altered samples from
the Garon Lake sulfide deposit fell within the calc-alkaline
field, whereas unaltered samples exhibited tholeiitic
trends. Therefore, in the following figures all of the
available analyses were plotted to try to differentiate
such a trend in the Skeleton Lake samples. The Al_2O_3-FeO-MgO
(AFM), and Al_2O_3 vs. normative plagioclase composition plots
of Irvine and Barager (1971) (Figures 14 and 15), and the
Feo_T vs. Feo/MgO plot of Miyashiro (1974) (Figure 16) all
showed tholeiitic trends for both the altered and unaltered
samples. Although individual samples fell within the
calc-alkaline area on the various graphs, no sample or
group of samples consistently illustrated a calc-alkaline
trend on all the plots.

General Comparison with other Analyses of the Western Vermilion District

Although the K_2O and Na_2O contents were generally
higher than values reported by Green (1970), Goodwin (1968),
and Wilson (1965) for various Archean volcanic suites, the
Skeleton Lake rocks still plotted well within the subalka-
line field of Irvine and Baragar (1971) (Figure 17).
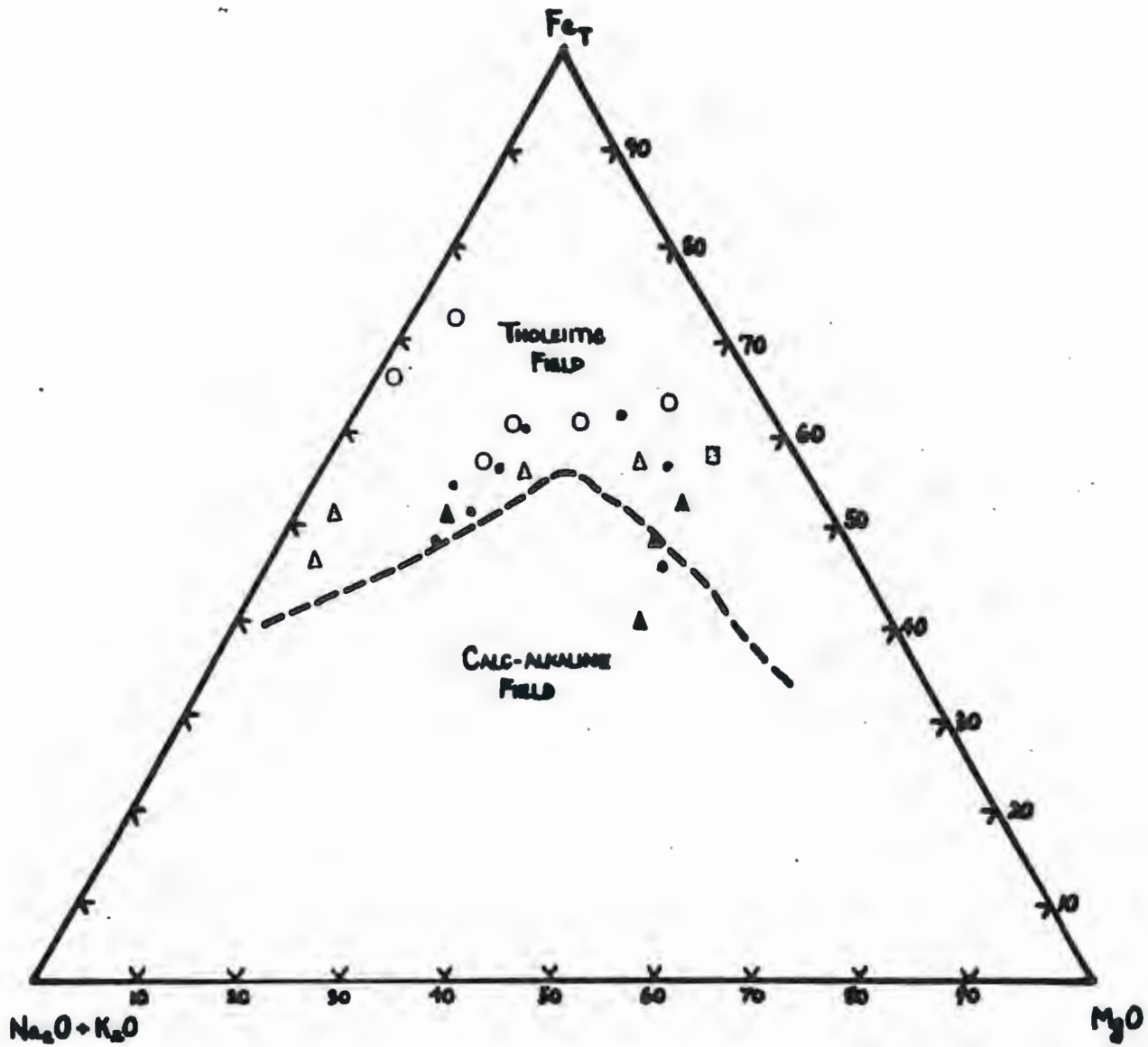
Figure 14   AFM Diagram (after Irvine and Baragar, 1971).
For all chemical plots: 1) solid symbols
represent unaltered samples 2) open symbols
represent altered samples 3) rectangle repre-
sents volcaniclastic sample (see Table III).
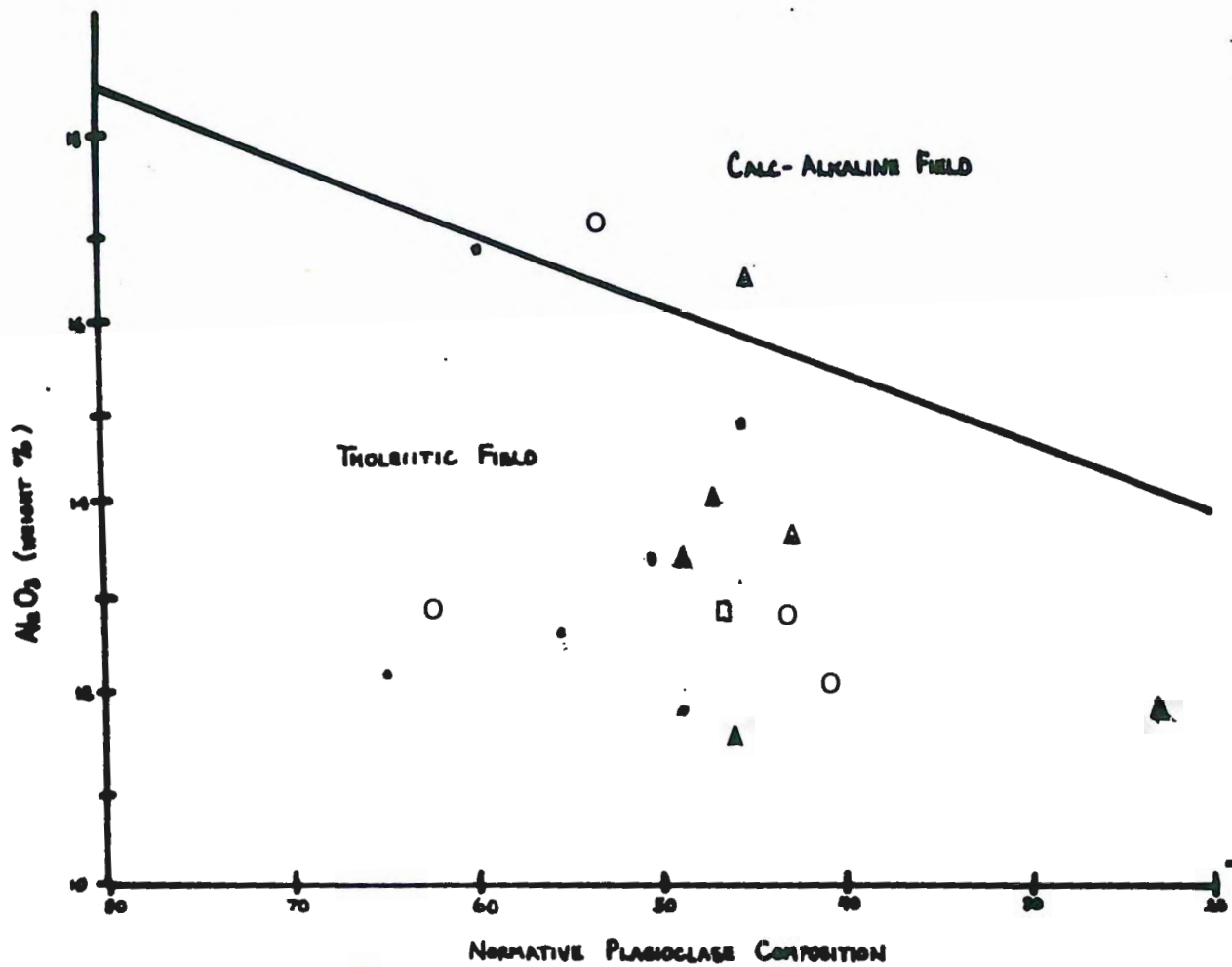
Figure 15 Al_2O_3 vs Normative Plagioclase Composition
Plot (after Irvine and Baragar, 1971).

$O \rightarrow 7.07$

$O \rightarrow 38.11$

$\triangle \rightarrow 27.07$

$\triangle \rightarrow 13.68$

THOLEIITIC FIELD

CALC-ALKALINE FIELD

FeO (WEIGHT %)

FeO/MgO (WEIGHT %)
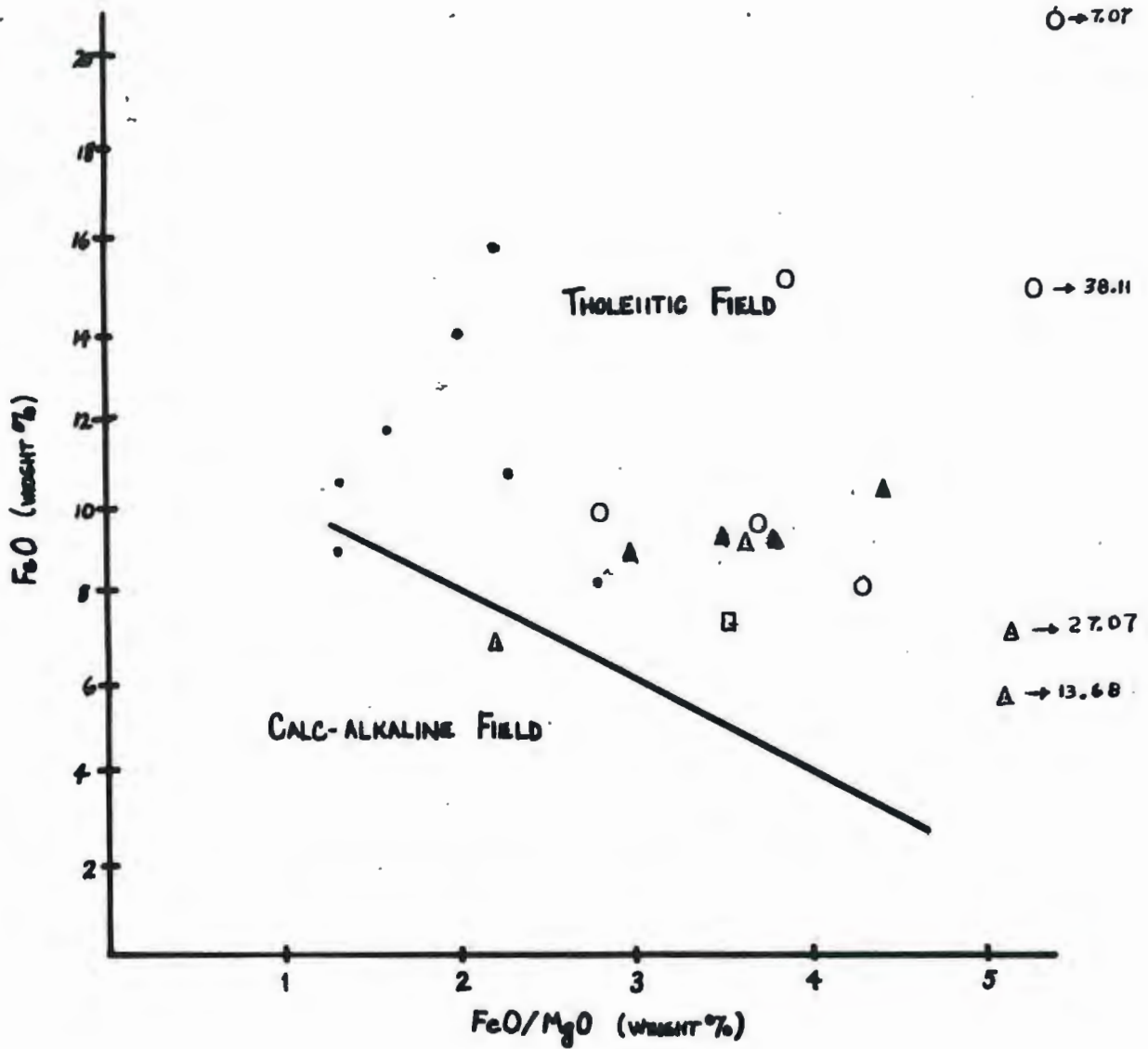
Figure 16   FeO vs. FeO/MgO Plot (after Miyashiro, 1974).
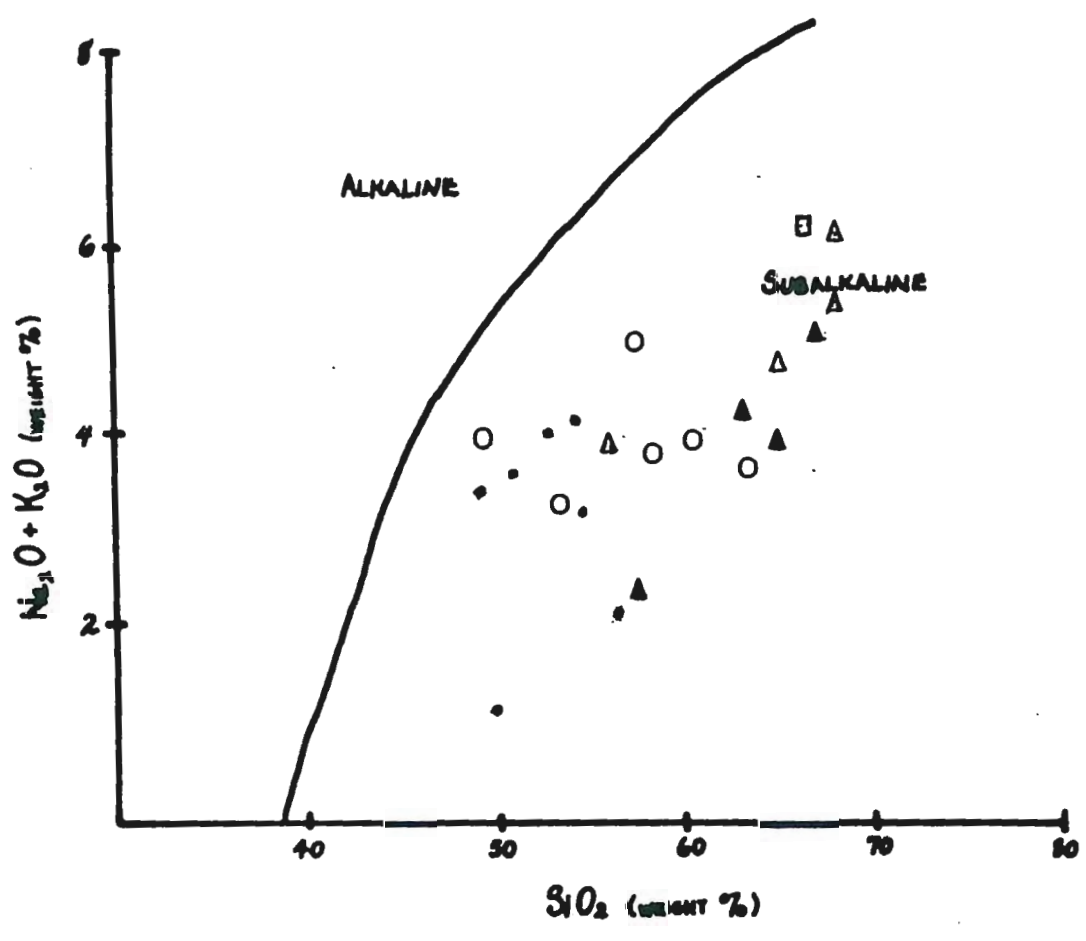
Figure 17 Na$_2$O+K$_2$O vs. SiO$_2$ Plot (after Irvine and Baragar, 1971)

Cann (1970), Pearce and Cann (1971), and other workers have established that Yt, Zr, and Ti are relatively immobile during metamorphism, and thus provide the most accurate means of classifying chemically altered basalts. Such data were unobtainable for this study, but Schulz (1978) analysed samples from the vicinity of Skeleton Lake for these and other trace elements. Due to the proximity of the sampling and the petrographic similarity with the Skeleton Lake volcanics, Schulz's results are applicable to discussions pertaining to the study area. From his study of the western Vermilion district, Schulz (1978) concluded that the upper Ely Greenstone had tholeiitic affinities. On this basis, the volcanic rocks of the Soudan Iron Formation, exposed near Skeleton Lake, are related to the volcanism which produced the upper Ely Greenstone. Schulz (1978) made a further differentiation of the upper Ely Greenstone based on TiO_2 content. The generally low TiO_2 ($< 1.19\%$) content and high Al_2O_3/TiO_2 ratios indicate that the Skeleton Lake volcanics are typical of Schulz's "low TiO_2 basalts".

Archean tholeiitic basalts have been compared and referred to as either ocean floor type basalts (Glickson, 1971; Viljoen and Viljoen, 1969; and Anhauser, 1973) or low-K island arc tholeiites (White, et al, 1970; Goodwin and Ridler, 1970). Jahn, et al, (1975) and Arth and Hanson (1975) have proposed that the Ely Greenstone is the result of island arc volcanism based on trace element (Rb, Sr, Ba, REE) comparisons. Schulz (1978), using Y-Ti-Zr and Si-Y-Ti plots (after Pearce and Cann, 1973)

concluded that the upper Ely Greenstone was more representative of ocean floor basalts; but, he also found that the normalized major element variation of the upper Ely Greenstone had characteristics in common with both island-arc and ocean floor basalts.

Because the Archean mantle probably differed from the Phanerozoic mantle (Schulz, 1978) geochemically and thermally, tectonic regimes were probably also different; thus, it is unlikely that modern tectonic models can be closely applied to the Archean (Schulz, 1978; Pearce, et al, 1977).

HYDROTHERMAL ALTERATION

Definition of Alteration Zones

In addition to the pervasive regional metamorphism, hydrothermal alteration has locally affected many of the volcanic rocks. Generally, the regional metamorphism has affected the volcanic succession near Skeleton Lake in the following ways:

1) The replacement of calcic plagioclase by albite.

2) The replacement of pyroxene by actinolite.

3) The production of various secondary minerals such as quartz, carbonate, epidote, and chlorite, with a combined total of 5 to 35% in any one sample.

Atypical samples from the Skeleton Lake prospect have various assemblages of secondary minerals in amounts

between 50 and 100%. All of the more intensely altered
samples are confined to three zones within the mapping
area. The notably higher amounts of secondary minerals,
associated veining, and localization of these rocks, suggest
that they are reflecting the effects of a more local hydro-
thermal event in addition to the typical greenschist grade
metamorphism.

Description of the Alteration Zones

Two of the aforementioned zones are linear, swampy
lowlands that trend northwest to west and occur near the
lithologic breaks between andesitic and basaltic flows.
Outcrops along these zones are more commonly tuffaceous
(see Chapter 3) in comparison with the rest of the exposed
volcanic sequence. This would suggest that these zones may
have once been relatively permeable pyroclastic sequences
within the volcanic pile that were more susceptible to
hydrothermal alteration and geologically more recent
surficial weathering and erosion. Veins of quartz, epidote,
carbonate, and chlorite commonly comprise between 50 and 65%
of these samples (Figure 18). Any one or more of these
minerals along with minor amounts of sericite, and recrystal-
lized vein actinolite may predominate in a given specimen.
Rarely veinlets of prehnite and albite were also observed.
Plate III shows the location of the various hydrothermal
assemblages noted in the samples. Glomeroporphyritic albite,
actinolite pseudomorphs, and albite microlites are typically
present in areas between altered material, but in some
places original igneous textures have been totally obliterated
by hydrothermal alteration.

Figure 18 Hand samples of hydrothermally altered volcanics. Sample on left illustrates the pervasive veining of rocks from the northwest-trending zones. Sample on right exhibits the mottled apperance of altered samples from the discordant zone.
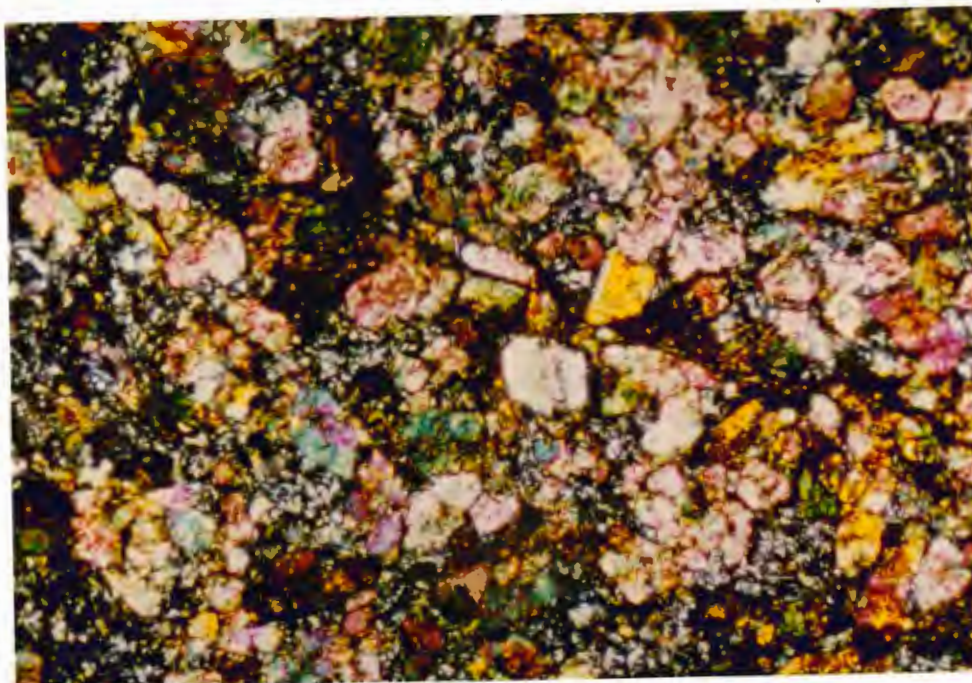
Figure 19 Quartz-epidote alteration envelope as seen in thin section. Field of view: 5mm

The third zone of alteration is a discordant area that lies within a highland ridge of relatively good exposure. Many of the rocks from this zone have a distinctive mottled appearance and are characterized by a quartz-epidote alteration assemblage (Figure 19), with varying amounts of chlorite, sericite, carbonate, and recrystallized vein actinolite. This patchy alteration occurs as veins and as envelopes mantling amygdules and fractures, and is apparently controlled by the original permeability of the various volcanic units. The gray-white alteration patches (up to 2 x 5cm.) contrast with the typical dark green or gray surfaces of the unaltered areas, thus giving some of these samples a pseudo-fragmental texture (Figure 18).

In addition to the previously mentioned alteration minerals, potassium-bearing feldspar occurs in numerous veinlets in samples within a central, potassium-rich portion of this alteration zone (Plate III). The feldspar is associated with quartz in a fine-grained ($<$.2mm.) mosaic within the veinlets. X-ray analysis indicates that the potassium-bearing feldspar is "high-albite", a variety of albite capable of accommodating potassium and usually formed under relatively high temperature. The presence of the high albite is best seen in stained section (Figure 20). Potassium saturation was further indicated by the presence of biotite and sericite. Sericite and biotite are minor constituents ($<$5%) of the unaltered volcanic rocks (see Chapter 3), but are present in amounts of 10 up to 30% in many samples from this area. Four samples from the other
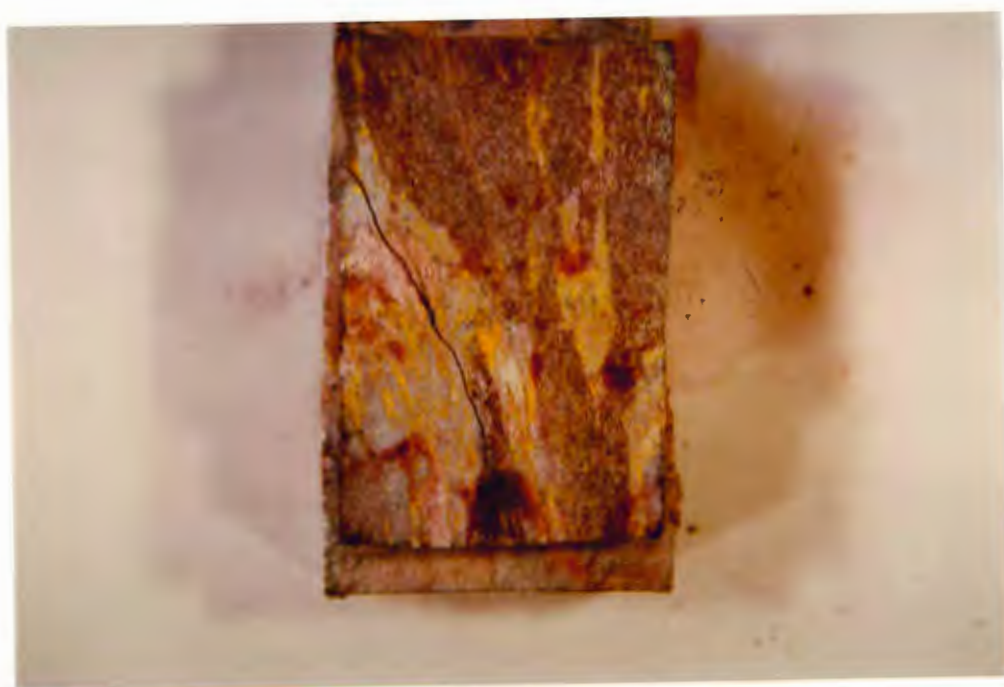
Figure 20 Fine-grained potassium-bearing feldspar and
quartz in a hydrothermal vein, as seen in
stained section. .

two alteration zones also had unusual concentrations
of biotite (Plate III).

In drill core, high albite and biotite were noted
over limited footages near the sulfide horizon. As at
the surface, silicification and epidotization also greatly
affected the rocks within or beyond the potassium-bearing
zone. Thus, there would seem to be correlation between
the zoned discordant alteration area at the surface and
the alteration occurring near the sulfide horizon in
drill core (Figure 21).

Geochemistry of the Alteration Zone

The rocks of the previously described alteration
zones are notable for their abundance of hydrothermal
veins and high percentages of alteration minerals such
as quartz, epidote, chlorite, and calcite. In addition,
these rocks are chemically distinct from their unaltered
counterparts.

The basaltic and andesitic rocks from Skeleton Lake
area also differ chemically and petrographically from
one another (see Geochemistry, this Chapter) and, there-
fore, an effort was made to distinguish between altered
samples of originally mafic or intermediate composition.
Direct observation of mineral assemblages was the most
reliable criterion for this distinction.

A sample was considered anomalous if its analysis
deviated significantly from analyses of unaltered samples
(as defined petrographically) of similar general composi-
tion. A normalization diagram (Figures 22 and 23) was
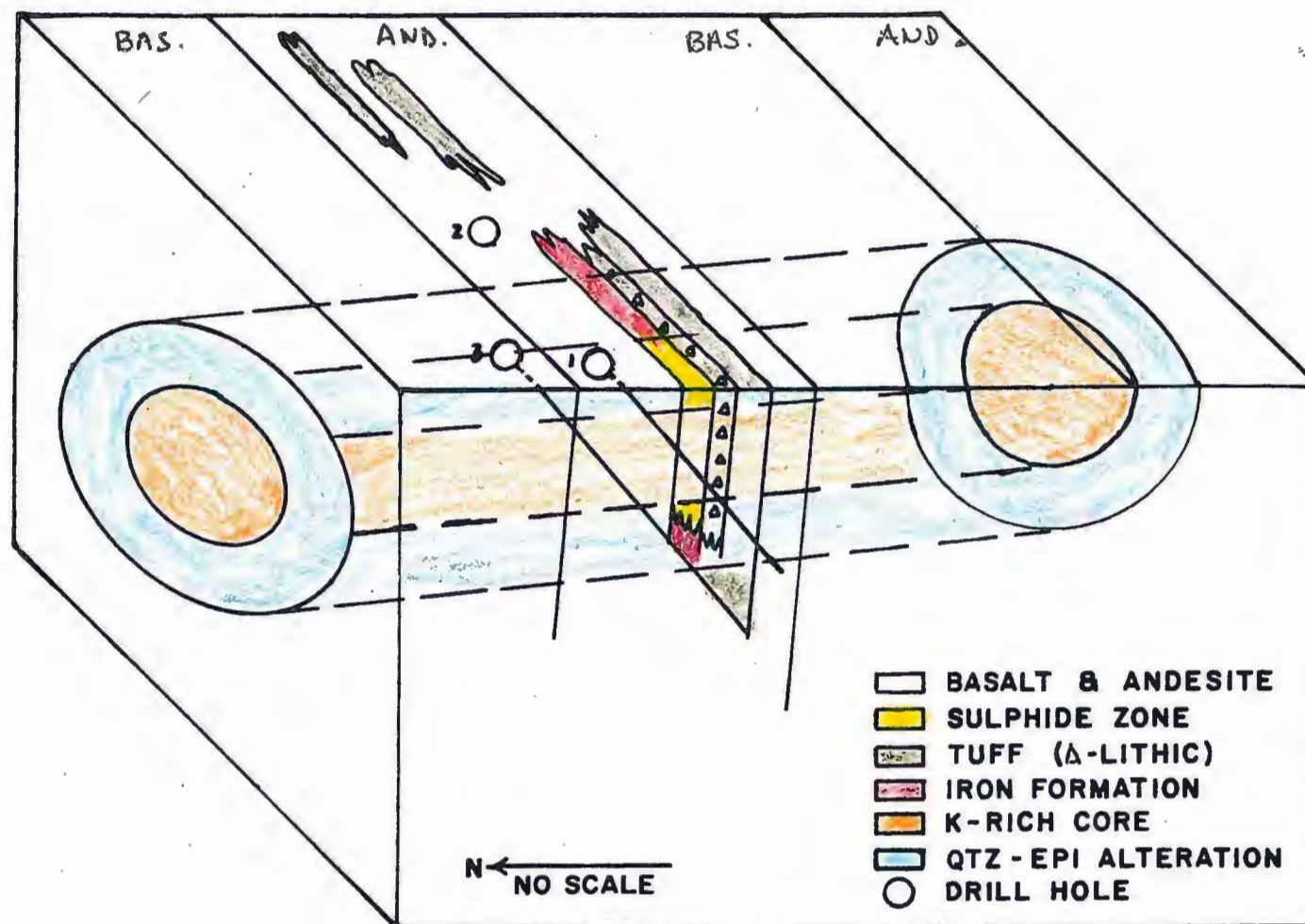
FIGURE 21: Diagramatic Illustration of General Geology and Relationship between Discordant Alteration Area and Similar Alteration Noted in Drill Core

used to illustrate the deviation of anomalous analyses from average values. This diagram shows the composition of an altered sample divided by the average composition of its unaltered rock types. The chemical variations of the individual alteration zones are discussed under separate headings.

Discussion of Northwest-trending Alteration Zones

Volcaniclastic rocks, interpreted as pyroclastic sequences (Chapter 3), were more prevalent within or near two northwest-trending, stratigraphically conformable alteration zones (Plates II and III). More intermediate volcanism was also associated with the occurrence of these volcaniclastic rocks and resulted in the andesitic flows within or marginal to the sequences (Chapter 3 and Plate II).

Many workers (i.e., Schulz, 1978) have noted that pyroxene was transformed to actinolite and calcic plagioclase to albite during regional metamorphic processes in the greenstones of the western Vermilion district. These reactions could result in the liberation of Si, Ca, Fe, and Mg and the formation of quartz, calcite, epidote, and chlorite within the affected rocks (Miyashiro, 1961).

The originally more permeable pyroclastic sequences would naturally make these rocks and peripheral units more subject to the effects of regional metamorphism. This could result in the more intense veining and greater abundance of secondary minerals observed in the rocks of these alteration zones. The enrichment of Si and depletion of Mg and Ti noted in these rocks could be attributed to
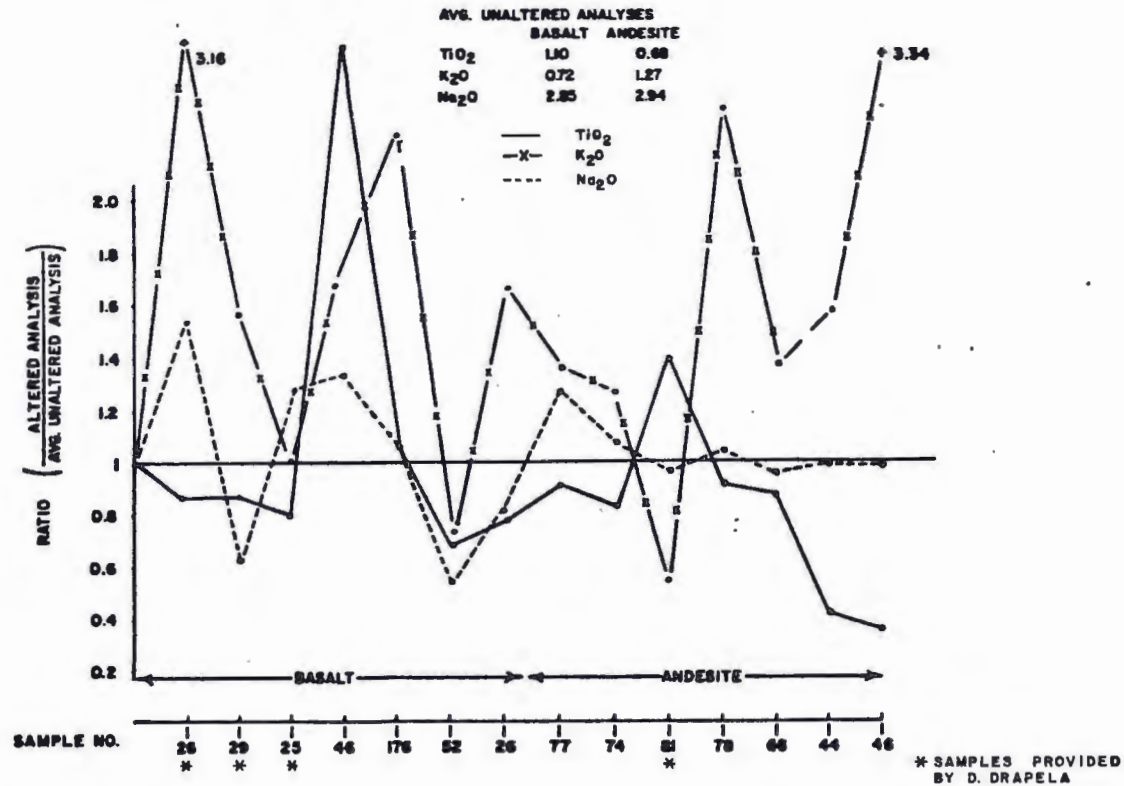
Figure 22   Normalization Diagram - Ilustrating the deviation
of TiO_2, K_2O, and Na_2O values of altered samples
with respect to the average value of their unaltered
counterparts (Table III). A ratio of "1" corresponds
with the average composition of an unaltered sample.
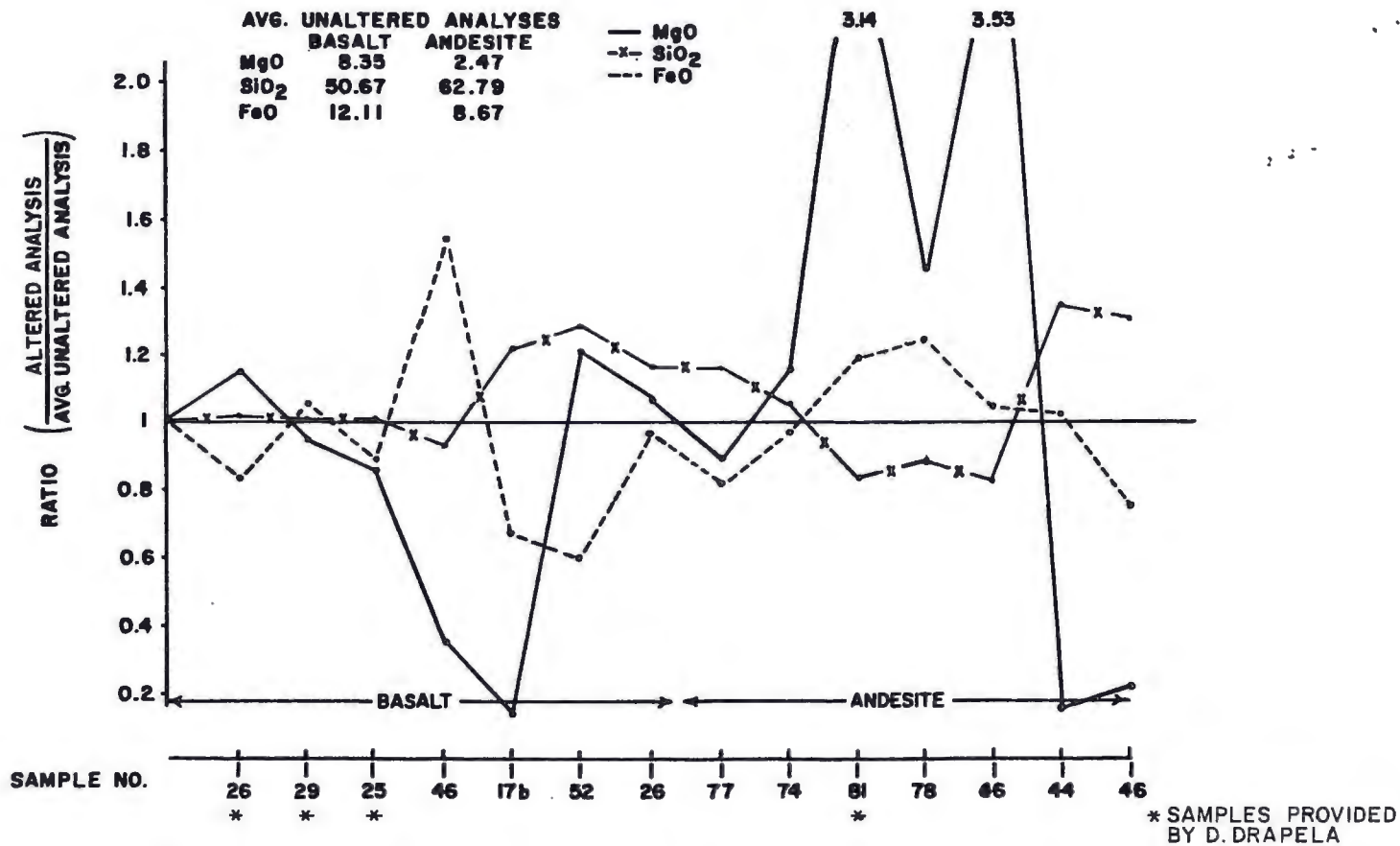
Figure 23   Normalization Diagram- Comparing hydrothermally
altered and unaltered samples (MgO, SiO_2, FeO).

the difference in composition between the andesitic rocks within the alteration areas and the basaltic flows outside these zones.

However, the geochemical interpretation of the alteration zones is further complicated by the enrichment of Si (65-67%) to a degree not normally associated with regionally metamorphosed andesitic rocks (many workers, i.e. Gelinas, 1974). Potassium has also been enriched to an unusual degree, resulting in the formation of biotite in percentages of up to 30% in some samples from these zones. Griffin (1967) stated that four of the eighteen mineral assemblages he delineated within the metavolcanic and metasedimentary rocks of the Ely Greenstone were biotite-bearing. Out of these, only one sample from the metavolcanic suite contained biotite. Therefore, the introduction of silica and potassium in restricted zones within the volcanic succession at Skeleton Lake, would indicate the effects of a local hydrothermal event not related to regional metamorphism.

In a comparison of the whole rock analysis of the altered basalts and andesites with their unaltered equivalents, a general enrichment of Si, K, and Na and depletion of Mg and Ti is noticeable in many of the altered samples. Such a trend is typical of "zones of enrichment" in hydrothermally altered rocks associated with exhalative sulfide deposits (Macgeehan, 1978). This type of alteration occurs below volcanic vents and usually stratigraphically underlies accumulations of pyroclastic material and exhalative rocks (Macgeehan, 1978).

These "enrichment zones" represent areas where hydro-
thermal fluids have leached the country rocks of base metals.
In a comparison of base metal values (Table V, Chapter 5),
the flow units from the alteration zones averaged 45ppm
Cu and 25ppm Zn, whereas analyses of the unaltered samples
averaged 80ppm Cu and 70ppm Zn. The base metals were
later concentrated in hydrothermal veins and a stratiform
sulfide zone (Chapter 5).

In conclusion, it can be stated that the rocks of
the northwest-trending alteration areas have been strongly
affected by both regional metamorphism and local hydro-
thermal metamorphism. The present geochemical trends of
these rocks reflect the effects of these alteration events
in addition to their primary compositions.

Discussion of the Discordant Alteration Area

The discordant alteration area has a distinctive
quartz-epidote alteration that occurs peripheral to a bio-
tite-sericite-potassium feldspar-bearing zone. An alkali-
rich zone is typical of many hydrothermal alteration pipes
associated with massive sulfide deposition (Parry and
Hutchinson, 1981). The equivalent of the wider-spread,
mottled quartz-epidote alteration has been noted in rocks
near the alteration pipes of the Garon Lake (Macgeehan,
1978), Millenbach (Gibson and Watkinson, 1979), and the
Four Corners (Parry and Hutchinson, 1981) prospects. Parry
and Hutchinson (1981) interpret this type of alteration to
be the result of initial seawater-rock interactions, as
large volumes of seawater circulate downward through

structurally favorable areas in the volcanic succession.

Geochemically the rocks have the same general trends as the northwest-trending stratiform zones; that is: Si, K, and Na enrichment, and Ti and Mg depletion. One exceptional sample (S-46) taken from the central part of the potassium-bearing zone, shows strong Ti and Fe enrichment. In drill core, potassium and iron-enriched works occur in the immediate vicinity of the sulfide zone.

The general relationship between these altered areas and sulfide deposition at Skeleton Lake will be further discussed in Chapter 5.

SULFIDE MINERALIZATION OF THE
SKELETON LAKE PROSPECT

Introduction

Interest in the Skeleton Lake area as a massive
sulfide prospect was first established as the result
of geophysical anomalies recorded near Skeleton Lake
by Exxon Corporation in the fall of 1974. Subsequently,
three drill holes were located just southeast of Skele-
ton Lake (Plate 2), all of which intersected pyrite-
·pyrrhotite-chalcopyrite mineralization.

Upon Exxon's relinquishing control of the land,
the MDNR conducted geophysical and geochemical surveys
to further assess the mineral potential of this area.
The following information concerning these preliminary
surveys was summarized from a report submitted to the
MDNR by M. K. Vadis and D. C. Meineke (1977).

Geochemical Surveys

The geochemical survey included sampling of organic-
rich lake sediments, organic stream bank samples, soil
and peat (Figure 24). Soil and peat sampling was very
limited and non-conclusive. Organic stream bank samples,
collected from streams adjacent to Skeleton Lake, indi-
cated a nearby copper source. This survey also indicated
that the source of the copper anomaly lies just north of
the conductor that was drilled. The results of the

Tee Lake

<u>3077</u>
Cu 18
Zn 137
Pb 10
Ni 6
As 0.14

<u>3076</u>
Cu 17
Zn 110
Pb 5
Ni 2
As 0.09

Lit. Skeleton Lake

<u>3074</u>
Cu 24
Zn 19
Pb 20
Ni 3
As 1.58

<u>3075</u>
Cu 24
Zn 19
Pb 10
Ni 3
As 2.0

Skeleton Lake

<u>3049</u>
Cu 190
Zn 21
Pb 13
Ni 21
As 0.8

<u>3048</u>
Cu 230
Zn 86
Pb 18
Ni 30
As 1.8

SL-3
SL-1   SL-2

<u>3269</u>
Cu 42
Zn 20
Pb 8
Ni 9
As 1.04

<u>3081</u>
Cu 31
Zn 36
Pb 0
Ni 13
As 0.14

<u>3084</u>
Cu 28
Zn 43
Pb 5
Ni 18
As 0.09

Putnam Lake

<u>3083</u>
Cu 26
Zn 84
Pb 10
Ni 14
As 0

<u>3082</u>
Cu 27
Zn 48
Pb 18
Ni 18
As 0.02

N

<u>3074</u> Sample site and
Cu 24 number. Metal
Zn 19 concentrations
Pb 20
Ni 3 given in (ppm).
As 1.58

True horizontal projection
of diamond drill holes

2000   1000   0   2000

Scale 1:24000

Figure 24   Organic-Rich Lake Sediment Survey of the
Skeleton Lake Area.

stream bank sampling were further substantiated by the organic lake sediment survey. The copper concentrations associated with Skeleton Lake fall within the upper 2% of all such samples from the Lake Vermilion-Ely region analysed by the MDNR. The mineral deposit which contains the copper was inferred to be approximately 1000 feet down drainage, 70 feet lower in elevation, and is down glacial ice direction from Skeleton Lake. Therefore, it is unlikely that the portion of this deposit drilled by Exxon produced the geochemical anomaly in Skeleton Lake.

Geophysical Surveys

Horizontal shootback electromagnetics, proton magnetometer-total field, airborne fluxgate magnetometer-vertical field, and VLF-electromagnetic surveys were run by MDNR personnel to identify geophysical conductors which may reflect economic mineralization.

The general geophysical pattern of the area indicates several conductive horizons, which are more or less continuous in a N 60° W to N 90° W trend and are dipping to the north at approximately 45° to 90°. The conductors lie beneath and just north of Skeleton Lake and extend east and west from the lake. Copper mineralization, as well as iron formation, was intersected in a magnetic anomaly drilled by Exxon Corporation near Skeleton Lake. Due to the high magnetics associated with portions of the conductors, the conductors may in part be the result of iron formation. However, the combined geochemical and geophysical evidence

indicates that the conductors may be related to economic copper sulfide mineralization.

Distribution of Sulfide Mineralization

The sulfides of the Skeleton Lake prospect occur in massive, laminated, and disseminated forms. Pyrite, and less commonly pyrrhotite, are found as accessory minerals ($<$2%) in all the major lithologic units. Both in drill core and at the surface, the sulfides can be seen to have been further concentrated in permeable areas throughout the volcanic pile. These sulfides are commonly associated with hydrothermal mineralization. Massive and laminated sulfide mineralization is restricted to a stratiform sulfide horizon.

Stratiform Sulfide Mineralization

A mineralized sulfide-rich horizon was intersected between the 170-to 190-foot level and 175-to 195-foot level in DDH-1 and DDH-2 (Plate 1) respectively. The cores from both these holes are lithologically similar and stratigraphically correlative (Figure 25). A sequence of crystal and crystal-lithic tuffs forms the hanging wall contact with the sulfide zone. Although a fine-grained quartz matrix gives these pyroclastic rocks a felsic appearance, the presence of mafic-intermediate volcanic rock fragments indicate that they are probably silicified andesitic and basaltic tuffs.

Banded to nearly massive sulfides occur in a siliceous host within the sulfide horizon. Bands (1.3 to 6.3mm) of pyrrhotite-pyrite with or without chalcopyrite and magnetite occur between laminated layers of fine-
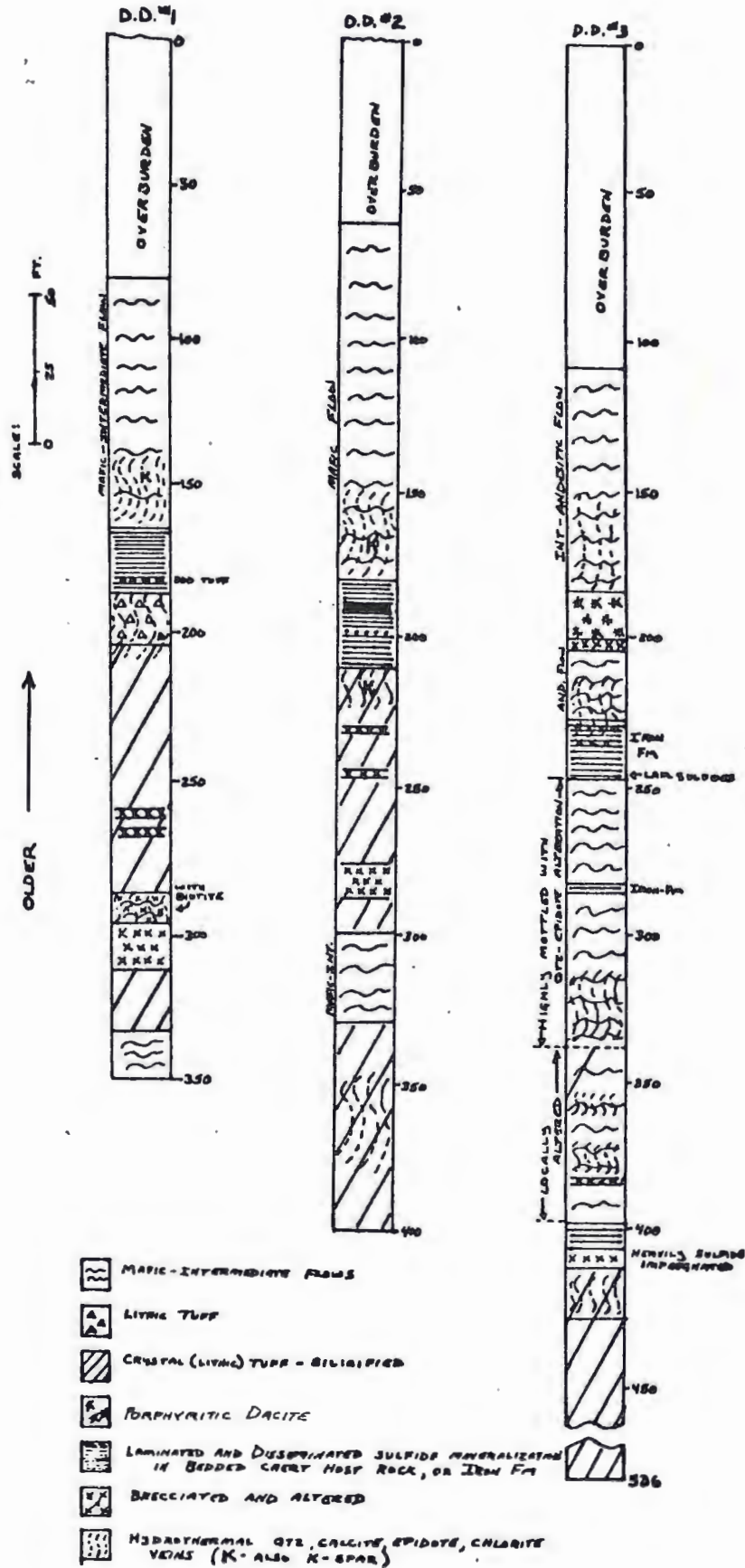
Figure 25   Illustration of Drill Hole Geology

grained (< 1mm) quartz. The bedding of the host rock is defined by alternating coarser (≈ 3/4mm) or fine (≈ 1/4mm) layers of quartz, or locally by graded bedding within an individual lamination. Between these banded zones, disseminated sulfides are distributed in the same host, becoming semi-massive (30-50% sulfides) or massive (> 50% sulfides) over short intervals (up to 15.5cm.). Pyrrhotite is generally the dominant sulfide; however, the pyrrhotite: pyrite ratio varies locally from 3:1 to 1:2. The interlayered sulfides (and magnetite) generally lack associated silicate minerals. Occasionally individual grains of pyrrhotite or pyrite may be partially mantled by epidote, carbonate, actinolite, or chlorite (Figure 26).

Altered mafic or intermediate flows, with minor interbeds of pyroclastic rocks, lie stratigraphically below the sulfide zone. Chlorite, epidote, and less frequently, quartz and carbonate fill amygdules and fractures, and commonly mask the typical mineral assemblage of plagioclase and actinolite.

Sulfide Mineralization Associated with Hydrothermal Mineralization

Sulfides have also been concentrated in amygdules, fractures, between clasts of volcanic breccias, and generally in permeable sites throughout the volcanic pile. These sulfides are always associated with hydrothermal mineralization, usually occurring toward the center of quartz-epidote or epidote-carbonate veinlets or stringers (Figure 27). These veinlets and stringers are especially
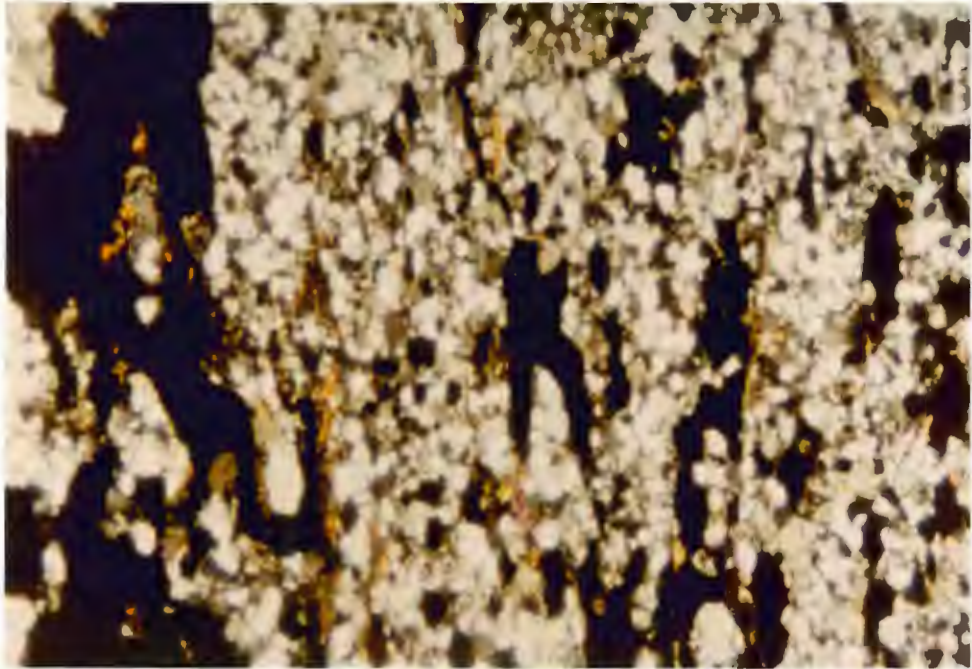
Figure 26   Laminated sulphides in quartz host rock.
Note lack of associated hydrothermal
minerals.   Field of view: 5mm
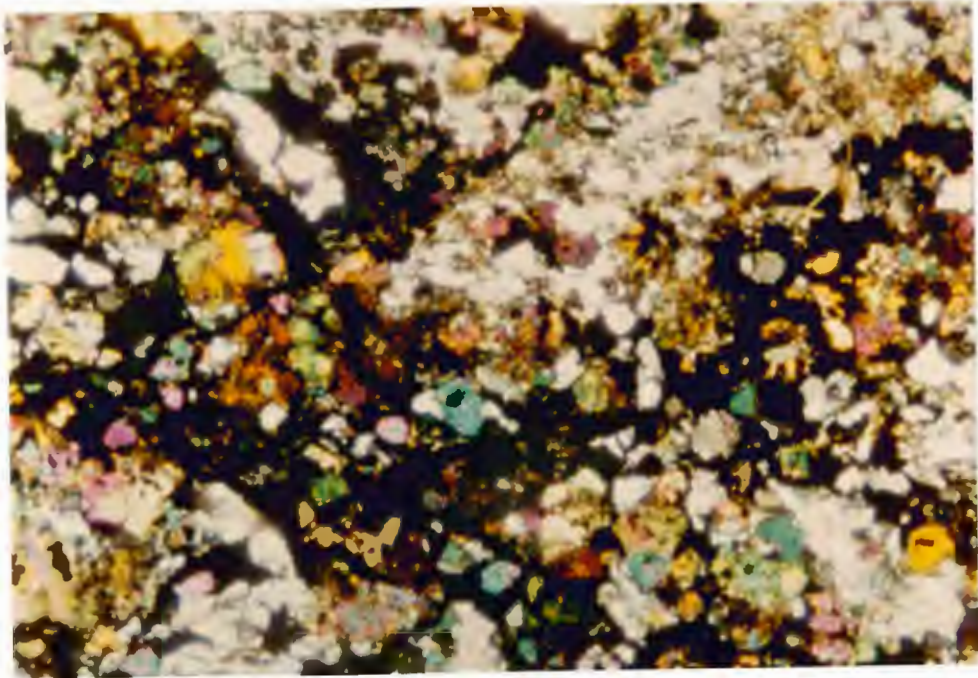
Figure 27   Typical epigenetic stringer sulphides, in
veinlets with quartz and epidote.
Field of view: 5mm

prevalent in the alteration zones (previously described, Chapter 3) at the surface and within the below the sulfide horizon in drill core. Zones of volcanic breccia exist locally, commonly in sequences stratigraphically below iron formation. These fragmental rocks are more intensely altered and contain higher percentages of sulfides than the adjacent flows. One such brecciated zone, between the 407.3-to 413.7-foot levels of DDH-3, represents the reported "massive sulfide mineralization" from this hole. This volcanic breccia consists of altered basaltic rock fragments cemented by sulfides and chlorite.

In some places the hydrothermal minerals show a crude zonation within the veins. The following paragenetic sequence was inferred from the relative position of these mineral assemblages:

Earliest:	1)	Fine-grained quartz.
	2)	Chlorite-amphibole.
	3)	Carbonate-epidote, Epidote-quartz.
Latest:	4)	Coarse-grained quartz, fine-grained quartz-Potassium feldspar.

Within a given vein, each of the mineral assemblages may predominate. Well-zoned amygdules show a similar sequence of mineralization from quartz rims to chlorite-amphibole to epidote-carbonate (with or without sulfides) at the center.

Sulfide Mineralogy

The sulfide minerals, in order of relative abundance, are pyrrhotite, pyrite, chalcopyrite, and sphalerite. In addition, magnetite is closely associated with the sulfides.

The common mineral assemblages are pyrrhotite-pyrite, pyrrhotite-pyrite-chalcopyrite, pyrrhotite-pyrite-chalco-pyrite-magnetite, chalcopyrite, and pyrite-magnetite. Sphalerite was only observed in three samples taken over a four-inch zone at the 189.4 level in DDH-2. The sphalerite occurs in veins, along, or in combination with pyrrhotite and/or chalcopyrite.

Pyrrotite is clearly the most abundant sulfide, sometimes comprising up to 60% of the sulfides observable in any one sample. Microscopically, it appears light tan to bronze in color with a bright to dull metallic luster and an uneven fracture. Under polarized light, the pyrrhotite has typical moderate to strong anistropy, and depending on the adjacent minerals, a pinkish-buff to yellow-tan color. In massive or laminated forms it occurs as aggregates of crystals, frequently exhibiting a polygonal or annealed texture (Figure 28). In disseminated zones, pyrrhotite occurs as fine-grained subhedral to euhedral grains or blebs. Gangue minerals, euhedral pyrite, and rarely chalcopyrite are found as inclusions.

Following a method described by Arnold (1966), two polished sections were etched with saturated chromic acid to differentiate between monoclinic and hexagonal pyrrhotite. Both types of pyrrhotite were found together as intergrown grains. In Figure 29, the monoclinic variety appears more tarnished and has a pinkish-brown color in comparison to the lighter colored hexagonal pyrrhotite.
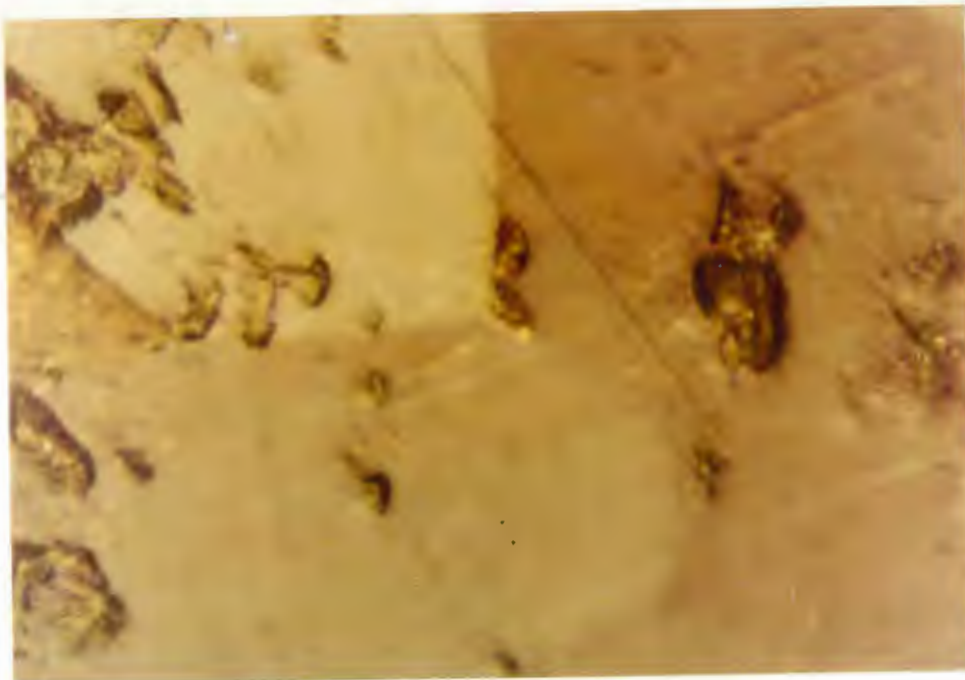
Figure 28　Polygonal or annealed texture in pyrrhotite. Note 120° triple junctions at grain boundaries. Field of view: 1mm
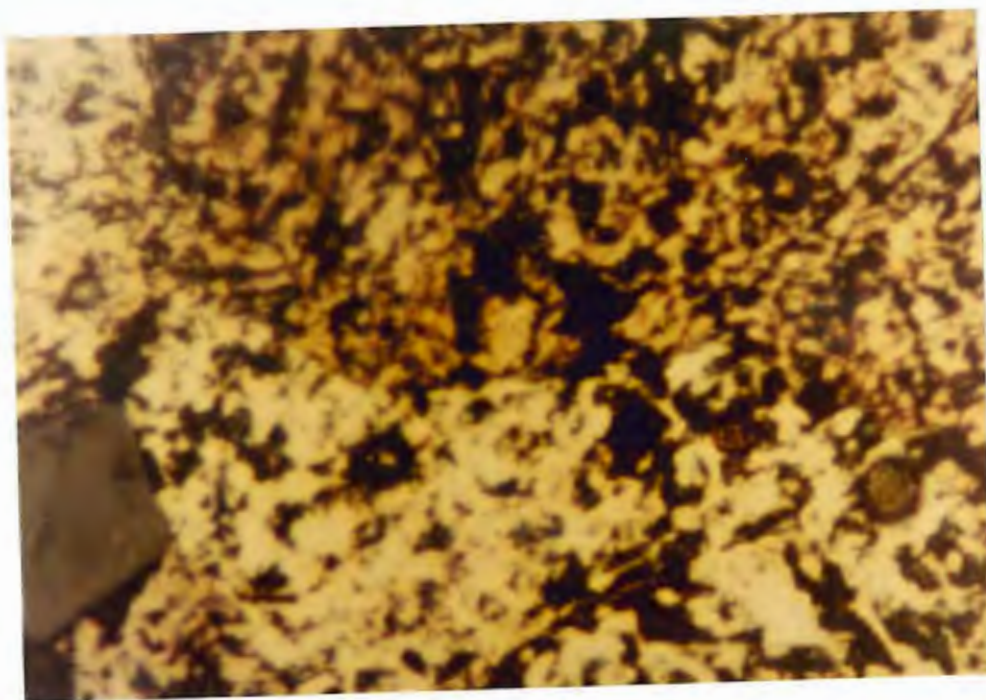
Figure 29　Tarnished monoclinic pyrrhotite and lighter colored hexagonal pyrrhotite, exhibiting an intergranular relationship. Field of view: 1mm

Pyrite, like pyrrhotite, is found in all the various sites of sulfide deposition at Skeleton Lake. Pyrite is notably more abundant in outcrops as compared to the drill core. Most of the pyrite at the surface has been weathered in some degree to limonite and other weathering products, giving such rocks a yellow or yellow-green stain. In some cases, the pyrite has been completely dissolved leaving squarish, vacant crystal sites as the only sign of former sulfide mineralization. Microscopically, the pyrite appears as yellow-white, euhedral to subhedral grains that are generally isotropic. Some pyrite was observed to be slightly anistropic. Rarely, zoned pyrite crystals were observed. A later stage of pyrite growth is marked by veinlets of coarse-grained pyrite that replace pyrrhotite. This later pyrite is usually, but not always, inclusion-rich. Various gange minerals, chalcopyrite, and magnetite, are the most common inclusions. Some of the earilier pyrite contains abundant inclusions of gange minerals and magnetite.

Chalcopyrite occurs as fine to medium-sized subhedral grains, irregular anhedral patches, and in small discontinuous veinlets. In the massive ore, it is associated with pyrrhotite, pyrite, and magnetite. The most common occurrence is along grain boundaries of pyrrhotite (Figure 30). Chalcopyrite is also common as a fracture-filling material in pyrrhotite and to a lesser extent, in pyrite and magnetite.
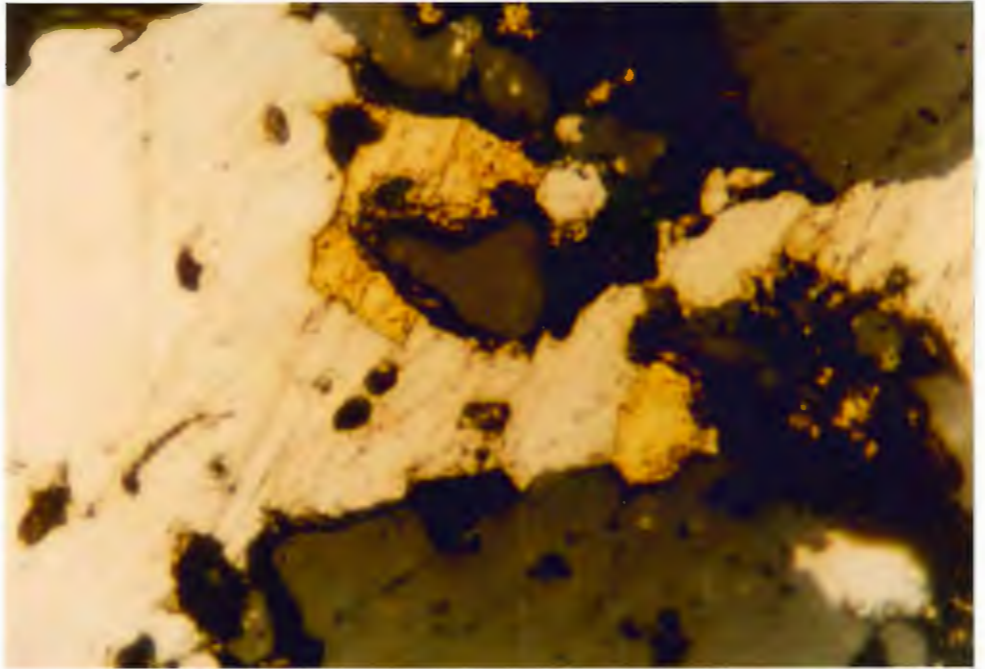
Figure 30   Occurance of chalcopyrite along grain boundaries
of pyrrhotite.   Field of view; 1mm

Magnetite occurs as aggregates of fine to medium-sized grains, that appear light gray and isotropic under reflected light. It is most commonly associated with pyrrhotite and commonly occurs as inclusions within that mineral. To a lesser extent, magnetite is also included in pyrite and chalcopyrite. In some samples, pyrrhotite and pyrite are found as inclusions within magnetite.

Sphalerite was found in three of four samples taken between the 189.4-to 190.0-foot level of the sulfide horizon in DDH-2. The sphalerite in these three samples represents the only observed occurrence of this mineral at Skeleton Lake. Progressing stratigraphically upwards in this zone, the sphalerite occurs as small discontinuous veinlets in a quartz gange, as coarse-grained aggregates with pyrrhotite and chalcopyrite, and as a relatively thick (1/2") vein, replacing pyrrhotite. Macroscopically, the sphalerite is light to medium brown in color and is generally coarse-grained to semi-massive. Microscopically, the sphalerite is gray (darker than magnetite) and exhibits a strong orange reflectively under crossed nicols.

Deformation and Recrystallization of Sulfide Minerals

Under an applied stress and over a wide range of conditions, pyrrhotite will behave plastically, whereas pyrite will respond brittly (Atkinson, 1975). This was reflected by the sulfides of Skeleton Lake, where local tectonic deformation has resulted in leaving islands of granular pyrite in a matrix of pyrrhotite (Figure 31).
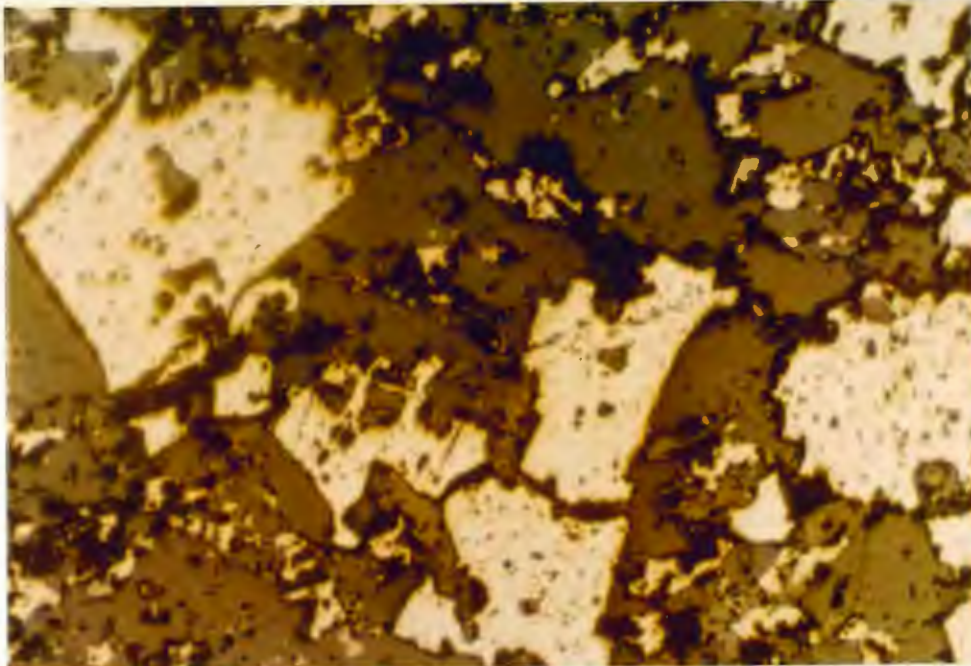
Figure 31   Granulated islands of pyrite in matrix of
pyrrhotite, within a small shear zone.
Field of view: 5mm
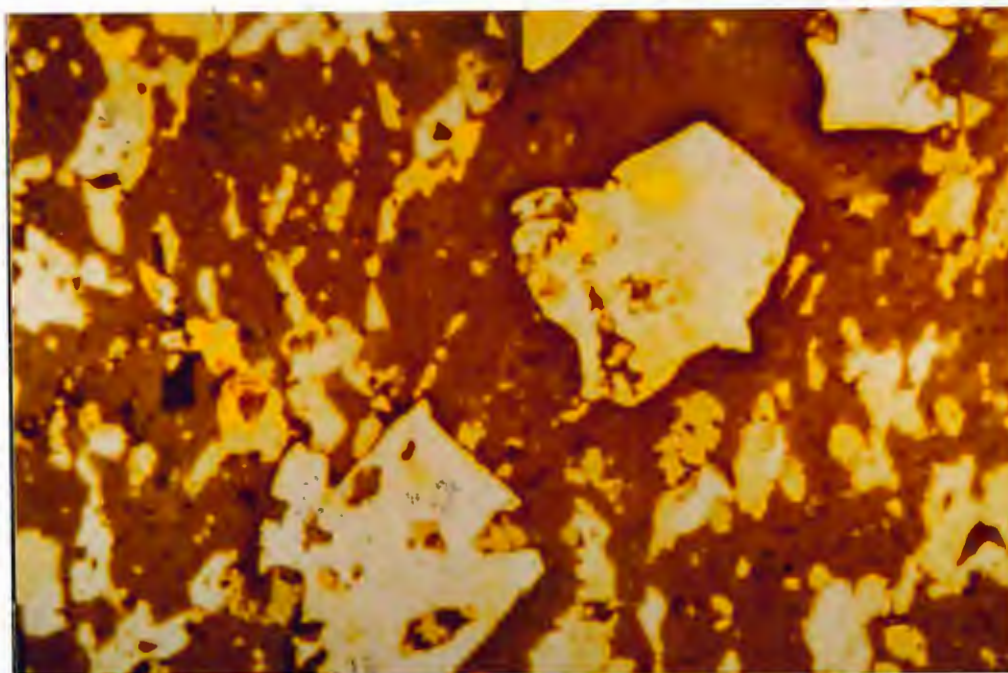
Figure 32   Late bands of coarse pyrite and magnetite
in massive ore.   Field of view:5mm

Recrystallization, due to thermal or hydrothermal metamorphism, may produce a similar texture, with coarsening and idiomorphic growth of individual pyrite grains. Vokes (1969) notes:

"The general result (of recrystallization) is to produce fabrics in which the minerals of high form energy-pyrite, arsenopyrite, and magnetite, chiefly-grown as metacrysts, often porphyroblasts, and are contrasted with the surrounding matrix of sulfides of lower form energy, chiefly chalcopyrite, sphalerite, galena, and pyrrhotite."

The bands of euhedral, corase-grained pyrite, and magnetite found with in the massive ore, probably formed as a result of this process (Figure 32). Adjacent grains of pyrrhotite commonly have conspicuous polygonal outlines and meet at angles near 120° at triple junctions (Figure 28). Such a texture is typical of non-deformational thermal metamorphism or a re-equilibrium of a higher temperature mineral phase upon cooling (Vokes, 1969). Rarely, pyrite grains exhibited the same texture.

Sequence of Mineralization

An apparent sequence has been determined from the textural relationships between the various sulfide minerals studies in polished section. The sequence as it is shown by the present relationships (Table IV) need not be similar to that before metamorphism. Stanton (1964) concluded:

"Apparent paragenetic sequences in many stratiform ores are in fact a crystalloblastic series..."

Undoubtedly, the sulfides of Skeleton Lake were subjected to metamorphic recrystallization (previous section), thus interpretation of observed paragenetic relationships is difficult.

Pyrrhotite   _____ _____

Pyrite   _____   _____

Magnetite _____   _____

Chalcopyrite   _____   _____

Sphalerite   _____
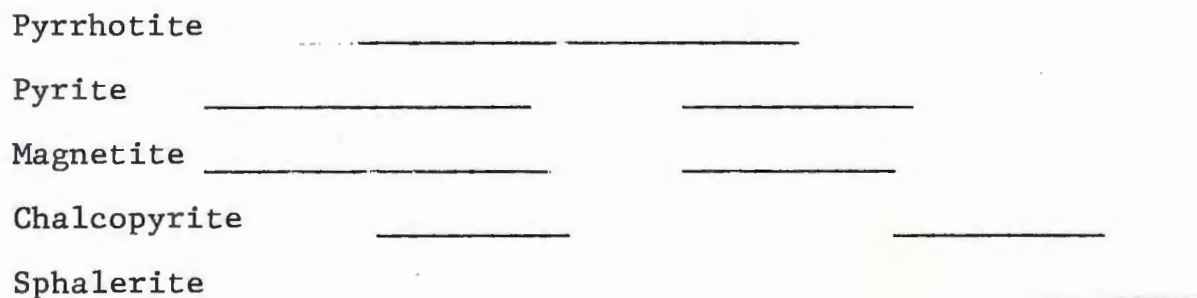
Table IV   Apparent Paragenetic Sequence of Sulphide
Minerals (and Magnetite)- after metamorphism
Solid lines indicate periods of deposition
for each of the minerals.

It would seem that an early stage of pyrite-pyrrhotite-magnetite, with or without chalcopyrite mineralization occurred at Skeleton Lake. Later remobilization of the sulfides was most likely responsible for the coarser, euhedral variety of pyrite in selected bands of the massive ore. The fact that chalcopyrite is commonly observed in fractures within pyrrhotite and along pyrrhotite grain boundaries, indicates a later stage of formation and/or mobilization. In deposits where sphalerite is an important constituent of the ore, many workers (i.e., Large, 1977) have interpreted it as being a late sulfide precipitate. On this basis, the single occurrence of sphalerite at Skeleton Lake was assumed to be a late-forming product in the sequence of mineralization.

Temperature of Sulfide Formation

Craig and Scott (1974) showed experimentally that the sulfide assemblage pyrrhotite-pyrite, with or without chalcopyrite can be stable to a temperature of $550^{\circ}C$. Yund and Kullerand (1966) and Ripley and Ohmoto (1977), determined that, in nature, ore-forming processes usually limit the stability range to $350^{\circ}C$. Above $350^{\circ}C$, cubanite is typically present in the sulfide assemblage.

Monoclinic pyrrhotite is not stable above 251° plus or minus $3^{\circ}C$ (Rising, 1973). The presence of monoclinic and hexagonal pyrrhotite together in an intergranular relationship may indicate equilibration after peak metamorphism at temperatures $\leq 250^{\circ}C$. The minimum temperature

is further limited by the presence of actinolite in hydrothermal veins. Spooner and Fyfe (1973) and Hart (1973) suggest from empirical evidence that actinolite forms in sub-sea floor systems at temperatures in excess of $300^{\circ}C$. Actinolite was produced in basalt-sea water experiments only at temperatures greater than $400^{\circ}C$ and at pressures higher than 500 bars (Mottl, 1976). It is not possible to determine whether the above temperature data reflects original temperatures of sulfide deposition or the last thermal event of the Skeleton Lake region. In any case, it would seem reasonable to assume that the sulfide mineral assemblages were either formed at, or subjected to, temperatures between $250^{\circ}C$ and $350^{\circ}C$.

Interpretation of the Origin of the Sulfides and their Relationship to the Alteration Zones

Conclusions regarding the origin of Archean massive sulfide deposits have had a history of pendulum-like swings (Sangster, 1976). Before 1960 it was generally held that all such deposits were the product of hydrothermal replacement. Since the middle 1960's, however, a number of authors (i.e., Boldy, 1968; Hutchinson, 1971; Sangster, 1972; Spooner and Fyfe, 1973; and, Solomon, 1976) have compiled increasing evidence for a volcanic-exhalative origin for these sulfide bodies. This theory is further strengthened from studies of the Miocene Kuroko deposits of Japan (i.e., Urabe and Sato, 1978) and of present day fumarolic or hot spring centers at the sea floor (Rona, 1978; Bonati, 1975, 1976).

The Skeleton Lake sulfide occurrence belongs to this class of mineral deposits, which are characterized by stratabound, massive, metallic sulfides, and are believed by many to be related to felsic volcanism and to have formed as a result of a sedimentary exhalative process (Hutchinson, 1973).

In general terms, the volcanic exhalative theory contends that massive sulfides in predominantly volcanic environments are an integral part and coeval with the volcanic complex in which the deposits occur (Sangster, 1976). The exhalative theory does not differ markedly from the classical hydrothermal replacement theory in terms of process. In both instances, ore deposition was from hydrothermal solutions originating in the crust of the earth and rising along fractures or other zones of weakness. The passageway through which the fluids rose is now preserved as the alteration "pipe" stratigraphically beneath many orebodies (Sangster, 1976). The theories diverge with regard to timing of massive ore deposition. In the exhalative theory, ore deposition takes place at or near the volcanic rock/sea water interface between successive volcanic episodes. The metals and sulfur are believed to have been leached (from the pre-existing volcanic pile) by the circulating hydrothermal fluids. Advocates of the replacement theory normally regard ore deposition as a secondary feature imposed on the host rocks a considerable time after their formation and lithification (Sangster, 1972). Modern proponents of a non-exhalative

theory such as Boyle (1977) contend that late granitic intrusives acted as a source for hydrothermal fluids and that pre-existing pyritic units provided a sulfur source for the precipitation of sulfides in structurally dilatant zones during regional metamorphism. Metal sulfide prescipitation in both theories is influenced by changes in temperature, pressure, PH, and solution chemistry of the hydrothermal ore fluids.

For several reasons, the sulfide mineralization at Skeleton Lake would seem to be related to exhalative rather than replacement processes. The massive and laminated sulfides at Skeleton Lake have relatively few hydrothermal minerals directly associated with them as one would expect if the sulfides were mobilized and transported to dilatant zones by hydrothermal fluids. Secondly, the rocks of the southern alteration area are well-foliated, but hydrothermal veining is in no way restricted to foliation or other favorable structural sites. In fact, this alteration zone is discordant with respect to both the stratigraphy and structure of the area. Thirdly foliation crosscuts sulfide-bearing, hydrothermal veins. This indicates that the veins were emplaced before regional metamorphism.

In terms of the exhalative theory then, the massive, laminated, and disseminated sulfides of the sulfide horizon are believed to be co-precipitates with an exhalative bedded chert unit. Circulating hydrothermal fluids

would alter the underlying rocks. Such an effect is now reflected by the pervasively altered rocks that lie stratigraphically below the sulfide horizon. As the fluids ascended through the volcanic pile, sequences of relatively permeable pyroclastic rocks would naturally be more susceptible to hydrothermal alteration than the more massive flow units. Such a situation could result in the two stratigraphically conformable alteration zones observed between the predominant flow sequences. The lenses of iron formation and bedded chert associated with many massive sulfide bodies are interpreted by many workers as being products of fumarolic exhalation. Exhalative processes are also thought to be more important toward the end of volcanic episodes (Sangster, 1976). This would account for the association at Skeleton Lake of iron formation, pyroclastic rocks, and alteration zones with the compositional break between basaltic and andesitic volcanism.

The sulfide-bearing hydrothermal veins found throughout the volcanic sequence are interpreted as being epigenetic "stringer ore". These veinlets are generally considered to be the result of sulfide deposition in favorable sites beneath the volcanic rock/sea water interface by ascending hydrothermal fluids.

The discordant, pipe-like alteration area in the southern portion of the Skeleton Lake prospect, stratigraphically overlies the massive sulfide zone encountered in drill core. Because of this, and the fact that the sulfide horizon is cross-cut by hydrothermal veins
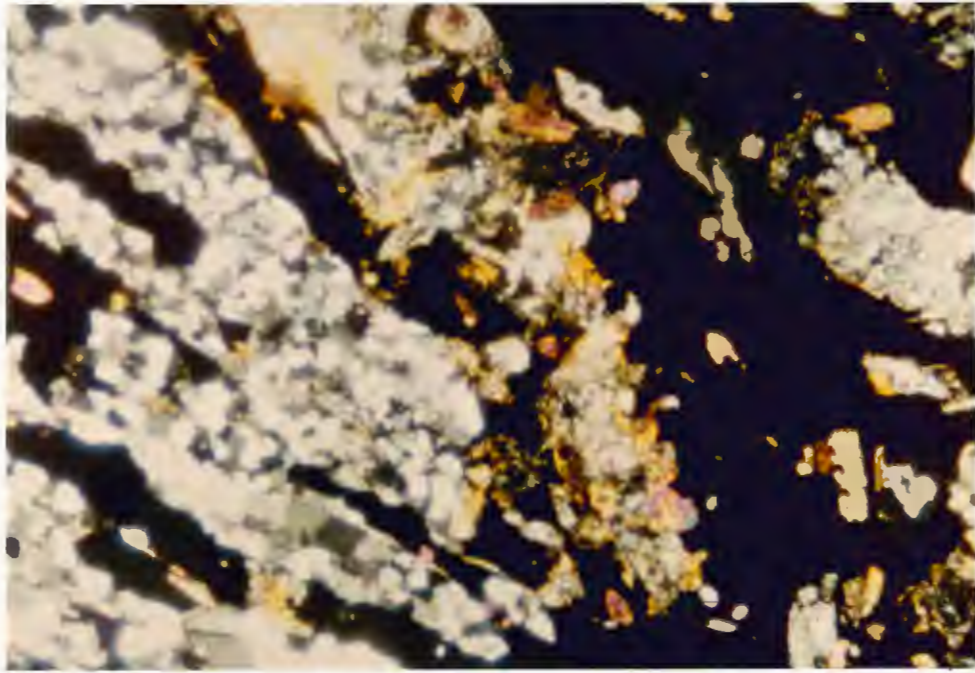
Figure 33 Later hydrothermal vein cross-cutting
        earlier quartz host rock. Fied of view: 5mm

(Figure 33), it would seem as if a second cycle of hydrothermal fluidization affected the Skeleton Lake rocks. The potassium-enriched alteration zone and discontinuous outcrops of poorly bedded iron formation occur toward the middle of the pipe, while the intensity and variety of alteration minerals decrease outwardly in successive zones from the central core (Plate III).

The presence of biotite and potassium-bearing albite indicate temperatures that are higher ($> 350^{\circ}$C) than one would expect in typical alteration pipes associated with volcanogenic exhalative deposits (Many workers, i.e., Ripley and Ohmoto, 1977). The resolution of this anomalous occurrence is beyond the scope of this thesis, but as a matter of speculation, it may be an effect related to a satellitic intrusion of the Giants Range batholith. Such an intrusion could have channeled hydrothermal fluids through the prepared alteration pipe and formed the higher temperature minerals at the expense of the more characteristic sericitic mineralization.

Sulfides that have been locally concentrated in foliation planes and joint surfaces, or that are present in outcrops removed from the alteration zones, probably represent the remobilization of previously deposited sulfides during regional metamorphism.

Base and Precious Metal Content

Atomic Absorption analyses of Cu, Zn, Pb, Au, and Ag on 20 outcrop samples and 24 drill core samples were available for the study by MDNR. In addition, analyses of Cu,

Zn, Au, and Ag were made over various intervals in the drill core by Exxon Corporation (Table V).

Base metal values from outcrop samples and low sulfide zones differed significantly from those of samples taken within the sulfide zone or from areas of sulfide concentration within the drill core. Copper values ranged from .12 to 188ppm in the outcrop and low sulfide group with the average being 67ppm. Within the sulfide zone, values ranged from 97 to 22,400ppm with the average being 2,283ppm. The highest copper values were 5,200 and 22,400ppm from the sulfide horizon of DDH-1 and DDH-2, respectively. There was a rough parallelism between zinc and copper values. The highest zinc values of 420ppm and 770ppm were recorded from the same high copper samples of DDH-1 and DDH-2. Lead values showed little variation from sample to sample. Gold and silver values were generally low, but analyses from select samples of high-sulfide concentration were fairly high. Seven samples ranged from 100 to 1,000ppb gold, and one sample from the 162.5 level of DDH-3 had a gold concentration of 6,000ppb. Silver values paralleled the gold values, with a range between 1,400ppb and 4,400ppb for the same seven samples, with the highest value of 10,000ppb recorded from the same sample from DDH-3.

Similar results were obtained from the samples collected over drill core intervals. The highest copper values were 3.38% and 1.19% over the 191.3-to 194.5-foot and 186.5-to 188.5-foot intervals of DDH-2. Overall, the

TABLE V

BASE AND PRECIOUS METAL VALUES

Surface Samples

Sample		Cu	Zn	Ag	Au
S- 1	DP	36	34	2	2
S- 2	MP	110	0.40	<.01	<.01
S-81	B	50	0.44	<.01	<.01
S-78	B	36	72	<.01	<.01
S-25	B	66	72	2	4
S-29	B	156	106	2	2
S-26	B	66	80	<.01	<.01
S-33	DP	32	38	2	2
S-66	A	0.25	54	2	2
S- 6	B	136	178	2	2
S-12	MP	0.12	0.46	<.01	<.01
S-70	B	98	0.34	2	2
S-71	AP	22	0.15	<.01	<.01
S- 8	B	24	0.20	<.01	<.01
S-19	B	100	70	<.01	<.01
S-18	AP	10	0.40	2	2
S-74	A	40	40	2	2
S-77	A	74	0.21	<.01	<.01
S-46	B	30	0.30	<.01	<.01
S-50	D	188	106	<.01	<.01

BASE AND PRECIOUS METAL VALUES (Cont'd.)

Drill Hole Samples

Sample (w/DH footage)	Cu	Zn	Ag	Au
SL-3-162.5	13,000	105	10,000	6,000
SL-3-172.5	680	56	4,000	980
SL-3-190.5	52	32	100	350
SL-3-225.3	1,150	105	8,000	100
SL-3-241.0	520	52	4,400	700
SL-3-320	520	56	1,200	NA*
SL-3-407.2	686	60	10	NA*
SL-3-432	244	51	1,400	300
SL-3-526	1,632	58	1,600	300
SL-2-170.3	1,517	50	1,900	25
SL-2-189.6	257	63	1,000	NA*
SL-2-193.7	22,400	770	100	NA*
SL-2-209.3	123	90	1,200	NA*
SL-1-182.7	5,200	420	350	90
SL-1-300.5	617	27	1,000	NA*
SL-1-315	97	77	1,200	NA*

All Cu+Zn values in ppm

All Ag+Au values in ppb

NA* ppb analysis not available value reported as 0.0 oz/ton

Letters refer to lithologic units (Plate II)

sulfide horizon of DDH-1 averaged .216% copper over
21.5 feet while the same zone in DDH-2 averaged 1.06%
copper over 17.5 feet. The sulfide-cemented brecciated
zone of DDH-3 had an average value of .455% copper over
7.6 feet. Again, zinc paralleled copper, as the highest
assays were over the same intervals. Gold and silver
values were generally low (< 20ppb and 1,000ppb, respec-
tively), except for select intervals within the sulfide
horizon. These samples ran between 30 and 150ppb gold
and 200ppb to 5,000ppb silver. One exceptional sample
assayed 13,000ppb silver.

In summary, copper, zinc, gold, and silver have
their highest concentrations associated with sulfide
mineralization. Except for this tendency, no other
trends in base metal distribution were apparent.

Trace Element Distribution

To permit the determination of various trace
element ratios, cobalt was also analysed along with the
base and precious metals. In addition, nine samples
taken over drill core intervals in DDH-1 were analysed
by Exxon Corporation for B, S, U, Cr, Ca, Ge, Se, Rb,
Sr, Zr, Mn, Ag, Au, Cu, Zn, Pb, Cl, In, Sn, Tl, Ba, Te,
Pb, Y, and Nb. Chromium showed a sharp increase within
the sulfide zone, whereas strontium was depleted in the
mineralized horizon. Vanadium showed enrichment immedi-
ately above the sulfide zone and depletion within and
below it. All of the other elements either recorded
little variation or varied randomly between intervals.

Metal ratios have often been used in trace element studies of ores and the enclosing rocks. Often, absolute values may be inconsistent or erratic, but ratios will tend to be consistent and characteristic of the ore in a given district (Fleisher, 1955; Wilson, 1965.)

Although ores in a given district may have distinctive trace element ratios, the use of such data as an exploration tool is limited. The alteration zones associated with orebodies are always much more extensive and more frequently encountered by the field geologist. In the present study, an attempt was made to determine whether the alteration zones had characteristic trace element ratios. Selected samples were arranged in order from north to south across the mapping area. Ten trace element ratios were calculated using the data shown in Figure 34.

Unfortunately, no systematic variation was readily apparent between the altered rocks and their unaltered counterparts. In an area such as Skeleton Lake, where the alteration history is complex, differences in analyses from the same alteration zones can frequently occur and make simple comparisons with unaltered rocks difficult. For example, samples 74 and 77 come from the southernmost stratiform alteration zone and have appreciable differences in their base metal content (Table V). Such differences would lend a great variability to the Cu/Zn ratios of the altered rocks.

FIGURE 34
TRACE ELEMENT GEOCHEMISTRY
SKELETON LAKE PROSPECT
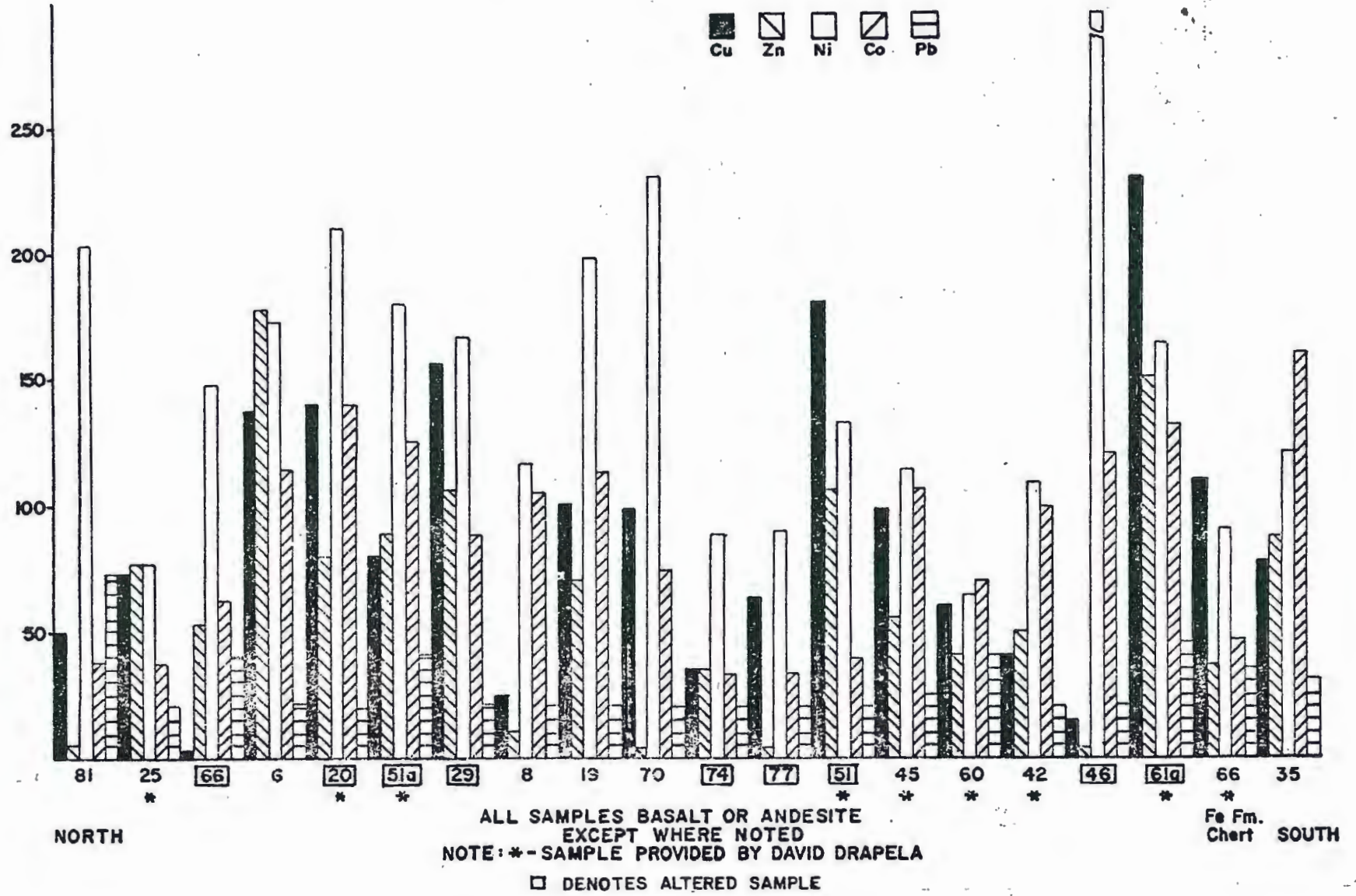
Copper values tend to either be equivalent to, or else significantly greater than, the zinc values in both altered and unaltered rocks. Thus, the Cu/Cu + Zn ratio consistently had values near one-half and one. Geochemically, the alteration zones have similarities with "zones of enrichment" (Chapter 4), where hydrothermal fluids have leached base metals from the country rock. One might expect a contrast in ratios between altered and unaltered rocks. However, some of the rocks in the altered zones have a primary intermediate composition, as opposed to the generally basaltic composition of the unaltered units. Therefore the decrease in base metals from altered zones is frequently neutralized by a parallel decrease in nickel and cobalt. Commonly used trace element ratios such as $\frac{Cu + Zn}{Co}$ and $\frac{Cu + Zn}{Ni + Co}$ do not illustrate any notable difference between the various zones. The above explanation illustrates some of the difficulties involved with interpreting the available data.

Pending a more extensive sampling program, the usefulness of trace element ratios as an exploration guide in the Skeleton Lake area, remains undeterminable.

Economic Potential

At the present price of copper (83¢/lb.), a deposit would have to be very large or of superior ore grade to be economically feasible to exploit. The results of this study indicate that a suitable environment for massive sulfide deposition existed at Skeleton Lake, but the copper was not concentrated to a degree that could be considered economic.

This study was originally undertaken, in part, to
determine the economic potential of the sulfide minerali-
zation, mainly with respect to copper. However, the high
gold values recorded from the sulfide horizon warrant
further investigation. At the present price of gold
($443.25/tr. oz.), large low-grade deposits associated
with the carbonate facies of Archean iron formation are
now being mined in Rhodesia (Fripp, 1976). The ore grades
vary from 6.6ppm to 124ppm gold. Kwong and Crockett
(1978) have determined the range of gold values for the
various lithologies of an Archean greenstone belt near
Katagi Lake, Ontario, to be between .78 and 4.26ppb.
Therefore, assays between 30 and 150ppb over the sulfide
zone at Skeleton Lake may be considered promising, while
individual samples with assays between 1-6ppm approached
ore grade.

Suggestions for further exploration in the Skeleton
Lake area would be:

A. The drilling of an area at the southeast
extreme of alteration zone 2 (Plate III).
This area has a similar magnetic signature
as the drilled sulfide zone.

B. Drilling of the northernmost alteration
zone. This area is geophysically, geologically,
and petrographically similar to the other north-
west-trending alteration zone. Furthermore, it
is located downstrike from the highest geochemi-
cal anomalies recorded in the Skeleton Lake area.

Either one of these alternatives has the possibility of locating a different sulfide body that may have economic ore grade of copper or gold.

CONCLUSIONS AND GEOLOGIC HISTORY

Geologic History

Tholeiitic basalts and andesites, deposited in a
shallow to moderately deep submarine environment, repre-
sent the oldest supracrustal rocks exposed in the Skele-
ton Lake area. These units are stratigraphically corre-
lative with the Soudan Iron Formation but are geochemi-
cally related to the upper Ely Greenstone. Hydrothermal
activity responsible for sulfide deposition, was in part
contemporaneous with the accumulation of the volcanic
pile. The banded sulfides, associated iron formation,
and barren chert units were probably deposited syngene-
tically as exhalites at the volcanic rock/sea water
interface. Porphyries of varying composition were em-
placed as dikes and irregular intrusions contemporane-
ously during the early volcanism.

The next recognizable event is the deformation
associated with the intrusion of the Giants Range and
Vermilion batholiths during the Algoman orogeny, in which
the rocks became part of a major overturned anticline.
The regional folding and faulting imparted a steep folia-
tion to all the rocks within the district, and the rocks
were metamorphosed to greenschist facies assemblages.
During the period, some of the sulfides were remobilized
and concentrated along foliation planes and other favor-
able sites within the volcanic pile. Based on radiometric
dating, Goldich (1972) bracketed the Algoman orogeny
between 2.70 and 2.75 billion years. A long period of

erosion followed the Algoman orogeny. No record of this period is readily evidenced in the present exposures near Skeleton Lake.

Volcanism during Keeweenawan time (1.1 billion years ago) resulted in the accumulation of lava sequences several kilometers thick in what is now the Lake Superior basin. It cannot be readily established if any of these lavas covered the map area. However, the relatively fresh diabasic dikes found at Skeleton Lake may have served as feeders for surface flows. Since Keeweenawan time, the Skeleton Lake area has probably remained above sea level.

Pleistocene glaciation was responsible for the formation of Skeleton Lake and the deposition of unsorted tills, which form the ridges just north of the Lake. Weathering and erosion of the Skeleton Lake rocks has continued through the present day.

Conclusions

1. Basaltic to andesitic flows, diabase, and pyro-
clastic rocks along with smaller amounts of iron forma-
tion and intrusive porphyries of variable composition
comprise the volcanic suite exposed near Skeleton Lake.
Their stratigraphic relationships and present orienta-
tion reflect the evolution of the western Vermilion
district, a typical Archean greenstone belt of the Cana-
dian Shield.

2. Iron formation, pyroclastic rocks, sulfide minerali-
zation, and hydrothermal alteration zones are all spa-
tially related and occur near the compositional inter-
face between basaltic and andesitic volcanism.

3. Stratabound sulfide mineralization may have occurred
between 250 and 350°C, but probably reflects the effects
of later regional metamorphism.

4. Precipitation of sulfide and oxide minerals from
hydrothermal fluids which had circulated through the
volcanic pile could have occurred on or near the sea
floor (exhalites).

5. The presence of a pipe-like hydrothermal alteration
area stratigraphically above the known massive sulfide
horizon would indicate that two cycles of hydrothermal
circulation probably affected the rocks near Skeleton
Lake.

The presence of a bedded non-mineralized chert unit
south (stratigraphically above) of this alteration pipe,
suggests that the hydrothermal fluids of this recent
cycle may have reached the sea-floor.

6.   The base metal content of the sulfide minerals is
concluded to be uneconomic; however, gold values over
limited distances within the sulfide horizon are econom-
ically promising.

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