GEOLOGY OF THE GULLBRIDGE COPPER DEPOSIT CENTRAL NEWFOUNDLAND

H. D. UPADHYAY

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by

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A Thesis

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ABSTRACT

This thesis deals with (i) the geological setting of the Gullbridge copper deposit at Mineral Point, (ii) the petrography of various rock types occurring within the Gullbridge mine area, (iii) textural relationship among various ore and gangue minerals, (iv) ore genesis, and (v) a sequence of geological events concerning the ore body.

The Gull Pond area is underlain by predominantly volcanic and pyroclastic rocks that range from Ordovician to Silurian in age. The ore body occurs within mafic volcanic rocks of the Roberts Arm Formation of probable Middle Ordovician age. These rocks are regionally metamorphosed to greenschist facies grade. They were intruded by granite-diorite bodies during the Devonian period. Numerous faults of regional scale traverse the Gull Pond area. One fault, which is only partly defined, is assumed to pass through Mineral Point.

The ore body has a somewhat lenticular form with a northeasterly trend and a westerly dip. It was disrupted by several faults that were, at a later stage, intruded by predominantly mafic dykes. The sulphides are associated with cordierite, andalusite, and anthophyllite assemblages. The host rock for the ore body is a chloritic cordierite rock that contains the cordierite-andalusite assemblage. This is bounded on both sides by cordierite-anthophyllite rock. Hydrothermal activity involving chloritization, silicification, and sericitization affected the zone which is now occupied by the ore body.

The opaque minerals occurring in the ore samples include chalcopyrite, pyrrhotite, and pyrite with subordinate magnetite, ilmenite, hematite,

sphalerite, galena, and one unknown mineral referred to as "X". The sulphides have replaced some of the pre-existing gangue minerals. Several textures of special interest are described.

On the basis of meager petrochemical data, a subtractive metasomatism, accompanied by contact metamorphism, of metabasalts is suggested as a process for the origin of the cordierite-andalusite and cordierite-anthophyllite assemblages. Despite rather non-conclusive evidence, the author proposes a modified volcanic exhalative origin of the ore body whereby the sulphides were remobilized and emplaced along the assumed fault zone at Mineral Point.

Four phases of deformation have been recognized in the rocks underlying the mine area. A sequence of geological events and their time relationships to various ore and gangue minerals is presented. Suggestions are made for further geological investigation of the Mineral Point - Southwest Shaft area.

ACKNOWLEDGEMENTS

Special thanks are due to Dr. W.G. Smitheringale who suggested the subject of the thesis and supervised the work. The author is grateful to Mr. K. M. Newman, Chief Geologist, Gullbridge Mines Ltd. for help during underground work and for supplying information on the Gullbridge copper deposit through maps, cross sections, and oral communications. Thanks are also due to Drs. C. J. Hughes and M. J. Kennedy for their suggestions in interpreting certain petrographic information.

Mr. F. Thornhill and Mr. W. Marsh are thanked for providing technical and photographic services respectively.

The Geological Survey of Canada and the Mines Branch, Department of Energy, Mines, and Resources, Ottawa, prepared polished sections of ore samples.

Copies of J. Kalliokoski's map, enclosed with this thesis, were provided by Mr. J. McKillop, Provincial Director, Mineral Resources Division, St. John's.

During underground work in the Gullbridge mine, room and boarding facilities were provided by the mine management.

The author is thankful to Mrs. Glenys Woodland for typing the thesis.

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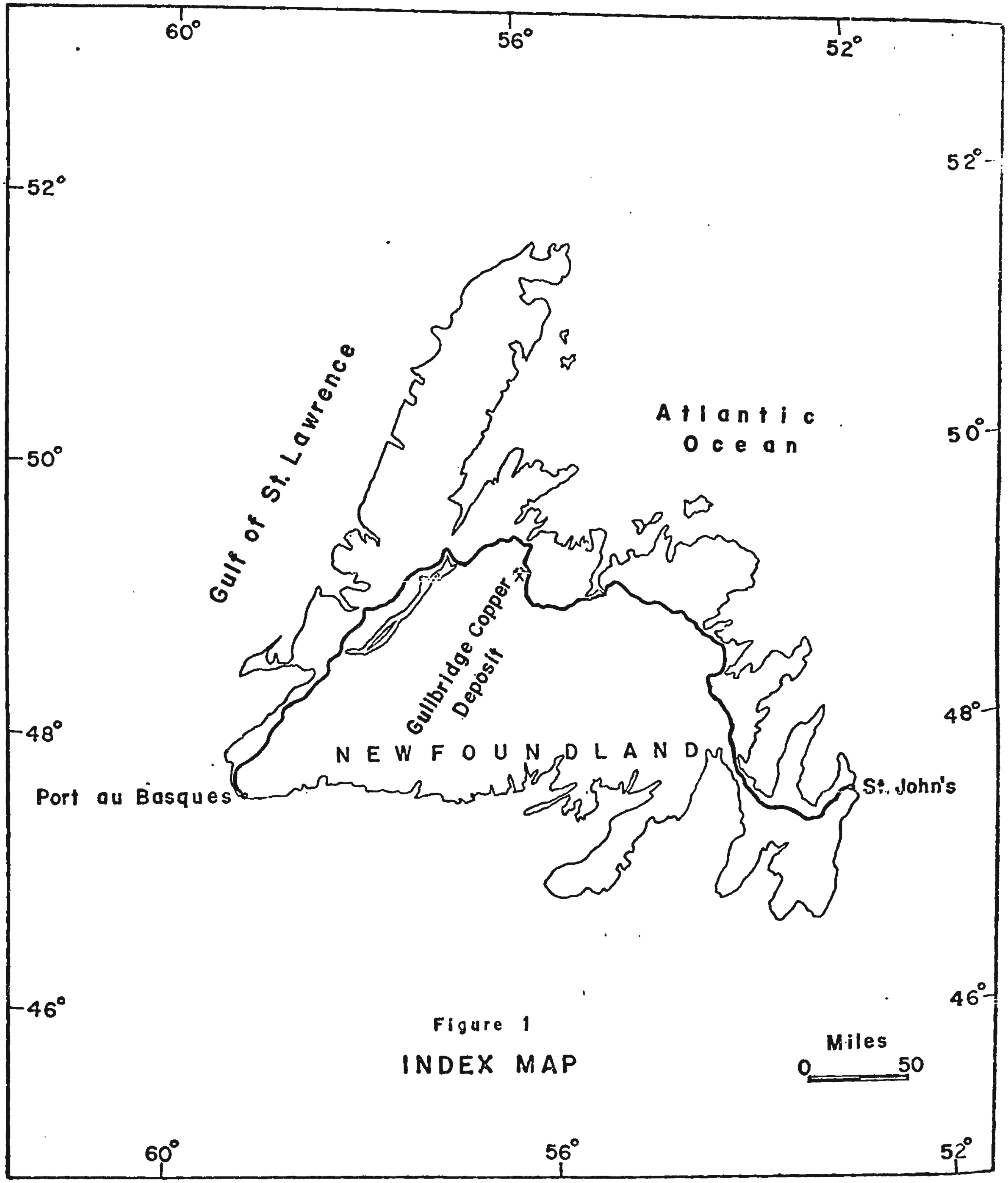

Figure 1

INDEX MAP

CHAPTER I

INTRODUCTION

Purpose of the Present Study

The present study was conducted (a) to discuss the petrography, mineralogy, and textures of the rock types and those of the ore samples of the Gullbridge copper deposit, (b) to establish a paragenesis of minerals and a sequence of geological events concerning the ore deposit, and (c) to propose a possible process of sulphide mineralization.

Location and Access

The Gullbridge copper deposit is located at Mineral Point (Figure 1), on the west shore of Gull Pond, in northcentral Newfoundland (approximately long. 56^{o} 9' 20" E, lat. 49^{o} 11' 54" N). It is about 16 miles NNW of Badger and about 16 miles SSW of South Brook. The place is more commonly known as "Gullbridge Mine" after the name of the mine.

Access to Badger is provided by the Trans-Canada Highway system. The Gullbridge mine lies on the west side of the Trans-Canada Highway and is connected with it by a dirt road about 3 miles long; the dirt road meets the Highway at a point about 13 miles NNW of Badger.

Physiography

The topography of the area around Gull Pond varies from gently sloping hills and ridges to relatively flat uplands and bogs. The bedrock geology appears to have a close relationship to the topography. In the eastern part, northwest of Crooked Lake, granite and diorite uplands have a relatively flat surface with an elevation up to 850 feet above sea level. West of Gull Pond the area is underlain by rocks of volcanic origin and is characterized by hills and knobs that rise up to 750 feet and are elongated towards northeast. The trend of the outcrops and that of the ridges, the flow direction of the streams and the longer dimension of various ponds and lakes are oriented towards northeast.

Gull Pond and Mineral Point both are roughly at the same elevation of about 450 feet. The highest point in the vicinity of Gull Pond is Nutmeg Hill (974 feet above sea level), about 4 miles northwest of Mineral Point. Gull Hill, 3 miles southwest of Mineral Point, is the second highest hill (958 feet above sea level) and has the steepest slopes in the area.

There are several small islands within Gull Pond, among which Burnt Island is closest to Mineral Point and has the largest dimensions. Southeast of Gull Pond, there are several lakes and ponds, most of which are connected with one another by streams of variable size. West of Gull Pond, South Brook runs almost parallel to the sides of Gull Pond and is joined by a few streams at various points. Most of the area is covered with forest. A considerable part of the area southeast of Gull Pond is swampy; the swamps also have a northeasterly elongation.

Exploration and Mining History of the Gullbridge Copper Deposit

The deposit was discovered in 1905. The name of the discoverer is not known. Since then several organizations and individuals, from time to time, carried out geological and geophysical surveys of the Gull Pond area. In 1956 M. J. Boylen took over this property, along with the Tilt Cove deposit in the Burlington Peninsula and formed the First Maritimes Mining Corporation Limited. In August 1967, K. C. Irving interests, through a take over of the First Maritimes Mining Corporation Limited, gained ownership of the mine. The mine went into production on January 1, 1967 at a rated capacity of 2,000 tons of ore per day.

Previous Work

The general aspects of the geology of the area around Gull Pond were known since the late nineteenth century but the occurrence of the copper deposit was not known until 1905.

The deposit attracted attention when in 1918 the owners of the property sank a shaft down to a depth of 75 feet and ran a 68 foot long cross-cut. Later, in 1922, nine drill holes were put down in the area of ore-bearing zone by the Reid Newfoundland Company Limited.

Dougherty and Lundberg (1929) conducted a magnetic and self-potential survey of the Gull Lake (Gull Pond) Property. These investigators also described the mineralogy and mode of occurrence of the ore on the basis of diamond drill data. Their work indicated the presence of an ore body containing 2,160,000 short tons of ore with an average width of 49.5 feet and an average grade of 2.62% copper. Their survey suggested the existence of a one-mile long northeasterly trending magnetic zone extending between points which are two and three miles northeast of Mineral Point. They also studied the glacial geology with the object of determining the source of the boulder train that extends northeast from Gull Pond.

From the available records it appears that A. C. Bray (1929), geologist for the Gull Lake Copper Company, was the leading worker to study the Gullbridge copper deposit. His work consisted of mapping the Great Gull Lake (Gull Pond) area and its vicinity at the scales of one inch equals

2000 feet, one inch equals 1000 feet,and one inch equals 100 feet (1929b). He drew several diagrammatic geological cross sections across Gull Pond. From a study of drill core samples he described various dykes adjacent to the ore and suggested a paragenesis of the ore minerals.

The Newfoundland Geological Survey drilled three holes in 1940 to test several geophysical anomalies near Mineral Point.

Stoiber (1940), David Williams (1940), and others, who worked for the Geological Survey of Newfoundland, described the mineralogy and mode of occurrence of the ore and various rock types associated with it. Stoiber's studies included both the Mineral Point and the Southwest Shaft areas; the latter lies about 1 1/2 miles southwest of Mineral Point. Thereafter various concerns carried out detailed geophysical prospecting in and around the deposit.

Kalliokoski (1951), geologist, Geological Survey of Canada, published a preliminary map of the Gull Pond area (18 x 24 miles; scale 1 inch = 1 mile) that included the granitic rocks exposed about 6 miles east of Mineral Point. Some of these granitic rocks lying east of the Badger - Halls Bay road were previously described by Hayes (1947). Kalliokoski (1955) later revised his preliminary map by plotting detailed geology and included descriptive notes with it.

Neale and Nash (1963) of the Geological Survey of Canada, published a report and a map (scale 1 inch = 4 miles) of the Sandy Lake (East Half) map-area. This map includes the Gull Pond area in its southeastern part. These investigators presented a brief description of the rock types around Mineral Point under the heading of "Exploits Group".

From 1967 onwards K. M. Newman (1968), geologist, Gullbridge Mines Limited, Gull Pond, has undertaken detailed underground mapping at various levels in the mine. On the basis of drill cores, he prepared cross sections showing structural setting of the rock types associated with the ore body at Mineral Point.

CHAPTER II

GEOLOGY OF THE GULL POND AREA

General Statement

The geology of the Gull Pond area is discussed under the following three sections:

(1) General Geology of the Gull Pond area.

(2) Geology of the area around Mineral Point.

(3) Geology of the mine area.

In each case a particular reference is made to the mineralization at Mineral Point. The sections are arranged in order from general to detailed geological descriptions. Thus the first section covers a relatively large area and deals with the broad aspects of the geology of the Gull Pond area, whereas in the second and third sections the geology of the area close to Mineral Point and the details of the ore body and enclosing rocks are discussed. The relationship of the rock units used by previous workers and in this study to depict the geology at these three different scales is shown in Table I.

General Geology of the Gull Pond Area

The geology of the Gull Pond area is described here with special reference to a 15 x 12 miles area (long. 56^{0} 00' to 56^{0} 20' E, lat. 49^{0} 05' to 49^{0} 15' N) lying around Gull Pond. This area is a part of Kalliokoski's Gull Pond map-area (1955). A copy of this map is included (in pocket) and referred to as "Figure 2" in this thesis. Since this map furnishes more detailed information than even some of the more recent reports, the following description is, therefore, based on Kallioski's work (Figure 2).

TABLE I

LIST OF ROCK UNITS USED BY VARIOUS INVESTIGATORS IN THE GULL POND AREA

Rock units underlying the mine area. (Modified after K.M. Newman, 1968) Notations refer to Figures 7 and 8		Rock units underlying the area around Mineral Point. (After A.C. Bray, 1929c) Notations refer to Figure 4B.		Rock units underlying the Gull Pond area. (After J. Kaliokoski, 1955) Notations refer to Figure 2	
				DEVONIAN	
					SPRINGDALE GROUP (6-14)
				14	Amygdaloidal and vesicular basic lava with abundant intrusions of basalt and coarsely porphyritic gabbro
				13	Reddish or purplish, flow-layered, spherulitic, rarely porphyritic, acidic lava; minor flow-breccia and tuff
	Northwest		Northwest	12	Basic, anygdaloidal and vesicular lava; minor acidic lava, tuff, and agglomerate
				11	Flow-layered, spherulitic, acidic lava with abundant flow-breccia.
H	Rhyolite	b	Andesitic lava	10	Porphyritic, massive, acidic lava; minor tuff, agglomerate, and flow-breccia
G	Quartz-sericite phyllite		Paragneiss	9	Basic lava; minor agglomerate and tuff; 9a, red sandstone, shale, and conglomerate; 9b, basic agglomerate

G	Quartz-sericite phyllite
F	Iron formation
E	Metabasalt
D	Cordierite-anthophyllite rock
C	Chloritic cordierite rock
B	Silicic tuffs of various types
A	Greenstone

Southeast

	Paragneiss
b	Andesitic lava
a	Tuff and chert
b	Andesitic lava
a	Tuff and chert
b	Andesitic lava
	Paragneiss

Southeast

9	Basic lava; minor agglomerate and tuff; 9a, red sandstone, shale, and conglomerate; 9b, basic agglomerate
8	Latite and quartz latite
7	Acidic and basic agglomerate and tuff; some basic conglomerate and basic lava
6	Red, arkosic sandstone with thin layers of conglomerate

ORDOVICIAN

MIDDLE ORDOVICIAN (?)

BADGER BAY 'SERIES' (1-5)

5A 5B	5A. *ROBERTS ARM FORMATION:* predominantly basaltic pillow lava; some undifferentiated volcanic rocks and tuff 5B, predominantly rhyolite, latite, tuff, tuffaceous shale; minor greywacke; 5Aa and 5Ba, pyritic schists derived from 5A and 5B
4	*CRESCENT LAKE FORMATION:* grey, green, and red tuffaceous shale, rhyolite tuff, and chert; greywacke; undifferentiated basalt and rhyolite; 4a, hornfelsic rocks
3	Basaltic pillow lava
2	Greywacke with some slate; minor conglomerate and basic lava; 2a, metamorphosed sedimentary rocks; 2b, basalt
1	Greywacke conglomerate; minor greywacke and slate

The central part of the area around Gull Pond is underlain by rocks of predominantly volcanic origin. This central belt, which is about three miles wide in an east-west direction, trends roughly northeastward. On each side it is bounded by intrusive rocks of granitic, granodioritic and dioritic compositions (map units 15 and 16)[1]. East of Gull Pond, contact metamorphic effects have been reported adjacent to the intrusives. The metamorphism produced paragneisses, which are predominantly metamorphosed tuffs with possible igneous gneisses. These were mapped by A. C. Bray (1929b) in the form of isolated patches within andesitic lavas, tuffs, and cherts (Figure 3). Several dykes, which penetrated the flows, caused local metamorphism.

The above mentioned volcanic rocks belong to the Badger Bay Series (map units 1 to 5), which constitutes the oldest succession in the area. Kalliokoski considered it to be of probable Middle Ordovician age. The two lowermost units consist of conglomerate, graywacke, and slate with minor basic lavas in the upper parts. The third unit consists of basaltic pillow lava and the fourth unit, called the Crescent Lake Formation, consists of vari-coloured tuffaceous shale, chert, graywacke, rhyolitic tuff and flows, and basalt.

Overlying the Crescent Lake Formation is the Roberts Arm Formation. The latter was defined by Espenshade (1937) as a succession of pillowed basalt with minor red and green ferruginous chert and rhyolite. Kalliokoski (1955) extended the name Roberts Arm Formation to include a volcanic assemblage that is composed mainly of basaltic lavas (map unit 5A) but which

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[1] Map units referred to in this section are Kalliokoski's (Fig. 2).

also includes large quantities of acidic volcanic rocks, siliceous tuff, graywacke, basic tuff, and agglomerate (map unit 5B).

The Roberts Arm Formation, which contains the ore bodies at Mineral Point and Southwest Shaft, is undated. Although the contact between this and the overlying Springdale Group is reported not to be exposed in the Gull Pond area, an unconformable contact has been presumed (Kalliokoski 1955). Twenhofel (1947) assigned a possible Devonian age to the Springdale Group. On the basis of lithological and palaeomagnetic similarities between the rocks of Springdale Group and those of the fossil-dated Silurian Botwood Belt, Williams (1967) ascribed a Silurian age to the Springdale Group (his "Springdale Belt"). The Springdale Group is openly folded whereas the Ordovician rocks are tightly folded in this area. On the basis of this comparison, Williams assigned a post-Ordovician lower limit for the age of Springdale Group. He also reported a conformable contact between the volcanics of the Roberts Arm Formation and the overlying Springdale Group red beds on Pilleys and Triton Islands. The Roberts Arm volcanics underlying the Springdale Group red beds at Pilleys and Triton Islands appear similar to the volcanic rocks of Springdale Group. On this basis Williams (1967, p. 119) suggested that "although previously assigned to Ordovician, the Roberts Arm Formation is possibly in part of Silurian age". Similarly, evidence accumulated over several years by the British Newfoundland Exploration Company geologists indicates that the portions of the Roberts Arm volcanics on Pilleys Island should possibly be re-assigned to Silurian (Peters, 1967).

In general, the Ordovician rocks of central Newfoundland represent eugeosynclinal deposition whereas the Silurian rocks, apart from some local exceptions, are mainly shallow water to terrestrial deposits occurring in largely fault-bounded belts (Williams, 1967). It is, however, difficult to test the validity of this generalization in the Gull Pond area as information available on the sedimentary rocks of the Roberts Arm Formation is too scanty to determine their environment of deposition. The lavas, however, are pillowed and are more characteristic of the eugeosynclinal Ordovician volcanics rather than the shallow water or terrestrial Springdale volcanics.

Apart from the basal conglomerate and a few beds of conglomerate, sandstone, and shale elsewhere in the succession, sedimentary rocks are lacking in the Springdale Group within the area under review. Kalliokoski (1955) mapped 9 distinct stratigraphic units within this group (map units 6 to 14). Dark green, grey, and dusty-red basic volcanic rocks occur at several stratigraphic intervals (map units 9, 12 and 14). Locally these are interlayered with a few acid flows and tuff layers. The uppermost basalt formation (map unit 14) is intruded by gabbro and coarse porphyritic basalt.

The composition of the coarse intrusives (map units 15, 16) varies from granitic to gabbroic. Towards the margins, the dark minerals in these rocks increase in abundance and accordingly their composition becomes more mafic, ranging from dioritic to gabbroic. The intrusives vary from massive to gneissose in structure and from granular to poikilitic in texture. According to Kalliokoski, these intrusives are of Devonian age.

Sill-like diabasic gabbros (map unit 17a) intrude the probable Ordovician rocks. A large body of massive dark green pyroxenite (map unit 17b) extends from northeast of Dawes Pond to the southwest corner of Gull Pond. Dykes of diabase, andesite and rhyolite, too small to be plotted on

Kalliokoski's map, are reported to be the youngest rock types in the area. They are most abundant around Powderhorn Lake and in the area of volcanic rocks near Gull Pond.

Major Regional Structures: The Ordovician rocks in the area, according to Kalliokoski (1955), are situated on the west limb of a northerly plunging anticlinorium which was probably broken by faults and granitic intrusions. Stoiber (1940, p. 43), on the other hand, wrote:

> ".... many drag folds in the grey and white tuffs indicate that these beds are on the northwest limb of a northeast plunging syncline that has been slightly overturned."

The difference between the reported directions of plunge is perhaps because of Stoiber's reference to magnetic north.

Kalliokoski is of the opinion that many steep-sided draws coinciding with geological contacts near Gull Pond may occur along longitudinal faults. On the west side of Gull Pond, Kalliokoski mapped one longitudinal fault, partly as a "defined" fault, running from Mineral Point southwestward (Figure 2). This fault strikes approximately N 21^{o}E. In this thesis this fault will be referred to as "Gull Pond fault zone". According to Kalliokoski, the Gull Pond fault zone seems to have exerted some control on the localization of the ore body at Mineral Point. Kalliokoski, however, did not present any evidence for the existence of this fault. In this connection, Stoiber (1940a) reported the presence of a zone of shearing about 1800 feet southwest of Mineral Point. This zone strikes approximately N 20^{o}E and, if extended towards northeast, would coincide with the major mineralized zone at Mineral Point. The zone of shearing, according to Stoiber, is marked by a cliff where it intersects Gull Pond. A. C. Bray (in Stoiber, 1940a, p. 43) is also reported to have observed the existence of sulphide replacement along a shear zone striking roughly north-northeast.

In the Gull Pond area the most extensive fault runs in a west-southwest direction from the northeastern part of Kalliokoski's map-area for a distance of about 20 miles (Figure 2). The "belt" of rocks within which the Mineral Point and Southwest Shaft deposits are located, terminates at this fault and possibly reappears at a point about two miles to the east where (on the north side of the fault) a concentration of sulphide-bearing boulders is reported (Kalliokoski, 1955).

Metamorphism and Deformation: In northeastern Newfoundland the regional metamorphism is, in general, of green schist facies grade (Williams, 1963). In many places the evidence of the regional metamorphism is masked by contact metamorphism caused by numerous Devonian intrusives.

In the Gull Pond area the regionally metamorphosed rocks were, in places, subjected to contact metamorphism by intrusion of the nearby granite-diorite bodies. The writer believes that along the assumed Gull Pond fault zone subtractive metasomatism, accompanied by contact metamorphism, locally altered the composition of the metabasalts, thereby preparing them for the development of cordierite-anthophyllite and cordierite-andalusite assemblages at Mineral Point.

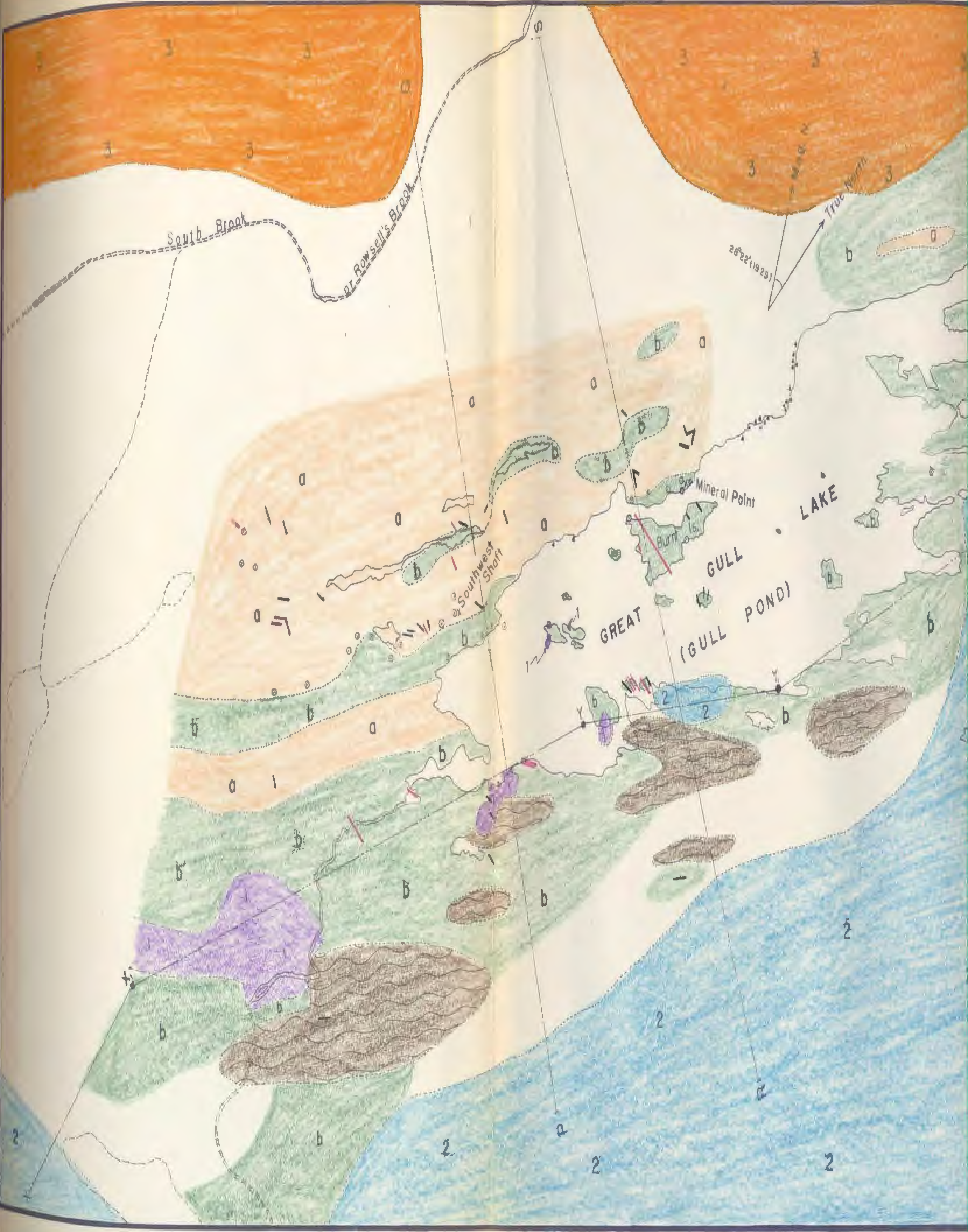
At a later stage, post-ore diabase dykes were saussuritized and uralitized.

The present study reveals that the rocks underlying the Gull Pond area were subjected to polyphase deformation. Four phases of deformation have been recognized in rocks underlying the mine area. The main deformation D_1 was related to regional metamorphism and produced the main schistosity S_1 which is stronger in some rocks than in others. In the ore-bearing zone, S_1 has been largely destroyed by contact metamorphism and hydrothermal alteration. The second deformation D_2 was cataclastic and local and did not produce any schistosity. The third phase of deformation D_3 produced strain-slip schistosity S_2 and crenulation in S_1 in some rocks underlying the mine area. The last deformation, which was post-ore, has been observed only within the ore-bearing zone. It produced foliation in chlorite and stress lamellae in pyrrhotite.

Geology of the Area Around Mineral Point

In this section the geology of a 7 x 3 miles area around Mineral Point is discussed (Figure 3). This area is bounded by the predominantly diorite outcrops in the east and granite outcrops in the west. The following description is based mainly on the work of A. C. Bray (1929 b and c).

On the eastern shore of Gull Pond the rocks are mostly andesitic lavas with subordinate interbedded tuffs and cherts. Kalliokoski (1955) later assigned these rocks to the Crescent Lake Formation and described them as "hornfelses". He, however, assigned isolated patches of basaltic pillow lavas along the shore of Gull Pond to the Roberts Arm Formation. On the west of Gull Pond, Bray mapped the rocks as predominantly tuffs and cherts with subordinate interbedded andesitic lavas (Figure 3). Kalliokoski included these rocks within Roberts Arm Formation, distinguishing the tuffs



South Brook
or Rowsell's Brook
Southwest Shaft
Mineral Point
Burnt Is.
GREAT GULL LAKE
(GULL POND)
True North
28°22' (1929)

LEGEND

b ANDESITIC LAVAS, in part pillow lavas and with subordinate interbedded tuffs & cherts

a TUFF & CHERT, with subordinate interbedded lavas

PARAGNEISS, predominantly metamorphosed tuffs but in part altered andesitic lavas and (possibly) igneous gneiss

OXIDIZED MINERALIZED OUTCROPS

3 GRANITE, with subordinate diorite

2 DIORITE, with subordinate granite

1 VERY BASIC DIORITE

DYKES & SILLS OF DIABASE

DYKES & SILLS OF FELDSPAR PORPHYRY

▲ Oxidized/Ore Boulders X Mine or Shaft

Contacts (largely inferred)

P—Q Geological sections

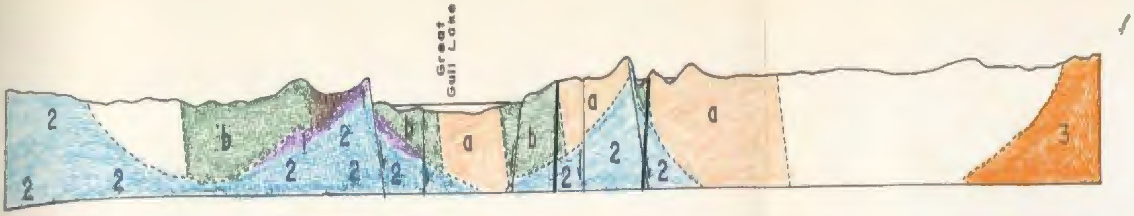
Figure 3

GENERALIZED GEOLOGICAL PLAN OF GREAT GULL LAKE (GULL POND) & VICINITY

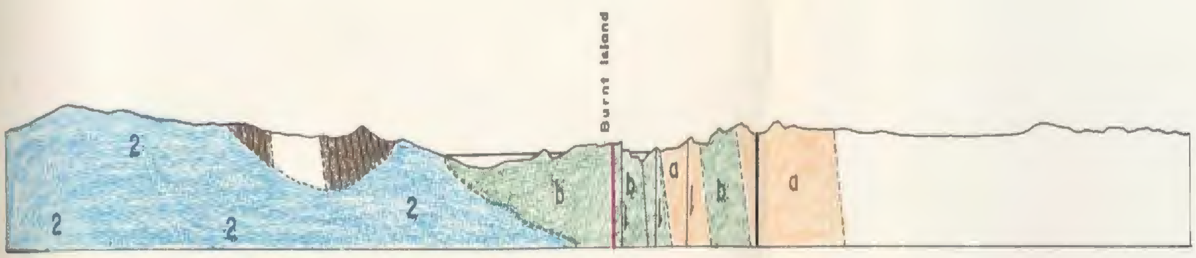
(Modified after A.C. Bray, 1929b)

Scale: 1 Inch = 2285 Feet (appr.)

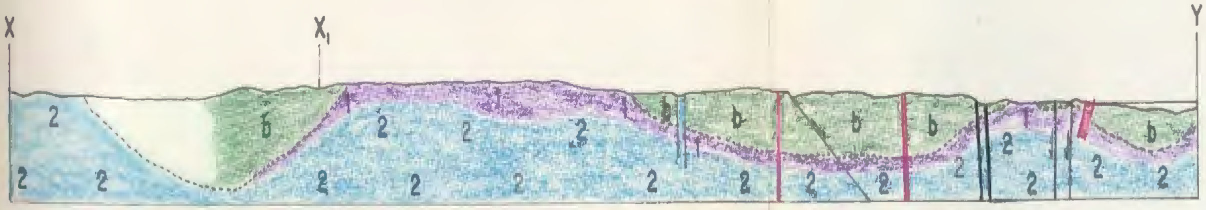
FEET
0 2000



(A) SECTION P-Q



(B) SECTION R-S



(C) SECTION X-Y

(D) SECTION Y-Z

LEGEND

- b ANDESITIC L
- a TUFF & CHEF
- PARAGNEISS
- 3 GRANITE
- 2 DIORITE
- 1 VERY BASIC
- DIABASE
- FELDSPAR P
- FAULT

NO

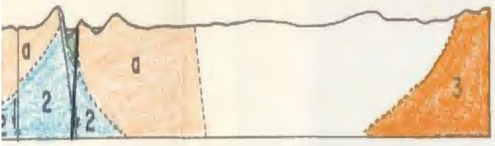
Sections P-Q &

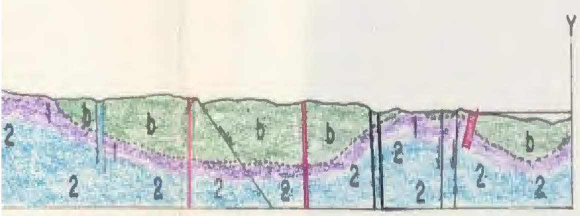
Sections X-Y &

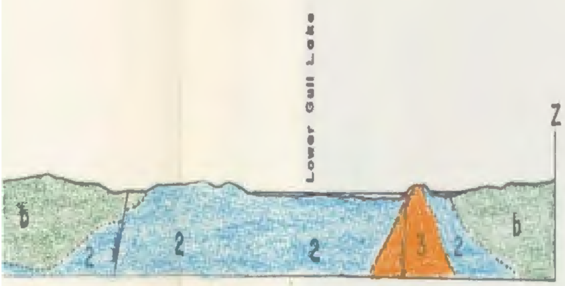
DIAGRAMM

GREAT GULL

SEE F







LEGEND

- b ANDESITIC LAVA
- a TUFF & CHERT
- PARAGNEISS
- 3 GRANITE
- 2 DIORITE
- 1 VERY BASIC DIORITE
- DIABASE
- FELDSPAR PORPHYRY
- FAULT

NOTE

Sections P-Q & R-S looking S.W.

Sections X-Y & Y-Z looking north

Figure 4

DIAGRAMMATIC GEOLOGICAL SECTIONS

OF

GREAT GULL LAKE (GULL POND) & VICINITY

(Modified after A.C. Bray, 1929 c)

SEE FIGURE 2 FOR LOCATION OF SECTIONS

Scales 0 2000' | 500' (app.) 0

with cherts, and the andesitic lavas as two sub-units (map units 5A and 5B, Figure 2). The contact between the two sub-units lies close to Mineral Point and runs along the west side of Gull Pond. Lenticular bodies of one type within the other also occur. Close to the contact between these two sub-units, Bray noted a number of mineralized outcrops including those at Mineral Point and Southwest Shaft. Some mineralized outcrops, however, are also reported to lie some distance from this contact (Figure 3).

Isolated outcrops of diorite occur along the eastern margin of Gull Pond, the nearest mappable one being about 4,000 feet east of Mineral Point. Small outcrops of diorite, hardly visible in Figure 3, are also reported from small islands within Gull Pond. These isolated outcrops appear to represent stock-like offshoots of the main diorite intrusive (Figure 2, map unit 15) exposed farther east. Bray mapped lenticular bodies of paragneisses — "predominantly metamorphosed tuffs but in part altered andesitic lavas and (possibly) igneous gneiss" — which seem to be the products of contact metamorphism caused by the granite-diorite intrusives.

Diagrammatic geological cross sections across Gull Pond drawn by Bray (Figure 4) show that the volcanic rocks have an average dip of about 70° towards west. Section RS (Figure 4) passing through a point about 2,000 feet southwest of Mineral Point, shows that the simple dipping sequence of andesitic and tuffaceous rocks is cut by three steeply dipping faults. In all these faults the western side is downthrown, although in some faults, for instance, in section PQ near Southwest Shaft, the downthrown side is on the east. Bray's geological sections indicate his belief that the volcanic rocks are underlain and intruded by the dioritic body and that the faults referred to above cut both volcanics and diorite. In section YZ (Figure 4) Bray shows granitic rocks to intrude the dioritic body.

Geology of the Mine Area

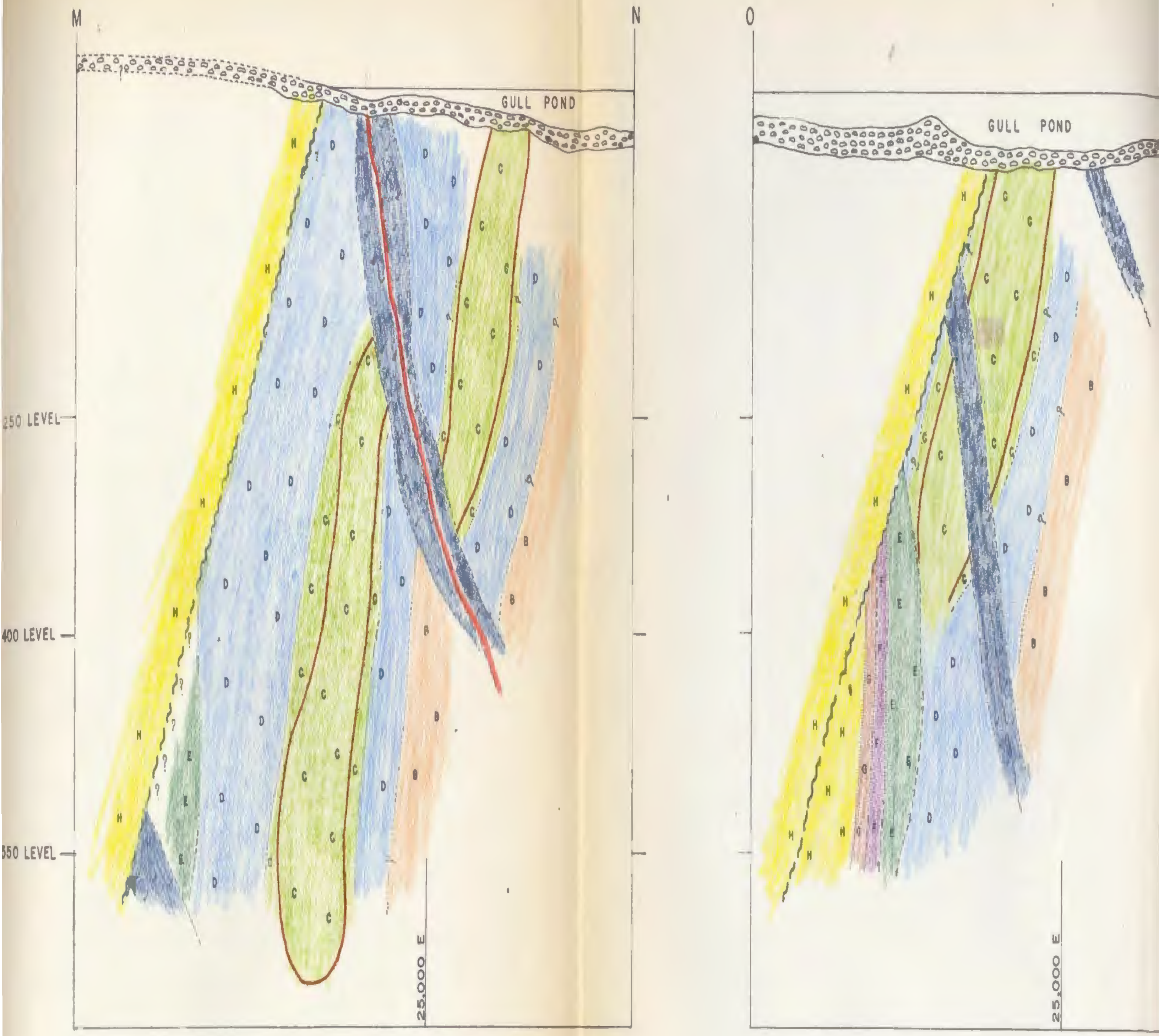
General Geology: The term "mine area" here refers to an area about 1400 feet by 850 feet that lies between Mineral Point and the northwestern margin of Burnt Island. This area is underlain by the ore body and various associated rocks which are largely covered by Gull Pond. A generalized geological plan of the mine area, based mainly on the geology of 400 level, is presented in Figure 7 (in pocket). Due to a northeasterly trending fault, hereafter called "West Fault", some rock units such as the iron formation and the quartz-sericite phyllite, do not appear on or above the 250 level. The 400 level is, therefore, chosen to show the detailed geology of the mine area. Figures 5 and 6 (in pocket) show the variation of the geology and structures with depth. These geological plans, modified after Newman (1968), are based mainly on underground observations and partly on the diamond drill data. Some of the significant modifications made by the author are as follows:

(a) Rock units mapped as "andesite" by Newman are renamed "metabasalt" (although some of these units may be more andesitic than basaltic).

(b) Newman's "altered andesite" has been divided into two groups: (i) chloritic cordierite rock, (ii) cordierite-anthophyllite rock.

(c) From diamond drill data some additional rock units have been introduced.

The western portion of the mine area is marked by the West Fault



(A) SECTION M-N

(B) SECTION O-P

Figure 8

GULLBRIDE MINE

GENERALIZED GEOLOGICAL CROSS SECTIONS OF THE MINE AREA

(MODIFIED AFTER K. M. NEWMAN, 1968)

SEE FIGURE 7 FOR THE LOCATION OF SECTION LINES

(B) SECTION O-P

:

ECTIONS OF THE MINE AREA

AN,1968)

CTION LINES

NOTE: BOTH SECTIONS LOOKING APPROXIMATELY NORTHEAST

Scale of feet

0 100

that moved the rhyolite in its hanging wall upwards relative to the other rock units in its footwall. In plan, the trace of this fault and the length of the ore body show a close parallelism with each other. The approximate dip of the West Fault is 60° west, whereas the axis of the ore body shows an inclination of about 70° in the same direction (Figure 8). This fault can be traced down to a depth of about 850 feet. It contains a gouge zone about 1 1/2 to 2 feet thick, and the rhyolite adjacent to it is highly brecciated. This fault reaches the surface beneath the Gull Pond and is believed to be the main source of water underground. It offsets some rock units occurring within the mine area. The post-ore dykes also terminate abruptly as they meet the West Fault. This suggests that the West Fault is post-ore in age.

The mine area has undergone a post-mineralization transverse faulting along more than four planes, the traces of which are almost parallel to one another. These faults, hereafter referred to as "ore body faults", have approximately an easterly trend and have an apparent dip of about 70° towards southeast. The distance between two consecutive faults varies from 200 to 500 feet. The separation of various rock units due to some of these faults, and the sense of movement, is shown in Figure 7. A maximum throw of about 160 feet has been determined in one of these faults (Newman, personal communication). The ore body faults are now occupied by silicic to mafic dykes that were intruded along them.

From the diamond drill data it has been noted that the silicic tuffs and the metabasalts are interbedded with each other. In places these units occur in lenticular forms. Because of this, various cross sections across the mine area show different arrangements of the rock units. The dip of such irregular units varies from almost vertical to about 80^{o} towards west (Figure 8).

The inconsistency and irregularity of various rock units, their disruption by the ore body faults, and the meager (surface) information about the predominantly water-covered mine area, make it difficult to work out a strictly stratigraphic or even structural succession.

Various rock units occurring within the mine area are given in Table I. It must be emphasized that this is a structural rather than a stratigraphic succession. The rock units in this table have been arranged such that the structurally lowest rock type (the greenstone outcropping on Burnt Island) is listed at the bottom and the rhyolite, occurring towards Mineral Point, at the top. The detailed structure within the mine area, especially the presence or absence of isoclinal folds, is not known. Similarly, it is not known whether the repetition of certain rock units, e.g. metabasalts and silicic tuffs, is a stratigraphic or a structural phenomenon.

In Figure 7 some of the geological boundaries, particularly the one between the chloritic cordierite and the cordierite-anthophyllite zone, are generalized. The rocks containing the cordierite assemblages, although listed with stratified rocks, are not necessarily stratified. They show a lateral gradation into the metabasalt. The greenstone unit, exposed on the northwestern margin of Burnt Island, has been extrapolated from surface to the 400 level.

Form of the Ore Body: The ore body has the approximate form of several northeasterly trending lenses that dip about 70^{0} to the west (Figures 5 and 8). The lenses, as seen in the plan outline, pinch and swell and their continuity is broken by the crosscutting post-ore dykes. Beneath the 250 level the two main lenses appear to represent a single lens that was offset by a fault along which a "composite" dyke was intruded.

The total plan-length of the ore body at a depth of about 35 feet is 1400 feet; this gradually reduces to 1200 feet, 700 feet, and 350 feet at the depths 250 feet, 400 feet and 550 feet respectively. The maximum plan-width, which exists in the southern part of the 250 level, is 210 feet. At a depth of about 35 feet below surface, the ore body pinches to about 60 feet in its northeastern part and then gradually vanishes with a tapering end to the northeast (Figure 5). The longitudinal profile of its bottom is irregular. It reaches a maximum depth of about 620 feet in its central portions. The southern and northern ends of the ore body have depths of 360 feet and less than 400 feet respectively.

CHAPTER III

PETROGRAPHY AND PETROLOGY OF THE ROCK TYPES OCCURRING WITHIN THE MINE AREA

The geology of the mine area has been discussed in detail in the last chapter. Following is a petrographical and petrological account of the rock types underlying the mine area.

Greenstone

This rock type outcrops on the northwestern margin of Burnt Island and represents the structurally lowest unit within the mine area. Being covered with water, its westerly limit is not known. The rock is greyish green, medium-grained, and in outcrops appears to be weakly foliated.

A microscopic study of the rock suggests that it consists almost entirely of hornblende with subsidiary chlorite, magnetite, albite, and scanty grains of augite. On a microscopic scale the rock shows a distinct schistosity due to the preferred orientation of hornblende. This is the oldest schistosity observed in the rocks of the mine area and will be referred to as "S_1". The deformation related to S_1, which is believed to be of regional scale, will be referred to as "D_1".

Textures and optical characters suggest that there are two generations of hornblende in the greenstone. The hornblende of first generation (hornblende - 1) constitutes about 90% of the rock. It occurs as whispy anhedral grains whose orientation defines the schistosity S_1. The size of the hornblende grains is of the order of 0.5 millimeter. Some of the hornblende grains show marked pleochroism from pale green to green. Because of the partial alteration to chlorite, its colour varies in different parts of the same grain.

This type of hornblende appears to have developed during the regional deformation D_1.

The hornblende of second generation (hornblende - 2) usually occurs in subhedral form and possesses a well-defined outline (Figure 13). It is relatively fresh and shows no preferred orientation. It occurs within veins that run oblique to the main schistosity S_1. Some hornblende occurs as small felted masses of non-oriented, almost submicroscopic needles, forming a kind of matrix among the larger hornblende grains. This appears to be genetically related to hornblende-2 and, therefore, of the same age. The free growth of hornblende-2 in veins may be responsible for its larger grain size. Hornblende-2 is post-S_1 and its growth is considered to have taken place during the contact metamorphism related to the emplacement of the nearby granitic rocks in Mineral Point area.

Some scanty grains of euhedral augite also occur in the rock. A few hornblende grains that appear as augen within hornblende-1 possibly developed from the alteration of augite.

Veins, 0.4 to 0.6 millimeter in width, run oblique to the main schistosity S_1 and are filled with albite, hornblende-2, and aggregates of a sericite-like fine-grained mineral. Albite is partially altered to sericite. All these minerals are epigenetic and post-date the regional deformation D_1.

Magnetite is primary and forms aggregates which are extensively elongated parallel to S_1.

The present form and mineralogy of the rock gives little clue about its parentage. Hornblende-1 seems to be a prograde product of regional metamorphism. From the existence of primary augite and the overall composition of the present rock, it seems that the parent rock probably had a basic composition.

Magnetite-Actinolite Schist (?)

This rock type, obtained from a (drill hole) depth of 150 feet, comes from a point about 150 feet northeast of the eastern end of Burnt Island. If extended towards the southwest along the regional strike, it seems to merge into the greenstone. The distribution and thickness of the rock unit represented by this particular sample is not known. Nevertheless, a petrographic account of this rock is presented here as the first generation of magnetite (magnetite-1)*, to be described later, is best exemplified in this rock.

In handspecimen the magnetite-actinolite schist (?) is a medium gray, fine-grained rock with well developed schistosity. As seen in thin section, it consists of actinolite (40%), magnetite (30%) and plagioclase (30%). Pyrite occurs as an accessory mineral.

Actinolite occurs in tiny fibers and shows a faint pleochroism from pale green to green. These fibers possess a high degree of preferred orientation and render the rock schistose. A number of aggregates of actinolite fibers, however, occur in spherulitic form and do not show any preferred orientation. These non-oriented actinolite fibers, which are optically similar to the oriented ones, possibly developed towards the end

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* Different generations of the same mineral species are identified by a number or letter. Their paragenesis is described in Chapter IV and portrayed in Table III (in pocket). Thus "magnetite-1" refers to the oldest of two generations of magnetite.

of the regional metamorphism. The schistosity S_1 is believed to be related to the regional deformation D_1 which concurrently attended the regional metamorphism in the Gull Pond area.

Aggregates of magnetite-1 are highly deformed and elongated parallel to S_1. In places they also form thin and undulating streaks. These aggregates form augens which are wrapped around by the oriented actinolite fibers. This suggests that the magnetite aggregates existed in the rock before it was subjected to deformation. Magnetite has an average grain size of 0.5 millimeter.

Plagioclase (An_{35}) grains show polysynthetic twinning with slightly blurred twin planes. Trails of actinolite bend around the plagioclase grains and normally render them augen-shaped. Their average size is 0.2 millimeter.

<u>Silicic Tuffs</u>

This group of rocks occurs in abundance in the mine area. Units of silicic tuffs up to 20 feet thick are commonly interbedded with metabasalt (to be described later). The tuffs occur predominantly southeast of the ore body. Their limit in this direction, however, is not known.

On the basis of texture and mineralogy, the silicic tuffs can be divided into 4 types: 1. Crenulated silicic tuff, 2. Lapilli tuff (?), 3. Cordierite-bearing silicic tuff, and 4. Cordierite-spotted silicic tuff. All the four types of silicic tuff were observed in the mine. Their thickness and exact distribution is not known. All of them show a hornfelsic texture in handspecimens. The term "silicic tuff" is used here as it has been used by mine geologists and previous workers, although in the specimens collected by the author, nothing indicated positively that these are tuffs.

1. Crenulated Silicic Tuff: This type is most abundant among all types of silicic tuffs. The rock is aphanitic and in most cases shows discontinuous crenulated laminae, the thickness of which is of the order of one millimeter (Figure 19). The average amplitude of the crenulations is 5 millimeters. The laminae are differently coloured, ranging from light to dark gray. Tiny subhedral grains of pyrite up to 1 millimeter in size are disseminated throughout the rock.

As seen in thin sections, the chief constituents of the rock are quartz (70%), chlorite (chlorite-m) (25%), and biotite (biotite-1) and muscovite (5%). Calcite, epidote, and pyrite occur as accessory minerals.

The laminae are defined by alternate units, consisting predominantly of quartz and chlorite. Other minerals in the quartz-predominant laminae are fine laths of biotite and muscovite. The chlorite laminae are slightly thinner than those of quartz and consist solely of chlorite acicules. In places the lamination is also caused by difference in the size of quartz grains. Chlorite forms pseudomorphs after a mineral that, in cross sections, appears orthorhombic and which contains inclusions which, in some grains, are arranged in a cross. Except for the fact that the cross sections are rhombic rather than square, the original mineral would seem to have been andalusite (chiastolite).

The fine-grained quartz has an average grain size of 0.015 millimeter whereas in the coarse-grained variety the grain size ranges up to 0.2 millimeter. The quartz grains are normally equigranular with an irregular outline. A number of quartz grains show undulatory extinction. Pyrite is usually surrounded by, or associated with, the coarser variety of quartz. Aggregates of pyrite are elongated parallel to the laminae and some euhedral pyrite grains have quartz pressure-fringes. Elongated lenticular patches and veins running oblique to the lamination are filled with epidote, calcite, and chlorite of younger age.

The dominant schistosity defined by the micaceous laminae (composed of chlorite, biotite, and muscovite) seems to have developed during D_1. This schistosity has been crenulated by a later deformation D_3 which resulted in the development of a very weakly defined axial plane schistosity (hereafter referred to as "S_2") which runs along the troughs and crests of the crenulations. S_2 is of strain-slip type, the traces of which are widely separated; nucleation of fine chlorite acicules has taken place along them.

<u>2. Lapilli Tuff(?)</u>: This rock type, grouped under "tuff" by the mine geologist, was observed in 250 level. Spatially, it is associated with the crenulated silicic tuff. Its exact distribution is not known. The drill-hole logs, however, suggest a probable thickness of about 50 feet.

In hand specimens, the rock consists predominantly of possible "lapilli" i.e. angular fragments of volcanic material ranging in size from a fraction of a centimeter to one centimeter. The angular fragments are pinkish-gray in colour and occur within a groundmass of greenish-gray material. The sharp angles of the fragments give the rock a brecciated appearance (Figure 22). The rock does not show any lamination or preferred orientation.

As seen in thin sections, the rock consists chiefly of probable volcanic rock fragments (40%), chlorite (30%), and calcite (30%). Sphene, epidote, and pyrite occur as accessory minerals. Calcite and the probable volcanic rock fragments occur in a groundmass which consists predominantly of green massive chlorite. This chlorite is pitted with tiny grains of some turbid mineral, possibly sphene. In places calcite and chlorite fill the intergranular spaces among the rock fragments and also replace the latter. This gives rise to networks and pseudomorphs of calcite and chlorite. On a microscopic scale, the rock is traversed by many veinlets filled with calcite and epidote.

The rock fragments are irregular in shape but always have straight edges. They consist of silicic and mafic material, both present almost in equal quantity. The silicic fragments contain quartz and potash felspar, the latter have a turbid appearance due to alteration. The mafic fragments consist solely of plagioclase (An_{30}) laths. They show polysynthetic twinning and have a diffuse boundary. They contain abundant tiny inclusions of some unrecognizable opaque mineral. The plagioclase and the opaque mineral give rise to an indistinct spherulitic texture suggesting a possible relatively shallow emplacement.

A number of calcite grains show repeated contact-twins. Many of such grains indicate a gliding along twin planes. These grains show undulatory extinction and exhibit a sense of movement along their bent twin planes.

There are two possible origins of this rock: (a) The presence of angular fragments of mixed volcanic material and its association with the predominantly tuffaceous rocks suggests a pyroclastic origin. The rock, at a later stage, seems to have been subjected to metasomatism involving the addition of Ca and CO_2. This is represented by the abundant calcite and Ca-bearing minerals like sphene and epidote. The late introduction of calcite and chlorite is shown by their occurrence in the form of veinlets and their pseudomorphs after the pre-existing rock fragments. There are two possible sources of Ca for the growth of the Ca-bearing minerals: (i) The hydrothermal activity which is believed to have affected the rocks underlying the mine area. (ii) The Ca that was probably released during the growth of cordierite-andalusite and cordierite-anthophyllite assemblages at Mineral Point. (b) Despite the close spatial association with the deformed rocks underlying the mine area, the lapilli tuff (?) does not show any deformational features. Even the angular rock fragments do not show any stretching or any foliation around them. This, along with the indistinct spherulitic texture mentioned earlier, indicates a possible epigenetic origin of the rock under discussion. The rock may be a diatreme of late igneous origin, possibly related to the igneous activity that formed the "composite" dyke (to be described later). Since this rock does not occur immediately adjacent to the ore body or the cordierite-anthophyllite rock, the introduction of Ca and CO_2 to it from either of the two possible sources mentioned earlier, could have been structurally controlled by some fault or breccia zone. If this rock is a diatreme, the introduction of Ca and CO_2 could also be attributed to the gases that caused the possible brecciation.

3. Cordierite-Bearing Silicic Tuff: The exposures of this type of silicic tuff exist in 400 level where, if projected parallel to the general

strike, they seem to merge laterally into the cordierite-spotted silicic tuff, a variety to be described later. The limits of the cordierite-bearing silicic tuff are not known.

Megascopically, the cordierite-bearing silicic tuff is a light gray, very fine-grained rock and has a somewhat greasy lustre. It lacks any recognizable bedding or lamination. It, however, contains a moderately developed schistosity which shows a weak crenulation. The maximum amplitude of these crenulations is about 0.5 millimeter. Some samples carry up to 1 centimeter thick discontinuous bands of grayish black cordierite in a light gray groundmass (Figure 20). Pyrite grains, 0.5 to 1.0 millimeter in size, are usually disseminated throughout the rock.

In thin sections, the rock consists predominantly of fine-grained quartz with subordinate muscovite, biotite, chloritized cordierite, chlorite, magnetite, and pyrite. The percentage of various subordinate minerals is variable.

Quartz constitutes about 75% of the rock. It has an average grain size of 0.01 millimeter. Aggregates of a coarser variety of quartz, with an average grain size of 0.1 millimeter, occur in veins and lenticular patches.

The micaceous minerals render the rock a moderate schistosity S_1 which is the predominant fabric in the rock. This schistosity is crenulated by a later phase of deformation D_3. Some of the samples show a poorly developed axial plane schistosity S_2 which passes through the crests of the crenulations.

Cordierite forms up to 10% of the rock. It occurs in bent patches with poorly defined outlines (Figure 12). It shows a mild alteration to pale chlorite. The degree of alteration is uniform in all parts of a single grain. Inclusions of tiny quartz grains are fairly common in the cordierite patches. Some of the cordierite patches, which are bent parallel to the crenulation, show undulatory extinction. The main schistosity S_1 does not form any augen around the cordierite grains. These suggest that the cordierite was formed before D_3 and after D_1.

Some optically unrecognizable pink mineral forms pseudomorphs after magnetite. These pseudomorphs usually occur in square or rhomb-shaped grains. The pseudomorphs contain unreplaced thin lamellae of some opaque mineral, possibly ilmenite.

The growth of cordierite may have taken place through the following type of reaction:

$$\text{chlorite} + \text{muscovite} + \text{quartz} = \text{cordierite} + \text{biotite} + H_2O$$

Schreyer (<u>in</u> Winkler, 1967, p. 179) reported that such reaction requires a temperature of at least $500^{\circ}C$ at 2000 bar pressure. At Mineral Point the growth of cordierite in silicic tuffs could have been the product of normal contact metamorphism. The formation of the adjacent cordierite assemblages in the metabasalt, however, is believed to have involved subtractive metasomatism as well as contact metamorphism (this is explained in Chapter V).

<u>4. Cordierite-Spotted Silicic Tuff</u>: This type of silicic tuff, best developed in 400 level, lies approximately along strike from the cordierite-bearing silicic tuff.

In handspecimen the cordierite-spotted silicic tuff has a hornfelsic structure. Randomly oriented dark gray porphyroblasts of cordierite occur in a light gray, fine-grained, non-laminated matrix (Figure 21). The rock, therefore, has a spotted appearance. The size of the cordierite porphyroblasts ranges from about one-tenth of a centimeter to nearly two centimeters. On close examination, the extremities of the nearly oval cordierite porphyroblasts show a fibrous form. Rectangular to square-shaped grains of pyrite occur uniformly distributed throughout the rock.

Microscopic study suggests that the rock is composed of fine-grained quartz (60%), cordierite (20%), biotite, muscovite, and chlorite (20%). Pyrite and magnetite occur as accessory minerals. It shows a very weak foliation which is defined by biotite. This foliation is masked by the growth of large cordierite porphyroblasts over it.

Cordierite contains inclusions of aggregates of quartz, biotite, muscovite, and chlorite. Its porphyroblasts are surrounded by a rim of massive chlorite which has an average width of 0.5 millimeter. The cordierite porphyroblasts do not show any bending. Biotite has a diffused boundary. Pyrite grains vary from 0.1 to 2.0 millimeter in size and are almost oval to rectangular in shape. They show a special association with cordierite porphyroblasts or the aggregates of coarse-grained quartz.

The occurrence of the cordierite-spotted variety along strike from the cordierite-bearing variety of silicic tuff and their similar mineralogies, possibly with the exception that cordierite is more abundant in the spotted variety, suggests that the original compositions of the rock from which they formed were similar. The occurrence of cordierite in distinct clots (spots) in one and in bands and laminae in the other suggests that the main reason for their different appearance now is that initially one was massive and the other laminated. It is also possible that the spotted variety was more intensely metamorphosed. The reaction which gave rise to cordierite bands and laminae in one variety and to cordierite porphyroblasts in the other variety was possibly the same in each case.

Metabasalt

This rock type is closely associated with the cordierite-anthophyllite and the chloritic cordierite rocks within the mine area. It also occurs in thin units interbedded with the silicic tuffs described earlier. Underground mapping at various levels suggests that the metabasalts grade into the cordierite-anthophyllite and the chloritic cordierite rocks. In places the metabasalts lie almost directly along the strike of these rocks (Figures 6 and 7). In addition to this, remnants of the metabasalt within the cordierite-anthophyllite rock have been reported (Newman, personal communication). It, therefore, seems likely that the metabasalts are the rocks from which the cordierite assemblages developed.

The metabasalts are of two types: (i) non-amygdaloidal, (ii) amygdaloidal. These two types, however, have not been mapped separately. In handspecimen they are grayish-green and fine-grained.

As observed in thin sections, the constituents of the non-amygdaloidal metabasalt are hornblende (60%), sericitized plagioclase (30 to 40%), and up to 10% partly altered augite. The rock shows equigranular non-schistose texture with an average grain size of 1 millimeter. Most of the hornblende occurs in lath-like forms. Its colour varies even within a single grain.

The pleochroism in most of the grains is as follows:

X = Pale green
Y = Brownish pale green
Z = Dark green

Most of the hornblende (hornblende-2) has developed from the alteration of augite; crystals of augite partly replaced by hornblende-2 are not uncommon. In addition to this, hornblende (hornblende-1) also occurs in matrix as shredded patches and small individual needles. The matrix is weakly to distinctly foliated. The foliation is defined by the oriented patches and streaks of semi-transparent aggregates of very fine-grained sphene(?). These streaks occur within and around the edges of hornblende-2 grains and they also form discontinuous trails parallel to S_1. Although the oriented hornblende (hornblende-1) was involved in deformation D_1 (as were the large pyroxene grains that were, at a later stage, replaced by hornblende-2), some of the hornblende in the matrix has random orientation and appears to have grown statically.

Plagioclase laths, although completely sericitized, still preserve their original form. The mineralogy and especially the texture of the rock suggests that the parent rock was a basalt. The results of the chemical analysis of the non-amygdaloidal metabasalt (Sample K-3) are presented in Table II.

In the amygdaloidal variety the amygdules are up to 1 centimeter in length. The rock consists of hornblende (60%) and altered plagioclase (40%). Magnetite occurs as an accessory mineral. The elongated amygdules are filled with Ca-bearing minerals such as vesuvianite, sphene, calcite, diopside, and garnet (possibly grossular). Since these minerals are almost equidimensional, it is therefore believed that they grew in the pre-elongated vesicles.

Hornblende usually occurs as aggregates of lath-like or fibrous units. It is strongly pleochroic from yellowish-green to dark green. All the hornblende in the amygdaloidal variety grows over ilmenite trails that are the possible representatives of S_1. It occurs as randomly oriented fibrous units and rosette-like aggregates. It is, therefore, believed that the hornblende in this variety of metabasalt is post-D_1 and is the "hornblende-2" of contact metamorphic origin. There are no pyroxene phenocrysts altered to hornblende in the amygdaloidal metabasalt.

The plagioclase (An_{10}) laths have irregular boundaries and their longest dimensions range up to 0.5 millimeter in size. Most of the grains are sericitized and lack twinning. In the rarely occurring twinned grains the traces of the twin planes are usually blurred. The low anorthite content of the plagioclase is presumably due to albitization of calcic plagioclase which existed in the rock before it was subjected to contact metamorphism.

The squashed amygdules indicate that the rock was once deformed, but if any other form of deformational fabric developed, it has been largely obliterated by the static growth of hornblende-2. The rock, however, contains ilmenite trails which strongly resemble the sphene(?) trails mentioned earlier in the non-amygdaloidal metabasalt. These ilmenite trails are regarded to be the possible representatives of S_1 in the amygdaloidal variety. The ilmenite possibly developed through the contact metamorphism of sphene(?).

Rocks Containing Cordierite Assemblages

This group of rocks is closely associated with the sulphides and a part of it contains the ore body. These rocks contain cordierite with either andalusite or anthophyllite, which are referred to as "cordierite assemblages" in this thesis. The term does not include the cordierite-bearing silicic tuffs. In plan-outlines the width of these rocks varies from about 250 feet in southwest portion of the mine to about 100 feet in northeast portion of the mine. On the basis of mineralogy, texture, and degree of alteration, this group can be divided into the following two sub-groups, hereafter called "zones".

1. Chloritic cordierite zone
2. Cordierite-anthophyllite zone

The chloritic cordierite zone encloses the ore body. It is bounded on both sides by the cordierite-anthophyllite zone, and the boundaries between the two zones run roughly northeastward, parallel to the axis of the ore body (Figures 6 and 7). The outer limits of the cordierite-anthophyllite zone are not well defined due to inadequate sample distribution. It is emphasized that the boundaries of the rocks containing the cordierite assemblages and those of its sub-groups are highly generalized in Figures 6 and 7. The boundaries of the chloritic cordierite zone lie very close to that of the ore body. In 250 level and above it the West Fault passes very close to the northwestern side of the ore body. In 250 level the thin slice of rock between the ore body and the fault is presumably a part of the outer cordierite-anthophyllite zone, but due to hazardous rock conditions in this part of the mine, samples could not be obtained to confirm this assumption.

Both chloritic cordierite and the cordierite-anthophyllite zones contain sulphides in various amounts. In the former they are more abundant and generally have a massive structure whereas in the latter they occur only as accessory constituents and are sparsely disseminated.

From several places within the cordierite-anthophyllite and the chloritic cordierite rocks the occurrence of features that are indicative of remnant volcanic pillows has been reported (Newman, Personal communication). This suggests a volcanic origin of the rock which, in the author's opinion, was metasomatised to give rise to the cordierite assemblages at Mineral Point. On the other hand, some specimens from the chloritic cordierite zone contain bands up to 1 centimeter thick of disseminated pyrite. The general appearance of these specimens suggests that the parent rock was possibly of mixed volcanic origin, containing both tuffaceous and flow rocks.

1. Chloritic Cordierite Zone: This zone occurs in the central portion of the cordierite-anthophyllite zone. There exists a gradational contact between the chloritic cordierite and the cordierite-anthophyllite zones. The thickness of the chloritic cordierite zone varies from a maximum of 200 feet to almost nothing.

Megascopically, the rock of this zone is distinguished by its grayish green colour and relative softness, both of which are attributed to the chloritization of the rock. Where foliated, the rock assumes the form of a "sulphide-chlorite schist" (Figure 31). In handspecimen the sulphides appear as lenses and thin ribbon-like bands almost parallel to one another. The sulphides show a preference for the replacement of the chloritized part of cordierite (Figure 15) and for filling intergranular spaces among quartz grains (Figure 42).

The chief constituents of this rock type, as seen in thin sections, are cordierite, chlorite, quartz, chalcopyrite, pyrrhotite, and pyrite. Biotite is abundant in some specimens but nearly absent in others. Andalusite is a minor but important constituent of this zone. Among accessory minerals are sericite, muscovite, garnet, magnetite, ilmenite, an unknown mineral pseudomorphing magnetite, and rarely anthophyllite. The percentage of the chief constituents of the rock varies with the degree of chloritization and silicification in different parts of the zone. Practically all the minerals occur within a groundmass of green massive chlorite. A high degree of hydrothermal alteration has obscured the primary textures of the rock.

Abundant chlorite formed by alteration of cordierite, a higher content of sulphides, much less anthophyllite, and the presence of andalusite in the chloritic cordierite zone are the main features that distinguish it from the cordierite-anthophyllite zone.

Cordierite alters to chlorite to a variable extent. The degree of chloritization decreases from the core towards the margins of the chloritic cordierite zone and finally in the surrounding cordierite-anthophyllite zone it becomes almost insignificant. The remnant anhedral grains of cordierite occurring in a groundmass of chlorite are highly variable in size. The alteration has occurred along grain boundaries, fractures, and cleavage of cordierite. In some grains it has progressed to the degree of producing islands of small cordierite grains which show simultaneous extinction. Such an extinction is the only means of determining the pre-alteration shape of the cordierite grains. These remnants are usually fresh-looking and pale gray in colour. Cordierite less commonly alters to sericite. It usually contains inclusions, most abundant among which are magnetite, chalcopyrite, pyrrhotite, and pyrite. Magnetite, whether occurring within or outside cordierite, always has euhedral shape whereas pyrrhotite and chalcopyrite assume the shape of the chlorite altered from cordierite.

Chlorite occurs in three forms: (i) massive chlorite (chlorite-1), (ii) acicular chlorite (chlorite-2), and (iii) reaction-rim chlorite (chlorite-3). The massive chlorite is the most abundant. Textures suggest that it is formed mainly through the alteration of cordierite. It occurs in large patches and, in places, encloses the remnant cordierite grains. The outline of these patches is very irregular and blurred. It does not show any distinct cleavage. In detail, it is an aggregate of extremely fine and equidimensional units of chlorite. It is pale green in colour without any noticeable pleochroism. It shows first order bluish gray polarisation colours which are not uniform in all parts of its patches. Sulphides are very commonly found in the massive chlorite and in quartz aggregates. In places, where it occurs on both sides of a stretched sulphide grain, it is foliated parallel to the length of the stretched sulphide grain (Figure 43).

The acicular chlorite is much less abundant than the massive chlorite. It normally occurs along the margins of massive chlorite and the needles show very well developed cleavage (Figure 16). The needles in most cases are contorted. It shows a marked pleochroism from pale green to almost colourless. It shows anomalous Berlin blue polarisation colours.

The optical characters suggest that the acicular chlorite is probably penninite. Its form, pleochroism, and polarisation colours distinguish it from the massive chlorite.

The reaction-rim chlorite is developed at the contacts of silicates (massive chlorite, cordierite) and sulphides (pyrite, chalcopyrite, pyrrhotite). It forms a thin rim of uniform width around the sulphides and follows their outline very closely (Figure 18). This indicates that the growth of this type of chlorite post-dated that of pyrite, chalcopyrite, and pyrrhotite. The reaction-rim consists of extremely fine fibers of chlorite which run parallel to one another but at right angles to the length of the rim. It shows a very weak pleochroism from pale green to almost colourless. The polarization colours are first order gray. Its relationship to the sulphides and its pleochroism suggest that it is possibly an iron-rich chlorite.

Sulphides show a preference for replacing chlorite-1 and chlorite-2. Chalcopyrite and pyrrhotite replace only those parts of cordierite which are altered to chlorite (Figure 15). This, in places, gives rise to irregular vein-like features of sulphide in cordierite. Where both types of chlorites occur together, the sulphides show a higher preference for replacing chlorite-2. Sulphide-bearing needles of chlorite-2 are normally contorted (Figure 17). Chlorite-3 does not contain any ore minerals.

Biotite occurs in isolated aggregates, each aggregate consisting of several randomly oriented irregular grains. These aggregates, in places, suggest a very weak preferred orientation. The outline of biotite grains is usually diffused. It is strongly pleochroic from light pinkish brown to dark brown. Textures suggest that biotite grew later than cordierite and anthophyllite, that is, during the retrograde phase of contact metamorphism. The growth of the cordierite assemblages, to be discussed later, is considered to be related to the prograde phase of the same contact metamorphism. Although this type of biotite is not found associated with the biotite-1 of regional metamorphic origin, yet in order to avoid confusion, this biotite is listed as "biotite-2" in the paragenesis (Table III).

Quartz occurs as an aggregate of tiny equidimensional anhedral grains. It either forms microscopic bands usually alternating with cordierite-chlorite bands or fills intergranular spaces among cordierite grains. In places, aggregates of quartz show "pinch and swell" structure, the "necks" of which are occupied by sulphides (Figure 25). Such structures are observed only where relatively incompetent minerals like sulphides and chlorite occur adjacent to the bands of quartz aggregates. This quartz seems to have originated largely from the silicification associated with the hydrothermal activity at Mineral Point. Chalcopyrite and pyrrhotite display a very high preference for filling intergranular spaces among such quartz grains.

Andalusite, not visible in hand specimen, constitutes about 5% of the rock. It normally shows spatial association with cordierite. In places, it occurs in the core of cordierite grains such that the irregular outlines of both minerals show a vague parallelism with each other (Figure 26). The outline of andalusite in such grains has a corroded appearance. It is colourless with a pinkish tint and does not show any appreciable pleochroism. It can be distinguished from the associated cordierite by its higher relief and relative freshness.

No evidence of anthophyllite was found in the andalusite-bearing specimens from the chloritic cordierite zone with the possible exception of a few small radiating sheafs of biotite that could be pseudomorphous after anthophyllite. These sheafs, however, do not have quite the same form as anthophyllite in the adjacent cordierite-anthophyllite rock. In one specimen a small amount of anthophyllite was found but no andalusite was observed.

In the cordierite-anthophyllite zone, to be described later, andalusite was not noted. It appears that in the chloritic cordierite and the cordierite-anthophyllite zones, andalusite and anthophyllite do not occur together in the same specimen. This can likely be attributed to the fact that except in systems containing the iron-rich end members of the cordierite and anthophyllite series, anthophyllite, cordierite, and andalusite are approximately co-linear in composition. Thus in most known occurrences of these three minerals, anthophyllite and andalusite are mutually antipathetic (Turner, 1968, p. 193-200).

The chloritic cordierite zone could be named after andalusite, but chlorite being more abundant and easier to recognize in the field, the zone is named after chlorite.

Some rhomb-shaped and completely altered grains commonly occur in the chloritic cordierite zone. This unknown mineral is turbid gray to pink in colour and it has an extremely low birefringence. Its noticeable optical characters are too meager to allow identification. A study of polished sections reveals that these grains include thin lamellae of ilmenite and tiny remnant-like irregular grains of magnetite. The ilmenite lamellae are oriented in two to three directions. It appears that the unknown mineral is pseudomorphous after magnetite. Additional comments on this will be made in Chapter IV.

The lense- and the ribbon-like structure of ore specimens is believed to be inherited from a pre-mineralization schistosity. In the immediately adjacent cordierite-anthophyllite zone such a schistosity is considered to be S_1, and most likely it is this schistosity that has left its imprint on the ore-bearing chloritic cordierite rock. The stretching and lensing out of the sulphide units is believed to be accentuated by a post-mineralization deformation D_4. Although not very pervasive, D_4, in places, also resulted in the development of foliation in the massive chlorite. The foliation runs parallel to the length of the associated stretched sulphides (Figure 43).

<u>2. Cordierite-Anthophyllite Zone:</u> This zone occurs next to the chloritic cordierite zone. The boundary between the two zones lies very close to the outline of the ore body (Figures 6 and 7). Due to the West Fault, the west side of this zone is displaced down to a depth of about 300 feet. Beneath this, the zone lies almost symmetrically on both sides of the ore-bearing chloritic cordierite zone. Underground mapping shows a lateral gradation of the cordierite-anthophyllite zone into the meta-basalts and the chloritic cordierite zone. The thickness of this zone is highly variable.

The cordierite-anthophyllite zone shows very little or practically no alteration to chlorite. The rock, therefore, is relatively hard and massive. In places a foliation due to sulphide streaks is visible in hand specimens. This zone contains some scanty sulphides but it does not form a part of the ore body. The approximate proportion of minerals in this zone is as follows: cordierite 50%, anthophyllite 40%, and accessory minerals mainly biotite, quartz, ilmenite, magnetite, chalcopyrite, pyrrhotite, and pyrite (10%).

The textural relationships between cordierite and anthophyllite suggest that the two minerals were formed almost simultaneously. In places, however, anthophyllite seems to have been formed earlier than cordierite as the former is subpoikilitically enclosed by the latter (Figure 27). Anthophyllite normally occurs in fibrous and rosette-like forms. In some samples it shows remarkable pleochroism from pale gray to pale green.

Cordierite in this zone is relatively fresh and shows practically no alteration to chlorite or sericite. Its optical characters are similar to those of the cordierite occurring in the chloritic cordierite zone.

Biotite-2 was formed later than anthophyllite. Its shape and growth is controlled by the intercrystal spaces among anthophyllite crystals. In places, therefore, it does not show its natural crystal habit. It normally occurs in isolated patches within the rock. Magnetite-2 occurs as euhedral grains and shows a uniformity in size, regardless of the nature of the enclosing silicates. Pseudomorphs of pyrite after anthophyllite are quite common.

The foliation observed in the hand specimens is mainly due to thin bands of cordierite-anthophyllite and quartz. The thickness of such bands varies from 1 millimeter to 3 millimeters. Anthophyllite fibers do not show any preferred orientation. In places they grow across the bands (Figure 24). Trails of some opaque mineral, possibly ilmenite-hematite, run parallel to these bands. Such trails in the chloritic cordierite rock represent S_1 and, therefore, it appears that the present foliation in the cordierite-anthophyllite rock is inherited from S_1. The effects, if any, of the post-mineralization deformation D_4 are not evident in this zone.

Andalusite was not observed in this zone. Pyrite, pyrrhotite and chalcopyrite either replace or show a special association with the quartz bands.

To summarize, the chloritic cordierite zone is distinguished from the cordierite-anthophyllite zone by its relative softness, higher degree of chloritization and silicification, higher sulphide content, and rare occurrence of anthophyllite. Andalusite, in general, seems to be confined to the chloritic cordierite zone. Texturally, in the chloritic cordierite zone cordierite occurs as remnants within a groundmass of massive chlorite, the latter being altered from cordierite. In the cordierite-anthophyllite zone, on the other hand, cordierite is mostly unaltered and it occurs as aggregates of small grains which subpoikilitically enclose the anthophyllite fibers.

Iron Formation

The cordierite-anthophyllite zone, northwest of the ore body, is structurally overlain by an iron formation unit. The latter is offset by the West Fault and for this reason it is not encountered down to a depth of about 350 feet (Figure 8). It is, however, reported to be exposed on surface beyond the northeastern and southwestern extremities of the West Fault. In cross sections, this is the only rock unit within the mine area which generally shows maximum parallelism with the ore body. The thickness of the iron formation varies from about 60 feet to 5 feet. It is disrupted by eastward trending ore body faults which were later intruded by dykes.

In hand specimens the iron formation shows alternating laminae of reddish-brown and olive-green material. These laminae vary from 2 millimeter to 1 centimeter in thickness. Each individual lamina shows further fine laminae within it. The gently folded laminae are cross-cut by irregular quartz veins about 1 millimeter in width.

Microscopic study reveals that the constituents of the iron formation are quartz (60%), hematite and magnetite (25%), and green biotite and chlorite (15%). Garnet occurs as an accessory mineral. The laminated appearance is due to differences in mineralogy and texture. The reddish brown laminae consist of magnetite, very fine-grained hematite, quartz, chlorite, and green biotite; magnetite in these laminae is coarser than in others, varying from 0.2 to 0.1 millimeter in size. Hematite grains are almost round and their size ranges from almost submicroscopic to 0.002 millimeter. These are very closely spaced and distributed uniformly throughout the laminae. The reddish brown colour of the rock is due to the hematite grains. Laths of green biotite and chlorite show a strong preferred orientation parallel to the laminae. In the second type of laminae magnetite grains, with an average size of 0.02 millimeter, are more densely spaced than the adjacent ones. Hematite is very sparsely distributed. Green laminae consisting chiefly of chlorite and green biotite constitute a third type. These micaceous minerals have a strong preferred orientation.

Quartz grains have an almost uniform size of 0.015 millimeter in all the laminae. These grains have intergrown boundaries and show elongation parallel to the laminae. A number of grains show undulatory extinction. Numerous quartz-bearing veins, from 0.1 to 1.0 millimeter wide, run oblique to the laminae. Quartz in these veins is epigenetic in origin and coarser in size. The corrugated intergranular boundary between various quartz grains in the veins suggests a textural inequilibrium.

Garnet is distributed almost uniformly throughout the rock but a special concentration exists in the chlorite-rich laminae. It occurs in variable forms with an average size of 0.02 millimeter.

Quartz-Sericite Phyllite

This rock type has an average thickness of 20 feet. Like some other rock units, this is also disrupted by the West Fault and therefore not encountered down to a depth of about 350 feet. In 400 level it occurs in direct contact with, and structurally over, the iron formation.

In hand specimen the rock is grayish pink, very fine-grained, moderately foliated and has a phyllitic appearance. Its constituents, as seen under the microscope, are quartz (70%) and sericite (30%). Epidote occurs as an accessory mineral.

Quartz is of two types in this rock: (i) The one having equidimensional grains with an average grain size of 0.01 millimeter and forming the bulk of this rock. Most of the grains show undulatory extinction. The serrated type of mutual boundary between adjacent quartz grains suggests that the rock has been possibly recrystallised. Along strain-slip schistosity S_2, which is very well developed in this rock, the quartz grains have a high concentration. (ii) The second type of quartz occurs in patches up to 5 millimeters across, which consist of aggregates of small quartz grains. It seems to be of later origin, perhaps formed by the silicification of the rock. The presence of fractures in quartz grains and the wrapping of sericite trails around their aggregates, suggests that these aggregates were crushed by the deformation D_3 which gave rise to the strain-slip schistosity in this rock.

Sericite occurs in the form of thin flakes with a high degree of uniformity in size. It shows very strong preferred orientation. Epidote occurs only within fractures and is, therefore, of very late origin. Some of its elongated grains show undulatory extinction.

The preferentially oriented trails of sericite flakes representing S_1 are crenulated and disrupted by the strain-slip schistosity S_2 (Figure 10). The traces of S_2 run almost parallel to one another. The distance between two such adjoining traces varies from 0.1 to 0.05 millimeter. The traces of this schistosity pass through the crests and troughs of the crenulations.

The rock shows fractures of a microscopic scale. These fractures are subparallel to one another and aligned approximately in the direction of the strain-slip schistosity. Some of the fractures are filled with epidote.

From the foregoing description it appears that the quartz-sericite phyllite was subjected to at least two phases of deformation. The first deformation D_1 gave rise to the main schistosity S_1 which is defined by the trails of sericite. The second phase of deformation D_3 which was not as pervasive as D_1, is responsible for the development of crenulations and strain-slip schistosity S_2.

Rhyolite

Structurally, the rhyolite unit lies at the top of all the rock units underlying the mine area. It does not occur on the footwall side of the West Fault down to a depth of about 350 feet and therefore above this depth it has a faulted contact with the structurally underlying rocks. Its limit towards west is not known.

Megascopically the rhyolite is a light gray and fine-grained rock. It often contains patches and up to one inch wide veins of quartz and abundant narrow veins filled with epidote. The rock lacks any indication of megascopic flow structure.

The rock consists of quartz (80%) and felspars (20%). Epidote, muscovite, chlorite, leucoxene, and some opaque mineral, possibly ilmenite, occur as accessory minerals. The rock shows a moderately developed porphyritic texture in which felspars occur as phenocrysts and quartz constitutes the groundmass. Chlorite, leucoxene, and especially the altered felspars render the rock turbid in appearance in thin sections. Quartz is of two generations: (i) Fine-grained quartz forming the groundmass, is of earlier origin; its average grain size is 0.01 millimeter. These grains are equidimensional and somewhat angular. Most of them show undulatory extinction. (ii) Coarse-grained quartz, occurring within veins and patches, is of later origin. It has an average grain size of 0.2 millimeter. These grains do not show undulatory extinction.

Plagioclase (An_{10}) and potash felspars are the next most abundant minerals. They show polysynthetic and Carlsbad twinning respectively. Both felspars are present almost in equal quantity. The average size of the felspars is 1.0 millimeter. Some disrupted and bent grains of felspar are suggestive of a mild deformation. Practically all felspar grains occur in tabular or lath-like forms. Their outlines, however, are not sharp. Aggregates of very small flakes of sericite form pseudomorphs after felspars.

The suggestion of a weakly developed flow texture in thin sections and the alignment of the longer dimensions of the felspar phenocrysts indicates a probable volcanic origin of the rock. The rhyolites were subjected to silicification at a later stage which accounts for the relatively higher content of quartz in the rock.

Post-Ore Dykes

Dykes are the youngest rock types within the mine area. They occur in several swarms, each swarm consisting of a number of thin dykes separated by tuffs, chloritic cordierite, and cordierite-anthophyllite rocks. Figures 5, 6, and 7 show a very generalized form of these swarms. The thickness of the swarms and that of the constituent dykes is variable from one part to another within the mine area. The thickness of some of the constituent dykes is as little as 2 feet but on the average they are about 40 feet thick. The mine exposures of these swarms at various depths show a parallelism with one another. In detail, their form is highly irregular. The swarms have roughly an east-west trend and they make an angle of about 45^{0} with the length of the ore body. Drill-hole intersections show that the dykes, on the average, have an apparent dip of about 70^{0} towards southeast. The localization of the dykes is believed to have been controlled by the east-west running ore body faults that disrupt the ore body. Towards west, like some other rock units within the mine area, the dykes are offset by the West Fault. The dykes do not carry any sulphide minerals of economic value.

Compositionally and texturally the dykes can be divided into the following three groups:

1. Spherulitic felsite dykes
2. Andesite dykes
3. Diabase dykes

1. Spherulitic Felsite Dykes: These are spatially associated with the diabase dykes. The swarms containing both of these two types have been designated as "composite" dykes. Out of four swarms mapped within the mine area, only one is composite in nature. In Figures 5, 6, and 7 the spherulitic felsite dyke is shown as a single unit but in detail it branches out into several thin dykelets. The thickness of such dykelets is of the order of 5 feet. These, in places, show a discordance with the main trend of the enclosing diabase dyke, suggesting a younger age of the spherulitic felsite dyke.

In hand specimens the spherulitic felsite dyke is a fine-grained, grayish pink rock. As seen in thin sections, it consists of quartz (30%), potash felspar (10%), and grains showing a micrographic intergrowth of the two (60%). In some samples, however, quartz forms a major part of the groundmass and thus raises the quartz content to about 50%. Most of the grains showing micrographic intergrowth have a feather-like shape which radiate from a common centre and give rise to spherulites (Figure 23). The spherulites have an average diameter of 2.0 millimeters. In cross section their shape is almost circular. The micrographic intergrowth is coarser in the peripheral parts than in the centre of the spherulites. The felspathic component of the spherulites is altered to sericite. This results in a turbid appearance of the rock, especially along the periphery of the spherulites. Grains of microcline and orthoclase free from the intergrowth are rather rare. Quartz fills in the intergranular spaces among the spherulites and occurs in highly irregular forms. Calcite, chlorite, epidote, and quartz of late origin occur in veins.

One of the plausible explanations of the spherulites may be that the magma may have developed an immiscible hydrous silicate phase which formed globules that solidified as separate entities during cooling. The feather-like shapes of the units showing micrographic texture suggest that the spherulites perhaps developed rapidly in a highly supersaturated viscous solution. The growth of the spherulites seem to have been promoted by the rapid cooling of the thin dykelets of spherulitic felsite which intruded a relatively "cold" diabase dyke. The composition of the rock and the apparent absence of any remnant glassy material in the spherulites rules out the possibility of their growth through devitrification of glassy rocks.

The micrographic texture seems to have developed from an eutectic intergrowth between quartz and potash felspar. Its relative coarseness at the peripheral regions is believed to be due to a slower rate of cooling which was enhanced, or perhaps caused, by a probable increase in the residual water content during the crystallization of the peripheral parts of the spherulites.

2. Andesite Dykes: Dykes of intermediate composition occur within the diabase dykes. The thickness of the andesite dykes varies from a fraction of a foot to several feet. In Figures 5, 6, and 7 these dykes are included within "predominantly diabase dyke". The exact form and distribution of the andesite dykes is not known. Its chilled margins against the diabasic types suggest that the andesite dykes were intruded at a later stage.

Megascopically the andesite dykes can be distinguished, though with difficulty, from the diabase dykes by their dark gray colour and fine-grained texture. As seen in thin sections, the andesite dykes consist chiefly of plagioclase (An_{45}). Biotite, chlorite, and a very fine-grained opaque mineral, possibly magnetite, occur as accessory minerals. These minerals show a special association with the plagioclase phenocrysts. The rock shows a porphyritic texture in which laths of plagioclase form the phenocrysts as well as the groundmass. The phenocrysts have an average length of 0.5 millimeter. They invariably show polysynthetic twinning and some of them are zoned. They include unknown opaque grains of submicroscopic size. Practically all the phenocrysts are moderately altered to sericite.

The groundmass consists of thin laths of plagioclase with an average length of 0.05 millimeter. In narrow dykes with chilled margins, the groundmass contains extremely fine-grained (almost glassy) material. A high concentration of subrounded grains of an opaque mineral, possibly magnetite, seems to be responsible for the relatively dark colour of the rock. A subparallelism among plagioclase laths suggests a flow texture in the rock.

3. Diabase Dykes: These are the most abundant of the three types of dykes. Since the spherulitic felsite dykes and the andesite dykes are relatively thin, the general remarks made earlier under "Post-ore dykes" mainly apply to the diabase dykes.

The diabase dykes are usually light gray and medium-grained. Their chief constituents are plagioclase (An_{60}) and hornblende. Magnetite and actinolite occur as accessory minerals. The plagioclase laths are sericitized up to various degrees and show polysynthetic twinning. Their grain size is almost uniform except some larger grains occurring at scattered points. Most of the hornblende grains have columnar form with diffused boundary. The hornblende shows pleochroism from pale green to dark green. Quartz, chlorite, and calcite occur within veins. Chlorite is dark green, weakly pleochroic, and massive.

The rock is altered to various degrees in different parts of the dykes. Some of the less altered samples possess a subophitic texture in which the plagioclase laths are partly enclosed within hornblende grains. Saussuritization of plagioclase and development of secondary hornblende (possibly from some clinopyroxene), chlorite, quartz, and calcite indicate that the diabase dykes were subjected to saussuritization and uralitization.

CHAPTER IV

ECONOMIC GEOLOGY

General Statement

In the Gullbridge copper deposit the grade of the ore is variable in different parts of the ore body. The average percentage of copper is reported to be 1.92 (Kalliokoski, 1955). The copper content generally decreases towards the margin of the ore body, which is broadly defined by an assay boundary of 0.5% copper. Traces of gold, silver, lead, and zinc are reported to appear in the assays of bulk samples (Newman, Personal communication).

It is to be noted that by the time the present study was started most of the ore was worked out and, therefore, a very limited number of samples were collected from the central portion of the ore body.

Form of the Ore

Megascopically, the chief constituents of the ore are chalcopyrite, pyrrhotite and pyrite. The ore samples normally show a foliation involving sulphides as well as the associated gangue minerals. In most places such a foliation is caused by the replacement of some pre-foliated silicates which has been further accentuated by the post-mineralization deformation D_4. On the basis of mineralogy, form, and texture, the ore may be divided into the following groups.

1. (a) Massive Ore: This type consists chiefly of chalcopyrite with subordinate pyrrhotite, pyrite and gangue. The last three minerals occur in a groundmass of chalcopyrite and show a well developed preferred orientation

(Figure 28). This high-grade ore was observed only at one place in the mine where it occurs in the form of a lens which is about 20 feet long and up to 4 feet wide. It is oriented roughly parallel to the direction of foliation.

(b) Massive Pyrite: At isolated points within the ore body, pods of massive pyrite with dimensions up to 10 feet are observed. They are slightly elongated parallel to the main foliation and are composed of an aggregate of tiny euhedral pyrite grains. They also contain some thin streaks of gangue minerals showing a weak preferred orientation parallel to the main foliation.

2. Banded and Ribboned Ore: This type of ore occurs in abundance. It consists of alternating bands of gangue and semi-massive sulphides. The bands are discontinuous and vary in thickness from a fraction of a centimeter to 2 centimeters. The gangue minerals forming these bands are quartz and chloritized cordierite. The parallel sulphide "ribbons" and bands are joined by thin stringers of ore minerals running across the gangue bands. In some samples the sulphides form very fine and almost parallel bands about 2 millimeters wide. The combination of such bands gives rise to a ribbon-like form (Figure 29). In places a combination of several discontinuous lenticular sulphide units also gives rise to some poorly developed bands. These lenses, in some cases, are gently folded (Figure 30).

In some parts of the ore body semi-massive aggregates of pyrite form bands of uniform thickness alternating with similar bands of gangue. Both of these bands run parallel to the main foliation. Some samples show bands which seem to radiate from a common centre.

3. Semi-massive and Disseminated Ore: In this type the sulphides occur in the form of small patches consisting of aggregates of chalcopyrite and pyrrhotite with minor pyrite and magnetite. The proportion of sulphides to gangue is highly variable. Like some of the other types, this type of ore also shows a weak but distinctly developed foliation.

Mineralogy of the Ore

A microscopic study of polished sections of the ore samples from different parts of the ore body shows the presence of the following minerals: magnetite, ilmenite-hematite, pyrite of different generations, pyrrhotite, chalcopyrite, and one unknown mineral called "X" in this thesis. Galena (V.S. Papezik, Personal communication) and sphalerite (Peters, 1967) have been reported by other investigators.

Apart from a decrease in tenor towards its periphery, no mineralogical zoning was established within the ore body. The ore body is characterized by a relatively simple mineralogy and an ubiquitous occurrence of pyrite. The possibility of zoning, however, cannot be ruled out as the results of the present study are based mostly on the samples collected from the fringe of the ore body.

The ore samples, in general, show a strong preferred orientation on a microscopic scale. This preferred orientation, described elsewhere in this thesis, is believed to be largely inherited from S_1.

Various opaque minerals and their textural relationships are described below.

Ilmenite-Hematite: These minerals occur together as fine exolved phases of one from another. They normally occur as isolated specks within gangue minerals and, in places, they form weakly defined trails (Figure 35). These trails, also noted in thin sections of the ore-bearing chloritic cordierite rock (Figure 11), are regarded as representing the relict S_1 related to regional metamorphism and deformation. In detail, the ilmenite-hematite specks are aggregates or interlocks of tiny lath-shaped crystals. The average length of such laths is of the order of 0.015 millimeter. They rarely show any spatial association with the sulphide minerals. The exolved phases occur in the form of fine spindles which run almost parallel to one another. Ilmenite can be distinguished from hematite by its marked pleochroism from grayish white to pinkish gray. As mentioned in Chapter III, there exists a strong resemblance between the trails of ilmenite (-hematite?) in amygdaloidal metabasalt and those of sphene(?) in the non-amygdaloidal metabasalt. From this it seems that the ilmenite-hematite forming these trails were possibly developed through the recrystallization of sphene (?) during contact metamorphism (Stage 4, Table III).

Ilmenite also occurs in the form of lamellae within magnetite (magnetite-2) grains. As seen in polished sections, these lamellae form sets that are oriented in two or three directions. The angle between such sets varies from 60^{o} to 80^{o} (Figure 34). These lamellae are up to 1 millimeter long and have a uniform width. They do not carry any exolved phases of hematite. These lamellae are believed to be of different generation from the ilmenite-hematite grains that form the trails. Additional comments on the genesis of the ilmenite lamellae will be made later in this chapter.

Magnetite: On the basis of texture and mineralogical association, the magnetite occurring in various rock types underlying the mine area can be divided into two types:

(a) Magnetite-1, which is of earlier generation and existed in the rocks before they were subjected to various metamorphisms and deformations. It differs from the other type (magnetite-2) in three respects: (i) it does not show any spatial association with the main sulphide minerals, (ii) it does not contain ilmenite lamellae, and (iii) it is not replaced by any gangue mineral. Magnetite-1 was noted in iron formation and magnetite-actinolite schist (?) in which its aggregates are elongated parallel to the main schistosity S_1. Some of the unreplaced ilmenite-free magnetite grains occurring mostly with gangue minerals are the probable representatives of magnetite-1 in the ore-bearing chloritic cordierite rock.

(b) Magnetite-2 is mostly associated with the main sulphides. This is the most predominant non-sulphide opaque mineral in the deposit. Grains of magnetite-2 that are not replaced by silicates invariably occur in euhedral form and their average size is 1 millimeter. It also occurs as augens in samples showing deformed fabric. A number of grains contain inclusions of ilmenite lamellae that are oriented in two or three directions. Most grains have been replaced by some unknown gangue mineral which usually forms irregular veins within the magnetite-2 grains. The degree of such replacement is highly variable; almost unreplaced grains of magnetite-2 as well as those having ilmenite lamellae as the only remnant opaque mineral can be observed in the same polished section. In some thin sections, the predominant schistosity S_1 is cut sharply by the partly replaced ilmenite-bearing magnetite-2 grains (Figure 32). This indicates that magnetite-2 grew over S_1 and therefore it is post-D_1 in age. Similarly, a microscopic study of various polished and polished thin sections suggests that magnetite-2 was formed earlier than the main sulphide and gangue minerals.

Magnetite-2 presents evidence of having been subjected to a cataclastic deformation. This is shown by a number of its shattered and disrupted grains (Figure 37).

<u>Mineral "X"</u>: In a number of samples, magnetite-2 contains a medium gray mineral with irregular outlines (Figure 37). The margins of this mineral are darker than the central portion. In places it occurs in the form of isolated islands within a single grain of magnetite-2. Some of its grains possess what appear like tiny fractures running away from their margins. This mineral has a very low reflectivity. Its hardness is almost the same as that of the enclosing magnetite-2. It is isotropic but can be distinguished from magnetite-2 by its darker colour and lower reflectivity. The size of this mineral is too small to do any x-ray work for its identification. It is, therefore, referred to as mineral "X" in this thesis. The ratio between the size of "X" and that of the enclosing magnetite-2 grain is variable. In some grains magnetite-2 does not contain the mineral "X", although some tiny fractures radiating away from the core are present. In a number of grains several remnant-like islands of mineral "X" occur within a single grain of magnetite-2.

The relationship between magnetite-2 and mineral "X" can be interpreted in two ways: (i) "X" grew earlier than magnetite-2 and the latter replaced it from the peripheral parts so that the core and the various islands of "X" represent the unreplaced parts of the original "X"; (ii) magnetite-2 existed before the growth of "X" and the latter began to grow from the core. The growth of "X" could have been preceded by the development of the tiny fractures radiating away from the core.

In view of the existing information the first interpretation appears more logical than the second. A somewhat similar type of relationship between chromite and magnetite has been interpreted by Freund (1966, p. 430) as the replacement of one by another.

Pyrite: Much of the pyrite is believed to have been formed with the main phase of sulphide mineralization. On the basis of form, texture, and association, four generations of pyrite have been noted.

Pyrite of first generation (Pyrite-1) seems to be of primary origin. It is best seen in some cordierite-bearing silicic tuffs occurring outside the ore body. This pyrite is invariably euhedral and has an average grain size of 1 millimeter. It is distinguished from other generations of pyrite mainly on the basis of textural relationship and mineralogical association. In some of the S_1-bearing samples, quartz forms pressure fringes which are elongated parallel to S_1 on both sides of pyrite-1. In places S_1 wraps around pyrite-1 grains. These features suggest that pyrite-1 is pre-D_1 and was probably formed during diagenesis. It does not show any spatial association with chalcopyrite, pyrrhotite or other generations of pyrite.

Pyrite of second generation (pyrite-2) constitutes about 90% of the total pyrite observed during the course of the present study. Most of the pyrite-2 grains are euhedral to subhedral with straight margins. They occur porphyroblastically within a groundmass that consists of cordierite, andalusite, anthophyllite, and chlorite. The relict S_1, which is very poorly preserved in the ore-bearing rock, does not form any augen structure around the pyrite-2 grains. These features suggest that pyrite-2 was formed earlier than cordierite assemblages and later than the regional deformation D_1. Unlike pyrite-1, it shows a very close association with magnetite-2, pyrrhotite, and chalcopyrite. In places it is replaced by pyrrhotite and chalcopyrite. Shattered and disrupted grains of pyrite-2 are the evidence for cataclastic deformation (Figure 38).

Pyrite of third generation (pyrite-3) seems to have developed later than the cordierite assemblages as it selectively replaced the anthophyllite fibers (Figure 39). It forms pseudomorphs after anthophyllite and therefore has a corrugated outline. It also occurs along the boundaries of pyrite-2 grains (Figure 40).

Some pyrite grains consist of a porous, spotted-looking centre and a compact "spotless" margin. These grains have a highly irregular form and occur in a groundmass of chalcopyrite (Figure 41). Such an intensive porosity of the central portions diminishing against the margins has been described by Rehwald (in Maucher and Ramdhor, 1965, pl. 0352) as typical of pyrite originating from pyrrhotite. In the present case, the "spotted" pyrite appears to be genetically different from pyrite-2 and pyrite-3. It, therefore, represents a pyrite of fourth generation (pyrite-4). This pyrite, being "spotted", can be easily distinguished from the pyrites of earlier generations. The "spots" are of some silicate-like dark mineral with very low reflectivity. Pyrite-4 was noted only in a few samples.

Pyrrhotite: The quantity of pyrrhotite is comparable to that of chalcopyrite, the latter, however, being most abundant among sulphides. Pyrrhotite occurs in the form of inequidimensional and irregular patches. In most cases it fills in intergranular spaces among quartz grains and thereby forms a network (Figure 42). Practically no grains of pyrrhotite with euhedral shape were observed. It shows faint pleochroism from pink to grayish pink.

Pyrrhotite has a high preference for replacing chlorite and for filling intergranular spaces among quartz grains. Unlike chalcopyrite and pyrite, it does not show any preference for replacing anthophyllite. In several places the textures suggest that while pyrrhotite replaced silicates occurring immediately next to anthophyllite, it did not replace the latter. Pyrrhotite, in general, does not form any pseudomorphs.

Under crossed nicols, some pyrrhotite grains show an intergrowth of long lamellae (Figure 48). The margins of individual lamellae are undulatory and very rarely straight. The shape of the lamellae varies from elongated inequilateral triangles to lenses tapering on both ends. Within a single grain, the lamellae do not show any particular preferred orientation and, therefore, different lamellae extinguish at different positions. The lamellae do not have any definite orientation with respect to the main schistosity in the host rock. The various lamellae have the same hardness, pleochroism, interference colours, and roughly the same form. Owing to their different crystallographic orientations, they differ only in the position of extinction. The degree of perfection in the development of such lamellae is variable. There exists a gradation from grains without lamellae to grains with very well developed lamellae. The lamellae cross the grain boundaries of the pyrrhotite grains (Figure 48). Three possible mechanisms, which can give rise to this type of lamellae in pyrrhotite, are discussed below.

(1) Exsolution - Occurrence of exsolved phases of hexagonal pyrrhotite in monoclinic pyrrhotite can be considered as a possible explanation for such lamellae. The texture of the lamellae-bearing pyrrhotite grains and the proportion of the two possible "phases", however, does not conform with certain established examples of co-existing two-phase pyrrhotite (Arnold, 1967). The size of the lamellae-bearing pyrrhotite grains is so small that it does not permit to conduct x-ray studies.

(2) Twinning - Twinning in pyrrhotite is not uncommon. In most cases the twin planes are reported to be straight but in the present case the lamellae boundaries, which are being considered here as the possible twin planes, are undulatory. Moreover, in polysynthetic type of twinning, usually there exist two sets of lamellae whereas in the lamellae under discussion, there are no such sets. These points argue against twinning as a possible explanation for these lamellae.

(3) Stress Intergrowth - Crossing of the pyrrhotite grain boundaries by the lamellae suggests that the lamellae were developed after the formation of pyrrhotite. This also supports the view that the lamellae were developed through a physical deformation of the pyrrhotite grains. A post-mineralization deformation of the ore body is also suggested by some other textures and structures (see Chapter VI). It is, therefore, believed that the development of the lamellae in pyrrhotite was caused by the stress associated with the post-mineralization deformation D_4 (Stage 13, Table III).

The mechanism responsible for the development of the lamellae was possibly governed by translation gliding within the pyrrhotite grains. The glide planes perhaps run almost parallel to the length of the lamellae.

Several pyrrhotite grains in which the lamellae are not fully developed, are moderately bent and,on careful examination,show undulatory extinction. Such grains suggest that the gliding within pyrrhotite went on as long as the direction of maximum stress did not become almost perpendicular to the glide planes. This type of movement is reported to be temperature-independent and takes place on lattice planes, normally planes of densest atomic packing (Pitcher et.al., 1965). The development of the lamellae in some but not all pyrrhotite grains may possibly be due to the existence of a certain number of glide planes in a position appropriate for undergoing translation gliding.

Chalcopyrite: Chalcopyrite invariably occurs in irregular forms except where it forms pseudomorphs after chlorite-2 and less commonly after anthophyllite. The pseudomorphs after chlorite-2 occur along the margins of chlorite-1 and, in places, are highly contorted (Figure 17). The confinement of the contorted chalcopyrite pseudomorphs to the margins of chlorite-1 suggests that the deformation that was responsible for the contortion was not penetrative, since it did not deform the central portions of the chlorite-1 patches. The crenulation of the chlorite-2 acicules is believed to be related to D_3 (Stage 7, Table III) which also produced crenulations in some other rock types, for example, the cordierite-bearing silicic tuff and the quartz-sericite phyllite. The sulphide streaks occurring around the sulphide-bearing chlorite-2 acicules do not show any crenulations. From this it is inferred that the sulphides possibly replaced the pre-crenulated chlorite-2 acicules. There is, however, no concrete evidence to show whether the chlorite-2 acicules were crenulated along with chalcopyrite or chalcopyrite really replaced the pre-crenulated acicules.

Chalcopyrite is the last ore mineral in the paragenetic sequence. It replaced practically all the pre-existing opaque minerals. It "healed up" most of the crushed and shattered pyrite grains along fractures. This resulted in the formation of a network of chalcopyrite (Figure 38).

Crossed twinning is noted in chalcopyrite. Because of the weak anisotropism of chalcopyrite, the individual twin lamellae are not very distinct. The twin planes are almost straight. This suggests that the twinning possibly developed through inversion rather than deformation. The former takes place approximately at 550^{o}C when chalcopyrite inverts from cubic to tetragonal crystal structure (Yund and Kullerud, 1961, p. 180).

<u>Textures of the Ore</u>

Microscopic study of the polished sections of the ore, in general, shows abundant replacement textures. Almost every opaque mineral is replaced by the one which succeeds it in the paragenetic sequence. The grain size of magnetite-2 and pyrite-2 lies within certain limits whereas that of pyrrhotite and chalcopyrite is highly variable. Some textures of special interest are discussed below.

<u>Myrmekitic Intergrowth</u>: A very fine intergrowth of pyrite and chalcopyrite was noted in one sample obtained from the fringe of the ore body. The form of the intergrowth varies from irregular patches to veins. The veins spread out irregularly from the patches of intergrowth (Figure 44). These patches appear turbid yellow under lower magnification. They have very low reflectivity and look like poorly polished surfaces. These patches are surrounded by a rim of pyrite which has a variable width. The rimmed patches, in turn, occur within a groundmass of chalcopyrite. As seen under higher

magnification, the pyrite in the rim does not contain any chalcopyrite whereas the same pyrite continues inwards to form the intergrowth (Figure 45). The distribution of the intergrowth is not uniform within a certain patch. Pyrite is quantitatively predominant in the intergrowth. The chalcopyrite has pale yellow colours and occurs in the form of discontinuous and irregular "worms". There appears to be no crystallographic control on the localization of the worm-shaped units. The texture of the intergrowth is somewhat dendritic to myrmekitic.

Exsolution(?) Textures: (A) In only one sample, 3 feet away from a post-ore diabase dyke, spindles of chalcopyrite in pyrrhotite were observed (Figure 47). The spindles are oriented in a common direction within the pyrrhotite grain, reflecting a possible crystallographic control on their orientation. The spindles appear very much like exsolution features, and they have been so interpreted by the author. However, it is conceivable that they could have formed by replacement, for elsewhere in the specimen chalcopyrite has replaced pyrrhotite.

From experimental work it is known that chalcopyrite can exsolve from pyrrhotite above about 600°C, but that below this temperature cubanite becomes the stable phase exsolving from pyrrhotite (Kullerud and Yund, 1965). This suggests that if the spindles did originate by exsolution, the temperature of the sample under discussion was raised at least up to about 600°C.

(B) In places magnetite-2 carries thin and long lamellae of ilmenite that are oriented normally in two or three directions, making an angle of about 60° to 80° with one another. Some of such magnetite-2 grains also contain the mineral "X". In detail, the ilmenite lamellae are nearly rectangular in shape. In cross sections the width of all the ilmenite lamellae is about the same (Figure 34).

As regards the origin of the lamellae, any process involving a replacement of one mineral by another normally gives rise to a network of irregular veins of the replacing mineral. The rectangular shape and the straight outlines of the ilmenite lamellae, therefore, suggest that they did not develop through a replacement of magnetite-2.

One of the possible explanations of such lamellae may be that the ilmenite lamellae exsolved from mineral "X" before it was (possibly) replaced by magnetite-2. The main objection to this interpretation is that the ilmenite lamellae and mineral "X" do not necessarily occur together in the same grain. This objection would, however, be invalidated if (i) magnetite-2 did replace mineral "X" so that some of the "X"-free magnetite-2 grains having ilmenite lamellae represent grains in which "X" has been completely replaced by magnetite-2, or (ii) mineral "X" did not yield exsolved phases of ilmenite in all the grains, so that ilmenite-free "X" (partly replaced by magnetite-2) can exist.

Buddington and Lindsley (1964) present an explanation for such ilmenite lamellae in magnetite. This explanation, which is based on experimental and published work, could also be applicable to the present case. Discussing the evidence for a magnetite-ilmenite solid solution hypothesis, these investigators state that there are some textural and chemical grounds for assuming the existence of magnetite-ilmenite solid solutions at high temperatures. However, after a detailed discussion, Buddington and Lindsley (1964, p. 310) conclude that "the experimentally determined solubility of ilmenite in magnetite is much too small to account for most ilmeno-magnetites by simple exsolution."

Magnetite and ulvöspinel form a complete solid solution series. According to Buddington and Lindsley (op. cit.) the occurrence of $FeTiO_3$ as apparently "exsolved" lamellae in magnetite-ilmenite growths can be explained by the hypothesis of subsolidus oxidation of Fe_2TiO_4 in magnetite-ulvospinel solid solutions. They (p. 318) propose the following mechanism for the oxidation of magnetite-ulvospinel solid solutions: ".... at the time of their formation titanomagnetites contain mainly Fe_2TiO_4 and only minor $Fe\ TiO_3$ in solid solution. Unusually reducing conditions, such as those resulting from high contents of hydrogen or sulfur in the interstitial fluids or an excess of FeO relative to fluids, are required to maintain the Fe_2TiO_4 in solid solution upon slow cooling down to the magnetite-ulvöspinel solvus, whereupon an ulvöspinel-rich phase can exsolve in the (100) planes of the host magnetite. Under more 'normal' conditions, where water-rich fluids are abundant relative to ferrous minerals, much of the Fe_2TiO_4 in solid solution is oxidized directly to ilmenite$_{ss}$ (ilmenite-rich ilmenite-hematite solid solution) and magnetite$_{ss}$ (magnetite-rich magnetite-ulvospinel solid solution), the latter remaining in solid solution and the former 'exsolving' as lamellae in the (111) planes of the host. At intermediate partial pressures of oxygen it is possible to develop both ilmenite lamellae in (111) planes by partial oxidation and ulvöspinel lamellae in (100) by true exsolution."

Replacement Textures: (A) The ilmenite-bearing magnetite-2 grains have undergone overwhelming selective replacement by some unknown gangue mineral. This replacement has progressed to different degrees in different grains. A gradation exists between practically unreplaced grains of magnetite-2 and those in which only ilmenite lamellae are left (Figures 33 and 34). Ilmenite lamellae are not replaced by the gangue mineral. The replacement seems to have initiated from rims as well as fractures within magnetite-2, but the replacement from fractures is more common. In those cases where replacement from the rims is predominant, an almost elliptical remnant grain of some opaque mineral occurs at the centre of the pseudomorphs (Figure 36). This opaque mineral may be the mineral "X" that was not replaced by the gangue. Under transmitted light the replacing gangue mineral is pinkish gray in colour. It has a very low birefringence and it does not give a satisfactory interference figure. Magnetite-2 is commonly rhomb-shaped and because of this,these pseudomorphs, in places, resemble the shape of a carbonate mineral. The meager optical characters shown by the replacing gangue mineral are insufficient for its identification.

(B) Euhedral remnants of large pyrite crystals are common in the massive variety of the ore. These pyrite crystals are replaced by pyrrhotite (Figure 49) and in some places by chalcopyrite. The degree of replacement is highly variable from one crystal to another. The pyrrhotite replacing the large pyrite crystals and occurring inside them is finer-grained than pyrrhotite occurring outside. The pyrrhotite grains occurring inside the pyrite crystals have different orientations and most of them are equidimensional. The margins of the replaced pyrite crystals possess unusually long segments of remnant pyrite which run parallel to each other. The shape of the original pyrite crystals varies from subhedral to euhedral. The size of such crystals is variable and crystals up to 3 millimeters in size have been observed.

The shape of the tiny remnant pyrite segments is variable within each pyrite crystal but most of them are rhomb-shaped, and rarely square or rectangular. All such pyrite segments within a large pyrite crystal show a weak anisotropism and all of them extinguish simultaneously. The interference colours vary from light grayish green to pale brown. The simultaneous extinction suggests that all the tiny pyrite segments occurring within the outlines of a large pyrite crystal are the remnants of one and the same pyrite crystal. Practically all of the remnant pyrite segments have straight edges which are arranged in such a way that the edges of one segment run parallel to those of others. This gives rise to two vague sets of edges making an angle of about 80^0 with each other.

From the foregoing account it appears that this texture developed through a replacement of some large pyrite crystal by pyrrhotite and chalcopyrite. From the angular relationship mentioned earlier, it appears that the fractures along which the replacement began, possibly developed parallel to (100) planes of pyrite. Edwards (1954, p. 42) reported similar textures in which tiny remnant-like grains of euhedral pyrite occur in a groundmass of chalcopyrite. According to Edwards, the original large pyrite grain was first mildly sheared, which resulted in the development of prominent cleavage parallel to its (100) planes along which replacement by chalcopyrite took place.

Mutual Boundaries (?) Texture: In two samples, one occurring within one centimeter and the other within three feet of the contact of a post-ore dyke, the silicates and sulphides (chalcopyrite and pyrrhotite) show a texture which appears like a mutual boundaries texture (Figure 46), consisting of almost smooth, regularly curving contacts without any sharp projection of one into another. Under higher magnification, however, these contacts look slightly ragged. In places thin and curved laths of sulphides occur within the silicates close to the sulphide-gangue contact. Such sulphide laths show a close parallelism with these contacts.

This texture was not noted in samples located away from the post-ore dykes. From this it appears that the genesis of the mutual boundaries (?) texture is related to the intrusion of the dykes.

Cataclastic Textures: The cataclastic textures shown by pyrite-2 and magnetite-2 indicate that the ore body was subjected to a cataclastic deformation (D_2). Euhedral crystals of pyrite-2 and magnetite-2 have been broken into pieces with matching borders. The spaces between such pieces are filled with chalcopyrite or gangue minerals. A number of magnetite-2 crystals are broken and disrupted by this deformation (Figure 37). Apart from such disruptions, large pyrite-2 crystals are also fractured and crushed into small pieces. The fractures, in places, are "healed up" with chalcopyrite (Figure 38). The fractures in such grains are so numerous that the pre-deformation outlines of the pyrite-2 crystals are completely obscured.

Chalcopyrite and pyrrhotite do not show any evidence of cataclastic deformation. There are two possible reasons for this: (i) Pyrrhotite and chalcopyrite, being relatively soft minerals, could have deformed plastically. The harder minerals like pyrite-2 and magnetite-2, on the other hand, were broken, disrupted, and crushed. (ii) The cataclastic deformation took place prior to the formation of pyrrhotite and chalcopyrite. In view of the fact that chalcopyrite fills the fractures within the crushed pyrite-2 crystals, the author favours the second possibility.

Deformed Fabric: In practically all parts of the ore body, the ore and the associated gangue minerals show a deformed fabric on a microscopic as well as megascopic scale. The degree of the development of such fabric, however, is variable from one part to another within the ore body. Pyrrhotite, chalcopyrite, and chlorite, in places, show such a strong preferred orientation that the rock could be texturally termed a "sulphide-chlorite schist". Crenulated chalcopyrite-bearing chlorite-2 acicules (Figure 17), "pinch and swell" structures involving sulphides and silicates (Figure 25), presence of poorly defined augens around magnetite-2 grains,and the occurrence of bent lenticular units of sulphides are some examples suggestive of a deformed fabric in the ore body.

The present preferred orientation in the rocks containing cordierite assemblages seems to have been mostly inherited from S_1, a schistosity related to regional deformation and metamorphism. This is evidenced especially by the growth of cordierite over S_1, the latter defined by ilmenite-hematite trails (Figure 11) and also by the growth of anthophyllite fibers across the predominant fabric (probably S_1) in some of the cordierite-anthophyllite rocks (Figure 24). The sulphides are believed to have replaced the silicate minerals that already had a preferred orientation and deformed fabric. In places pyrrhotite and chalcopyrite form weakly developed "pinch and swell" structure in a groundmass of silicates. Since the sulphides are less competent than the enclosing silicates in this particular case, one would not expect lenses of sulphides to develop "pinch and swell" structure. Moreover, in some thin sections of the chloritic cordierite rock "pinch and swell" structures shown by quartz are partly filled in by some sulphide minerals (Figure 25). It, therefore, appears that the sulphides are pseudomorphous after some pre-existing "pinch and swell" structures.

The ore body, however, was subjected to a post-mineralization deformation (D_4), which was apparently not a major deformation involving much strain. This deformation is best evidenced by the growth of stress lamellae in pyrrhotite that cross pyrrhotite grain boundaries (Figure 48). In addition to this, chlorite-1, which is normally massive, in places, shows a moderate foliation parallel to the length of some associated sulphide streaks (Figure 43). This foliation in the massive chlorite is interpreted as having developed during D_4. On the basis of these and other textural evidence it is concluded that the predominant schistosity in the ore body is mainly due to the replacement of the pre-foliated silicates by sulphides. The largely inherited preferred orientation of the sulphides and the associated silicates has, however, been further accentuated by the post-mineralization deformation D_4.

Paragenesis

The sequence of the formation of various minerals in the Gullbridge copper deposit is best evidenced by the abundance of replacement textures. Table III (in pocket) shows the paragenesis of various ore and gangue minerals related to a progressive sequence of geological events. The ore and gangue minerals are shown by double and single lines respectively. Dotted lines represent the questionable period of growth of a certain mineral. The lengths of these lines do not have any bearing on the length of the time of formation of a certain mineral. In the following paragraphs a brief mention of the paragenesis of each mineral or group of minerals is made.

As mentioned earlier, magnetite-1 and pyrite-1 existed in the rocks prior to the regional metamorphism and deformation D_1. They probably developed during diagenesis. Trails of sphene(?) that define S_1 in the metabasalts probably developed during D_1. Similarly the growth of hornblende-1, actinolite, biotite-1, and chlorite-m that represent S_1 in several rock types within the mine area is related to D_1. Since no textural evidence is available to suggest a paragenesis among these four minerals, their position in Table III is arbitrary.

Hornblende-2, which grew over S_1, is believed to be of contact metamorphic origin. Magnetite-2 and pyrite-2 occur as euhedral grains in a groundmass of cordierite and anthophyllite. They show a uniformity in size and shape within and outside the cordierite grains. From this it is inferred that magnetite-2 and pyrite-2 were formed before the cordierite assemblages. Mineral "X" is tentatively interpreted to have been replaced by magnetite-2 which indicates a possible earlier origin of the former. Ilmenite lamellae free from exolved hematite, occur within magnetite-2 grains. If the mechanism proposed by Buddington and Lindsley (1964) for the origin of such lamellae is followed, then the ilmenite lamellae were formed slightly later than magnetite-2. Most textures indicate that magnetite-2 formed before pyrite-2, but there is some evidence to suggest slight overlap in the paragenesis of these two minerals.

In the paragenetic sequence the non-ore opaque minerals were followed by the cordierite assemblages, the latter comprising cordierite, andalusite, and anthophyllite. Where enclosed by cordierite, andalusite has corroded outline (Figure 26). This indicates that andalusite formed earlier than cordierite. On the other hand, anthophyllite fibers are subpoikilitically enclosed by the cordierite grains, suggesting that anthophyllite began to grow considerably earlier than cordierite (Figure 27). No textural evidence is available to determine the age relationship between andalusite and anthophyllite. The cordierite assemblages, to be discussed in Chapter V, are believed to have developed through a subtractive metasomatism which was concurrently attended by contact metamorphism. Biotite-2, in contrast to biotite-1 of regional metamorphic origin, has relatively larger grain size, lacks any preferred orientation, and has different appearance. Textures suggest that the formation of biotite-2 post-dated that of the cordierite assemblages and presumably grew during the retrograde phase of the contact metamorphism (Stage 4, Table III). Some Ca-bearing minerals such as garnet (grossular?), diopside, and vesuvianite occur in the amygdules of the amygdaloidal metabasalt and their genesis is attributed to the contact metamorphism. There is no textural evidence to determine the paragenetic position of these minerals. They are, however, considered to be later than the cordierite assemblages. This is based on the speculation that the Ca removed from the metabasalts during the growth of the cordierite assemblages was possibly consumed in the development of these Ca-bearing minerals.

Hydrothermal activity gave rise mainly to chlorite and quartz with minor sericite. These former two minerals constitute a major part of the gangue. This quartz of hydrothermal origin is listed as "gangue quartz" in Table III. Quartz occurring outside the ore zone is not listed in this table. Growth of chlorite through hydrothermal activity is believed to have involved a large scale alteration of cordierite to chlorite. This process, in general, is responsible for the growth of massive chlorite

(chlorite-1) and for the development of the ore-bearing chloritic cordierite zone. Although there is no concrete evidence to suggest the relative ages of chlorite-1 and the hydrothermal quartz, yet an overall impression of the author suggests that chlorite-1 commenced to grow slightly earlier than quartz. The acicular chlorite (chlorite-2), although not very common, occurs around the patches of chlorite-1. The acicules are usually crenulated. The growth of chlorite-2 seems to have taken place through a recrystallization of chlorite-1 under a stress environment, the latter possibly related to D_3 (Stage 7, Table III). The margins of the chlorite-1 patches being more susceptible to deformation (D_3) than its central part, chlorite-2 was formed only along the margins.

Pyrite-3 was formed by the replacement of anthophyllite and less commonly chlorite-2. Pseudomorphs of pyrite-3 after anthophyllite are fairly common (Figure 39). Pyrrhotite grew after pyrite-3 presumably with slight overlap; in places pyrite-3 and pyrrhotite both replace what appears to be a single crystal of some silicate mineral. Pyrite-4 grew from, and therefore later than, pyrrhotite. Among the sulphide minerals observed during the present study, chalcopyrite was the last mineral formed in the paragenetic sequence. Textures suggest that some chalcopyrite grew simultaneously with pyrrhotite. Sphalerite and galena, reported by other workers but not observed during this study, have been arbitrarily placed before and after chalcopyrite respectively.

Quartz and calcite (listed as "vein-quartz and calcite" in Table III), occurring in veins up to 8 inches wide, were formed during the Post-mineralization period (Stage 11). These veins do not contain any ore minerals. Reaction-rim chlorite (chlorite-3) is the last mineral known to be formed within the Gullbridge copper deposit.

Ore Genesis

In order to discuss the origin of the Gullbridge copper deposit, it is worthwhile to recollect some pertinent information relevant to its genesis.

The granite-diorite body exposed at a distance of about one mile southeast of Mineral Point, post-dates the deposition of the volcanic, pyroclastic, and sedimentary rocks of the area (Kalliokoski, 1955). A mention of the contact metamorphic effects, e.g. development of paragneisses and hornfelsic rocks around the intrusions and that of the cordierite-spotted silicic tuff having hornfelsic appearance, has been made in the previous chapters.

At Mineral Point the ore body is associated with an assemblage of cordierite with either andalusite or anthophyllite. These minerals form a part of the gangue. Several occurrences of pyritic deposits have been reported from Southwest Shaft area, which is about 1 1/2 miles southwest of Mineral Point (Stoiber, 1940b; Kelley 1940). The sulphide minerals, namely pyrite, chalcopyrite, and pyrrhotite, at the mine dump near Southwest Shaft are reported to have the same appearance and similar association with cordierite as at Mineral Point. The sulphides in the Southwest Shaft area show a special concentration in the cordierite-bearing silicic tuffs which are not reported to carry any anthophyllite or andalusite. The sulphides, however, also occur in the cordierite-free tuffs (Stoiber, 1940b). A number of oxidised mineralized outcrops were also mapped by A. C. Bray (1929a) in the tuffs and andesitic lavas exposed along the Mineral Point - Southwest Shaft "belt" (Figure 3). David Williams (1940, p. 39), after a preliminary reconnaissance survey of the ground adjacent to the shaft of the Mineral Point ore body, reported "a continuation of favourable host rocks carrying cordierite, fibrous amphibole (anthophyllite?), and biotite for more than 500 yards to the southwest of the shaft."

Previous workers including Kalliokoski (1955), Stoiber (1940), and Bray (in Stoiber, 1940a, p. 43) reported the probable existence of a shear zone (referred to as "Gull Pond fault zone" in this thesis), which is defined at a distance of about 1800 feet southwest of Mineral Point (Stoiber, 1940a) and which is assumed to pass through Mineral Point. Kalliokoski (1955) assumed a southwesterly extension of this fault zone, so that it passes through the Southwest Shaft area (Figure 2).

Regional metamorphism in the Ordovician and Silurian rocks of northeastern Newfoundland is of greenschist facies grade; it is most pronounced in the volcanic rocks (H. Williams, 1963, p. 40). In the Gull Pond area, Mineral Point, Southwest Shaft and partly the "belt" between the two, are the only places where relatively high temperature minerals like cordierite, anthophyllite or andalusite are known to occur. These localities, therefore, form "hot patches" within a low-grade metamorphic terrain. From this it is believed that the genesis of the cordierite assemblages constituting these "hot patches", is related to the nearby granite-diorite intrusives. On the basis of a comparison with similar assemblages reported from elsewhere, and from meager petrochemical data, a subtractive metasomatism involving the removal of Ca from, and an addition of Fe to, the mafic volcanic rocks is considered to be a possible process for the origin of the cordierite assemblages at Mineral Point. The metasomatic activity is believed to have been accompanied by contact metamorphism. This subject is further dealt with in Chapter V. The growth of cordierite without any anthophyllite or andalusite in the silicic tuffs is believed to have taken place through contact metamorphism without any significant role of metasomatism.

Some features of the Gullbridge copper deposit suggest a magmatic hydrothermal origin but others suggest a volcanic exhalative origin. Some of these features are classified and presented below.

(A) Features suggestive of a magmatic hydrothermal origin. The following features suggest that the ore is epigenetic and was deposited from magmatic hydrothermal fluids, the source of the ore elements being, by inference, the magma from which the fluids originated.

(i) Although the ore body broadly looks conformable to the enclosing rocks, it appears in detail, to be slightly discordant. As indicated by the drill hole intersections, the tuff and metabasalt units seem to be slightly steeper than the ore body.

(ii) As mentioned earlier, some of the previous workers assumed the existence of a shear zone passing through Mineral Point. The localization of the ore-bearing chloritic cordierite zone can be attributed to this shear zone. The occurrence of the ore body in the assumed shear zone, however, does not disprove the possibility that the sulphides could have been remobilized and emplaced along this zone.

(iii) The hydrothermal activity that was responsible for the development of chlorite in the ore-bearing chloritic cordierite zone provides a convenient medium by which various constituents of the ore could have been introduced. The most apparent source for these fluids is the granite-diorite body exposed southeast of Mineral Point.

(iv) Replacement textures are in abundance. Anthophyllite and chloritized cordierite have been replaced by the sulphide minerals, suggesting that the sulphide minerals attained their present form later than the formation of the gangue minerals.

(B) Features suggestive of a volcanic exhalative origin.

The following points suggest a similarity with many pyritic strata-bound sulphide deposits, for which a volcanic exhalative origin seems probable.

(i) The base metal mineral deposits of northeastern Newfoundland are almost exclusively clustered in the volcanic outcrop belts. Mineral occurrences that fall outside such belts are in most cases associated with lavas and pyroclastic rocks that occur sparingly within sedimentary rocks (H. Williams, 1963). Regarding the genesis of these deposits, Williams suggested that the base metal mineral deposits and volcanic rocks are genetically related and the sulphides originated with the volcanics.

(ii) In the Southwest Shaft area, Stoiber (1940b) mapped various mineralized outcrops occurring in tuffs and cordierite-bearing tuffs. Some of these outcrops also occur at the contact of the two adjoining rock types. These outcrops show an elongation parallel to the general trend of the enclosing rock units. Such mineralized outcrops, in places, form bands running parallel to each other. No geological structure is apparent in the vicinity of the mineralized outcrops that could serve as a control for epigenetic mineralization. These features suggest that the sulphide occurrences around Southwest Shaft area, which seem to have a genetic similarity with those of Mineral Point, are possibly of strata-bound type.

(iii) The ore body is associated with iron formation and tuffaceous rocks — a common association of volcanic exhalative deposits.

(iv) The Gullbridge copper deposit is essentially a pyrite-chalcopyrite ("pyritic") deposit with a relatively simple mineralogy.

(v) In general, a close parallelism exists between the axis of the ore body and the local structural trends, although as noted earlier, this is not necessarily so in detail.

From the foregoing account it is clear that at this stage neither a magmatic hydrothermal nor a volcanic exhalative hypothesis for the origin of the Gullbridge copper deposit can be supported unequivocally. The author, however, prefers a modified volcanic exhalative origin whereby the sulphides were remobilized and their emplacement was structurally controlled by the assumed Gull Pond fault zone at Mineral Point. The modified volcanic exhalative origin is preferred especially because of the following points:

(a) Williams' (1963) observation on the association of the sulphide deposits with volcanic and pyroclastic rocks in northeastern Newfoundland and his suggestion that this reflects a genetic tie.

(b) The lack of apparent structural control in the localization of the elongated and seemingly conformable sulphide occurrences in the Southwest Shaft area (Stoiber, 1940b).

(c) Ample evidence for hydrothermal activity.

(d) The probable structural control in the localization of the ore body at Mineral Point.

A possible sequence of the main events concerning the formation of the ore body by the modified volcanic exhalative hypothesis is given below. A more detailed sequence of events relating the minerals and textures of all the rocks described in this thesis is described in Chapter VI.

A. Deposition of the predominantly volcanic rocks underlying the Gull Pond area. The Roberts Arm Formation, which encloses the ore body at Mineral Point, is probably of Middle Ordovician age.

The metallic elements were deposited by volcanic exhalations associated with the volcanism that gave rise to the enclosing rocks. Material in such volcanic exhalations is thought to be in both a molecularly dispersed and a colloidally dispersed state where the exhalations enter a near-surface submarine environment, normally in the uppermost part of the volcanic pile (Kinkel, 1966).

Opinions still differ regarding the process involved in the formation of sulphides. In case of the massive sulphide deposits of Bathurst, New Brunswick, for instance, Stanton (1960) believes that the metals were derived from submarine thermal springs and fumaroles related to volcanism and that they reacted with H_2S produced from sulphurous thermal waters by sulphur reducing bacteria.

Kinkel (1966), on the other hand, emphasizes the role of colloidal processes particularly where metal-bearing exhalations are discharged into sea water, into unconsolidated water-bearing undersea sediments or volcanic debris, or along submarine outlets above subvolcanic magmas. He (p. 685) summarizes the process in the following steps:

(i) Metallic ions in a supersaturated liquid are peptized to a sol (colloidal solution) by excess H_2S (as HS^- and $S^=$ ions).

(ii) Sulphur forms a colloidal solution or suspension by reaction between H_2S and SO_2, O_2, or H_2 where temperatures and pressures are not excessively high.

(iii) Sulphur micelles in a sol combine readily with metallic ions to form sulphides, and the resulting sulphides would not commonly grow above colloidal size.

(iv) Sulphide and sulphur sols are coagulated, flocculated, or form gels when acted on by an electrolyte (Na Cl is particularly effective).

(v) Concentration may be built up in a flocculated sol by several methods, even though the saturation concentration of metal sols is very low.

(vi) Flocculates and precipitates are more dense than water and in the absence of strong currents would settle near their place of formation.

At Mineral Point the primary site of deposition of the sulphides has not been recognized. However, after regional folding the sulphides must have been in such a position (or positions) that they were accessible to the hydrothermal fluids that were probably responsible for their remobilization and ultimate re-emplacement. Presumably the primary sites lie adjacent to or close to the Gull Pond fault zone somewhere below the present position of the ore body. The distance that the "remobilized" material travelled might not have been far.

B. Deformation D_1 and regional metamorphism of the rocks underlying Gull Pond area. The predominant schistosity S_1 developed in various susceptible rocks.

C. Development of the partly defined Gull Pond fault zone which is assumed to pass through Mineral Point. This zone possibly extends southwestward to the Southwest Shaft area (Kalliokoski, 1955).

D. Intrusion of the granite-diorite bodies in the Gull Pond area. The intrusion was accompanied by contact metamorphism and metasomatism. The former gave rise to cordierite (in silicic tuffs), paragneisses, and metabasalts at and around Mineral Point. The metasomatism caused a removal of Ca and an addition of Fe in metabasalts along the assumed Gull Pond fault zone at Mineral Point. This produced a bulk composition suitable for the development of the cordierite-anthophyllite and cordierite-andalusite assemblages.

The remobilization and emplacement of the sulphides commenced at this stage. Although the major part of the sulphides was probably emplaced at a later stage, the emplacement of pyrite-2 seems to have taken place at this stage.

E. Cataclastic deformation (D_2) evidenced by the fractured grains of magnetite-2 and pyrite-2.

F. Hydrothermal alteration along the assumed Gull Pond fault zone, involving chloritization, silicification and sericitization.

G. Deformation D_3 of the rocks underlying the Gullbridge mine area. It caused the crenulation of S_1 and that of the chlorite-2 needles.

H. Remobilization and emplacement of sulphides along the assumed Gull Pond fault zone.

I. Ore body subsequently affected by faults, dyke intrusions, and a minor deformation and alteration (see Chapter VI and Table III).

CHAPTER V

THE CORDIERITE ASSEMBLAGES

General Statement

Cordierite-andalusite and cordierite-anthophyllite assemblages (referred to as "cordierite assemblages" in this thesis), such as those occurring at Mineral Point, are characterised by their low Ca content relative to Mg and Fe. Rocks of such chemical composition seem to have neither crystallized directly from a magma nor formed by any sedimentary process.

The field of stability of cordierite covers a fairly wide range of temperature which varies from 450^{o}C to 780^{o}C (approximately) at a pressure (PH_2O) of 2 kilobars. Cordierite, therefore, is a high-temperature low-pressure mineral. Similarly andalusite is also a relatively high-temperature low-pressure mineral. At a pressure of 2 kilobars, for instance, andalusite is stable at temperatures up to about 680^{o}C (Bell, 1963). Under conditions of higher temperature and pressure it may become unstable and invert to its polymorphs sillimanite or kyanite.

In most cases the cordierite assemblages of the type under discussion are reported to have a spatial, and sometimes a genetic, relationship with magmatic bodies. There seems a general agreement among petrologists regarding the significant role of temperature in the formation of the assemblages consisting of cordierite, andalusite, and anthophyllite. Opinions, however, still differ regarding the explanation of, and the process responsible for the excess of Mg, Fe, and sometimes Al, relative to Ca.

Before discussing the probable origin of the cordierite assemblages of Mineral Point, a brief review of some of the pertinent opinions regarding the origin of such assemblages would be useful. These opinions, some of which may not be directly applicable to the present case, are classified and presented here.

Metasomatic Origin

1. Allochemical Metasomatism: Eskola (1914, 1950) described a cordierite-anthophyllite assemblage from Orijärvi, Finland, where these minerals occur in an aureole around an Oligocene granite body. A gradual transition is reported to take place in the direction of strike as the cordierite-bearing rocks fade away into common leptites, the latter being very poor in mafic minerals. The cordierite-anthophyllite rocks, according to Eskola, are considered to have been derived from leptites and other silicic rocks that were metasomatised by iron- and magnesium-rich solutions from the Oligocene granite.

The metasomatic replacement of lime, soda, and potash by magnesia and iron oxide also resulted in the alteration of some associated limestones into skarn, and some amphibolites into cummingtonite-amphibolite. Eskola used the term "pneumatolytic metamorphism" for this process.

Eskola expressed the conversion of the plagioclase minerals into cordierite by the following equations:

$$\text{(i)}\quad \underset{\text{Plagioclase}}{4\,NaAlSi_3O_8} + 2\,MgO = \underset{\text{cordierite}}{Mg_2Al_4Si_5O_{18}} + 7\,SiO_2 + 2\,Na_2O$$

$$\text{(ii)}\quad 2\,CaAl_2Si_2O_8 + 2\,MgO + SiO_2 = Mg_2Al_4Si_5O_{18} + 2\,CaO.$$

These equations represent a total conversion of plagioclase into cordierite through a replacement of soda and lime by magnesia and ferrous oxide without any addition of alumina. According to Eskola, the formation of anthophyllite besides cordierite implies further addition of magnesia and iron oxide.

2. Internal Metasomatism: Floyd (1965) described biotite-cordierite-anthophyllite hornfelses from Tater-du, Land's End peninsula, Cornwall, England. This assemblage, in association with others, occurs in an aureole at the southeastern margin of Land's End granite. The aureole rocks are mostly banded amphibolitic hornfelses, some of which have been described as being of metasomatic origin.

Floyd divided the hornfelses into 3 types: (i) Fe-Mg hornfelses containing anthophyllite, cummingtonite, and cordierite. (ii) Ca-hornfelses containing diopside, grossularite, axinite, and epidote minerals. (iii) K-hornfelses containing very high proportion of biotite. All the three types are considered to have been derived from hornblende hornfels ("greenstone hornfelses") of basic intrusive origin. Plagioclase-hornblende hornfelses are regarded as the "parental greenstones" from which the metasomatic hornfelses developed.

The first type containing anthophyllite, cummingtonite, and cordierite is of special interest here. According to Floyd, these Fe-Mg hornfelses and other associated Ca-hornfelses are developed from an internal migration of Ca ions during metamorphism involving a localized redistribution of the original constituents of the hornblende hornfels. The K-hornfelses are supposed to have formed from an allochemical addition to K from the granite.

Floyd recognized the following three stages in the development of the internally metasomatised hornfelses:

(i) Removal of Ca from the hornblende hornfelses and the formation of Fe-Mg hornfelses (anthophyllite, cummingtonite, cordierite).

(ii) Addition of Ca to hornblende hornfelses forming the Ca hornfelses (hornblende, diopside, grossularite, etc.).

(iii) Removal of Si, Al, alkalies, and Fe during Ca metasomatism. Areas of silicification and felspathization may represent the result of the concentration of Si, Al, and Na.

Replacement of plagioclase by cordierite, and hornblende by biotite, chlorite, diopside, and garnet, and a gradation from plagioclase-cummingtonite to cordierite-anthophyllite have been taken as petrological evidences for metasomatic replacement.

3. Subtractive Metasomatism: Tilley (1935), after a study of the greenstone hornfelses of Kenidjack and Botallack, Cornwall, England, proposed a metasomatic origin of various hornfelses that include the cordierite-anthophyllite rocks. The latter are derived from greenstones which, according to Tilley, were originally lavas of basaltic composition. The metamorphosed greenstones are reported to pass by gradation into hornfelses. Tilley's opinion regarding the origin of these hornfelses differs from that of others mainly because he believes that there has been a removal of lime from the hornfelses which was accompanied by an accession of silica, alkalies, particularly potash, and an internal magnesia metasomatism. The greenstones suffered a loss of lime during the period of contact alteration as a result of the passage of hot solutions emanating from the nearby granite. The removal of lime from green hornblende leaves

Mg, Fe, Si, and Al in excess of that required for cummingtonite. The incoming of magnesia-iron-amphiboles and the disappearance of green hornblende probably involves a complex change in which the removal of lime from the rock is accompanied by an internal migration of magnesia and iron oxides as well as alumina. Introduction of potash resulted in the formation of biotite. Mineralogically the metasomatism is expressed by the replacement of green hornblende areas by cummingtonite and anthophyllite, and plagioclase by cordierite. Regarding the exact nature of the replacement, Tilley (1935, p. 197) wrote as follows:

> ".... we can not explain the process by any simple equation which represents it as an exchange of ferrous oxide and magnesia for lime."

According to Tilley, similar processes have given rise to cordierite-anthophyllite assemblage at Trelease Mill in the granulites of the Lizard, England,where this assemblage is believed to have been derived from quartz-hornblende schists.

Metamorphic Origin

1. Mafic Lavas: Vallance (1967) studied the mafic rock alteration of Yalwal, N.S.W., Australia and offered evidence of cordierite-anthophyllite rocks having been produced by essentially isochemical metamorphism. According to Vallance, mafic rocks can undergo extreme alteration and chemical reconstitution when exposed to the low-temperature, hydrous conditions of late magmatic and diagenetic environments.

At Yalwal, mafic lavas and breccia of Devonian age are reported to have suffered extensive alteration before invasion and metamorphism by a discordant Carboniferous granite. Alteration of the mafic lavas involved a redistribution of components with a common convergence to chlorite-silica mixtures. Within the aureole the commonest mafic hornfelses contain plagioclase (An_{40-50}) and green hornblende. They retain the traces of original basaltic textures. Since the association cordierite + anthophyllite + H_2O is chemically equivalent to a mixture of aluminous chlorite and silica, the isochemical metamorphism of chlorite-silica mixtures, according to Vallance, gave rise to the cordierite-anthophyllite assemblage.

Vallance plotted the chemical composition of average basalts, altered chloritic rocks, and cordierite-anthophyllite rocks in various ACF and AKF diagrams. The overlap in compositions in the pairs of diagrams also indicates the likelihood that the cordierite-anthophyllite rocks were derived from certain altered mafic rocks.

2. Pelitic Rocks: The thermal metamorphism of pelitic rocks can give rise to assemblages consisting of cordierite, orthoamphiboles, biotite, garnet, and Al_2SiO_5 polymorphs. Turner (1968, p. 128) suggested a high-temperature low-pressure field of stability for cordierite. He proposed a hypothetical diagram showing the field of stability of cordierite (Figure 9). In this diagram, the low-temperature boundary of the cordierite-bearing assemblages is a composite line having a variable positive slope. At low temperatures and pressures the cordierite field of pelitic schists abuts on fields of mica-chlorite assemblages. At higher temperatures and pressures, the adjoining fields are characterized by assemblages with garnet, biotite, and Al_2SiO_5 polymorphs. The appearance of cordierite and/or orthoamphibole is mainly due to reactions involving chlorite.

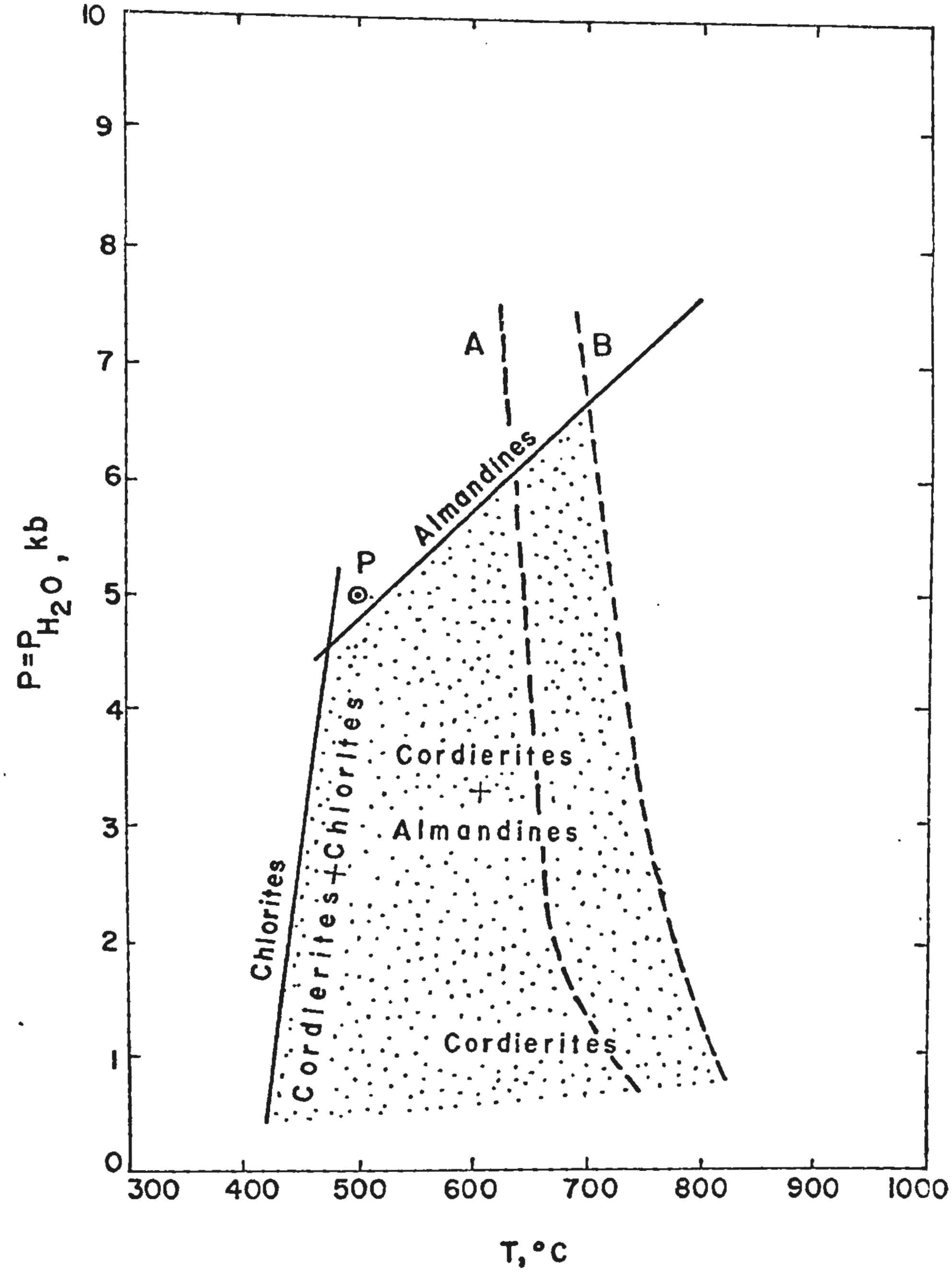

Figure 9

Hypothetical diagram showing shape of the field of stability of cordierites (stippled) as inferred from geologic data. P is a point experimentally determined for hydration and breakdown of magnesian cordierite to pyrophyllite and chlorite. A is the minimum melting curve of "granite." B is the melting curve of sanidine-quartz-water. Other lines entirely hypothetical. (Adapted from Winkler, 1967, p. 129).

Some of the reactions among various minerals in pelitic rocks, relevant to the present discussion, are given below (Winkler, 1967, p. 70-71).

(i) chlorite + muscovite + quartz = cordierite + biotite + Al_2SiO_5 + H_2O

The equilibrium temperature of this reversible reaction has been determined as follows:

510 $\pm$ 10°C	at	P_{H_2O}	= 500 bars
515 $\pm$ 10°C	at	P_{H_2O}	= 1000 bars
525 $\pm$ 10°C	at	P_{H_2O}	= 2000 bars

(ii) (Al-rich chlorite + quartz) $\rightleftharpoons$ (gedrite + cordierite + H_2O)

Using chlorite of intermediate Fe/Mg ratio as the starting material, the following equilibrium data have been obtained:

530 $\pm$ 10°C	at	P_{H_2O}	= 500 bars
550 $\pm$ 10°C	at	P_{H_2O}	= 1000 bars
560 $\pm$ 10°C	at	P_{H_2O}	= 2000 bars

Partial Melting of Common Rocks

Grant (1968) proposed that in high-grade metamorphic terrains, the cordierite-anthophyllite rocks may be formed from common high-temperature assemblages, particularly with compositions in the graywacke range, by a process of partial melting, removal of melt and recrystallization of the residuum. He investigated the possibility by considering the simplified but pertinent phase equilibria in the system Al_2O_3- MgO - K_2O - Na_2O - SiO_2 - H_2O with quartz present in all assemblages, and by the development of a semiquantitative petrogenetic grid. He found that the high-temperature subsolidus assemblages such as potassium felspar - plagioclase - biotite - sillimanite - quartz, potassium felspar - plagioclase - biotite - cordierite - quartz, plagioclase - biotite - sillimanite - anthophyllite - quartz may undergo melting of plagioclase - biotite - quartz with or without cordierite or sillimanite, yielding granitic melt - cordierite - anthophyllite - quartz with or without plagioclase or biotite. On sufficient removal of melt and crystallization back to subsolidus conditions, the assemblage plagioclase - biotite - cordierite - anthophyllite - quartz may be formed.

Preliminary Remarks on the Origin of the Cordierite Assemblages at Mineral Point

In this section some of the information relevant to the cordierite assemblages at Mineral Point is recollected and a comparison is made with some of the similar occurrences referred to earlier in this chapter. It is, however, emphasized that the remarks made on the origin of the cordierite assemblages at Mineral Point are based on insufficient field and laboratory evidence and, therefore, are of speculative nature.

At Mineral Point various volcanic flow and tuff units associated with, and enclosing the cordierite assemblages, are aligned parallel to the northeasterly trending ore body. The cordierite assemblages occur within and around the ore body. As one moves beyond the ore body along the projection of its axis, the rocks containing the cordierite assemblages merge into metabasalts (Figures 6 and 7). Even within the zone of cordierite assemblages, remnants of metabasalts with indications of pillow structures have been reported (K.M. Newman, personal communication). It is, therefore, believed that the rocks that gave rise to the cordierite assemblages at Mineral Point were originally mafic volcanic rocks.

In order to suggest any possible process for the origin of the cordierite assemblages at Mineral Point, its comparison with some of the similar assemblages referred to earlier in this chapter, is worthwhile. The cordierite-anthophyllite assemblage of Orijärvi, Finland, is reported to have developed from leptites and other silicic rocks (Eskola, 1914, 1950). It does not, therefore, match with the assemblages at Mineral Point where the parent rocks are believed to be mafic volcanics. At Yalwal, Australia, the reported derivation of the cordierite-anthophyllite assemblage from hornblende-plagioclase-bearing rocks and their spatial association with a nearby granitic intrusive is somewhat similar to the one under discussion. The common convergence to a chlorite-silica mixture, proposed by Vallance (1967) for the genesis of the assemblage at Yalwal, however, cannot be discussed at this stage as there is no information available on the alteration of mafic volcanics to a chlorite-silica mixture at Mineral Point.

A close parallelism seems to exist among various aspects of the cordierite assemblages of Mineral Point and those of Kenidjack and Botallack, and Land's End aureole, Cornwall, England. The derivation of the cordierite assemblages from mafic volcanics and the association with granitic rocks at Mineral Point, for instance, are similar to those of Kenidjack and Botallack. The reaction for the growth of cordierite from plagioclase can presumably be of the same type as the one suggested by Eskola (see page 88).

The growth of biotite in the amphibole hornfelses of Kenidjack and Botallack is quite comparable to that of Mineral Point. At Mineral

Point biotite is believed to have developed during the retrograde phase of the contact metamorphism which, in conjunction with contact metasomatism, gave rise to the cordierite assemblages.

The chemical composition of a sample of cordierite-anthophyllite rock (sample 250-41) and a sample of metabasalt, its postulated parent rock (sample K-3) at Mineral Point, is presented in Table II. For comparison, the compositions of two corresponding rock types from Kenidjack (Tilley, 1935, p. 182) are also given in this Table. The petrography of the rock types represented by these analysed samples (250-41 and K-3) has been described in Chapter III. The sample of metabasalt (K-3) occurs at a distance of about 300 feet from that of the cordierite-anthophyllite rock and lies almost along strike from it. The compositions of these two samples do not necessarily represent the true average composition of the rock types concerned and, therefore, remarks on the origin of cordierite assemblages of Mineral Point are not based solely on the analyses shown in Table II. These analyses serve only as examples.

The Ca content in the metabasalt and cordierite-anthophyllite rock samples shows a remarkable change from 10.95% in the former to 1.10% in the latter. There is no information available as to where the removed Ca came to rest. A very small part of it could have been consumed in the formation of the Ca-bearing minerals occurring in the amygdules of the amygdaloidal metabasalt referred to in Chapter III. The percentage of Fe, on the other hand, has been almost doubled in the cordierite-anthophyllite rock. The Mg content shows a slight reduction from the metabasalt to the cordierite-anthophyllite rock. However, it is the change in Ca/Mg ratio that is important.

TABLE II

Rock Analyses

	K-3	250-41	A	B
SiO_2 %	48.64	44.24	40.25	47.07
Al_2O_3 %	11.74	7.46	17.22	20.20
Fe_2O_3 %	14.26	27.94	1.88	brace
FeO %	---	---	11.16	12.73
CaO	10.95	1.10	14.82	2.14
MgO %	9.76	9.30	7.78	10.09
MnO %	0.15	0.10	0.24	0.11
Na_2O %	1.42	0.11	1.20	1.48
K_2O %	0.71	0.15	0.97	1.97
TiO_2 %	---	---	2.65	2.12
Cr_2O_3 %	---	---	---	0.02
H_2O + %	---	---	0.90	1.50
H_2O - %	---	---	0.20	0.16
Moisture %	0.46	0.97	---	---
P_2O_5 %	---	---	0.65	0.12
CO_2 %	---	---	nil	---
Copper %	---	1.13	---	---
Sulphur %	---	2.28	---	---
	98.09	94.78	99.92	100.21

250-41: Cordierite-anthophyllite rock, Mineral Point, Newfoundland. Cordierite and anthophyllite, small amounts of quartz, pyrrhotite, chalcopyrite (?), pyrite, and magnetite.

K-3: Metabasalt, Mineral Point, Newfoundland. Hornblende and sericitized plagioclase. (Analyses by Technical Service Laboratories, Toronto, Ontario).

A: Greenstone-hornfels, Carn Kenidjack. Green hornblende, small amounts of colourless augite, plagioclase (replaced by white mica), ilmenite, sphene, and apatite. (Tilley, 1935, Table I, analysis no. 1).

B: Anthophyllite-cordierite-hornfels, Carn Kenidjack (with biotite, plagioclase, ilmenite, and some cummingtonite. (Tilley, 1935, Table I, analysis no. 5).

From the foregoing account, the following conclusion — largely of speculative nature — is drawn regarding the genesis of the cordierite assemblages at Mineral Point: The regionally metamorphosed volcanic, pyroclastic, and sedimentary rocks underlying the area around Mineral Point were subjected to contact metamorphism by the intrusion of the nearby granite-diorite body. Different rock types seem to have reacted in different ways to this metamorphism. Some of the silicic tuffs, for example, gave rise to cordierite, without anthophyllite and andalusite. The growth of cordierite in this case may have taken place through reaction of chlorite, muscovite, and quartz in the same manner similar to that suggested by Winkler (1967, p. 70):

$$\text{chlorite + muscovite + quartz} = \text{cordierite + biotite} + Al_2SiO_5 + H_2O$$

However, at Mineral Point, no Al_2SiO_5 polymorph appears in the silicic tuffs that contain cordierite, possibly because the formation of cordierite did not occur according to a balanced equation requiring the formation of an Al_2SiO_5 polymorph, or possibly because the alumina content of the parent rocks was not sufficient for its genesis.

The main cordierite assemblages comprising cordierite, andalusite, and anthophyllite, occur within metabasalts. These are arranged in the following way: (a) An inner zone that consists of the cordierite- andalusite assemblage. This zone has been referred to as the "chloritic cordierite zone" in this thesis. (b) An outer zone that consists of the cordierite-anthophyllite assemblage. These assemblages are believed to have developed through contact metasomatism that was accompanied by contact metamorphism (Stage 4, Table III). Hot solutions emanating from the nearby granite-diorite intrusion are believed to have passed through the country rocks.

The apparent occurrence of the cordierite assemblages along the assumed Gull Pond fault zone suggests that this zone possibly acted as a channelway for the migration of solutions during the process of metasomatism. In the author's opinion, the most significant change that took place during this process, and which possibly led to the growth of the cordierite assemblages, is the removal of Ca from the metabasalts. This metasomatism is, therefore, referred to as the "subtractive metasomatism" in this thesis.

The remnants of pillowed metabasalts within the zone containing cordierite assemblages consist of hornblende and sericitized plagioclase. As suggested by Tilley (1935) and Floyd (1965), the replacement of plagioclase and hornblende by cordierite and anthophyllite respectively also seems to be a plausible process for the development of cordierite and anthophyllite at Mineral Point.

In the absence of more chemical analyses one can only speculate why andalusite is apparently restricted to the inner chloritic cordierite zone. It might indicate a higher degree of metasomatism in the inner zone, but more likely it is due to a higher proportion of Al to Mg and Fe in the inner than the outer zone. This difference might reflect differences in parent rock compositions, or it could be due to addition of Al to, or removal of Mg from, the inner zone during the metasomatism that removed Ca from both zones.

CHAPTER VI

SEQUENCE OF GEOLOGICAL EVENTS

General Statement

The sequence of geological events concerning the Gullbridge copper deposit can be divided into three periods: Pre-mineralization period, Mineralization period, and Post-mineralization period. Here the term "mineralization" refers to the emplacement of sulphide minerals in their present position. Events of the Pre-mineralization period are partly extrapolated from the reports of previous workers, and those of the Mineralization and Post-mineralization periods are mostly based on the present field and laboratory work. Table III (in pocket) shows the approximate time relationship between the events and the mineral paragenesis. The events, as far as possible, have been listed in chronological order, numbered, and described briefly below. In order to avoid discontinuities in the following account, all events are described even though the description of some events may represent a repetition of material mentioned in previous chapters.

Pre-mineralization Period

(1) The rocks of the Roberts Arm Formation were deposited probably during Middle Ordovician time. Along with other evidence, the occurrence of abundant volcanic rocks with minor shales and graywackes suggests that they are of eugeosynclinal facies.

The metallic elements that formed the sulphides occurring at Mineral Point were possibly deposited by volcanic exhalations associated with the deposition of the volcanic rocks of the Roberts Arm Formation. The genesis of the sulphides has been discussed in detail in Chapter IV.

(2) The rocks underlying Gull Pond area were subjected to upheaval, deformation D_1, and regional metamorphism. They attained the form of a northerly plunging anticlinorium. This deformation gave rise to the schistosity S_1 which is represented in rocks outside the ore zone by metamorphic actinolite, biotite, hornblende (hornblende-1) and chlorite (chlorite-m). In the metabasalt, trails of very fine-grained sphene (?) wrap around hornblende grains that altered from pyroxene. These trails are believed to represent S_1. Within the ore zone, for most part, S_1 appears to have been obscured by the subsequent hydrothermal alterations (Stage 6, Table III). In a few samples of the chloritic cordierite rock, however, the trails of small ilmenite-hematite grains strongly resemble the sphene (?) trails in the metabasalt and possibly represent S_1 within the ore zone.

The deformation D_1 was accompanied by regional metamorphism of greenschist facies grade.

(3) The almost northeasterly trending Gull Pond fault zone developed. This fault zone is partly defined southwest of Mineral Point (Stoiber, 1940a) and is assumed to pass through Mineral Point. Kalliokoski (1955) assumes its southwesterly extension towards Southwest Shaft area. Although the presence of this fault zone at Mineral Point is somewhat conjectural, yet in the author's opinion, it appears to have played an important role in subsequent geological events.

Mineralization Period

(4) It is believed that at Mineral Point the intrusion of granitic rocks, contact metamorphism, metasomatism, and possibly remobilization and re-emplacement of the sulphides are closely related. Although of speculative

nature, the following may be a plausible sequence for this combined process.

Accompanying the intrusion of the Devonian granite-diorite bodies in the Gull Pond area, a contact metamorphic aureole developed around the intrusives that probably extended at least as far away from their contact as Mineral Point. Close to the contact, paragneisses (Figure 3) and metabasalts developed by contact metamorphism. At more or less the same time heat and fluids from the intrusives were channeled along the assumed Gull Pond fault zone. This caused a subtractive metasomatism of the metabasalt occurring along the fault zone, causing a removal of Ca and an apparent addition of Fe. Then, as the temperature increased, the cordierite assemblages developed in the metasomatized metabasalt unit. In the rocks of somewhat pelitic composition, cordierite grew in response to the rising temperature without any appreciable role of metasomatism. This gave rise to the cordierite-bearing silic tuffs.

Textures suggest that in the rocks containing cordierite assemblages, andalusite and anthophyllite grew slightly earlier than cordierite. The growth of some of the Ca-bearing minerals such as garnet (grossular?), diopside, and vesuvianite occurring within the amygdules in the metabasalt, possibly took place during this process. The formation of mineral "X", magnetite-2, and the associated ilmenite lamellae seems to have been related to the contact metamorphism. Similarly the trails of ilmenite-hematite grains were probably developed at this stage from the sphene (?) trails representing S_1.

The remobilization and re-emplacement of the sulphides seems to have begun at this stage. This is suggested by the occurrence of pyrite-2 porphyroblasts in a groundmass of cordierite, anthophyllite, and andalusite.

(5) A cataclastic deformation D_2 is evidenced by the fractured and crushed grains of magnetite-2 and pyrite-2 (Figures 37 and 38). Pyrrhotite and chalcopyrite, on the other hand, do not show evidence of having undergone this deformation, but rather, chalcopyrite fills the fractures within pyrite-2 grains. A few broken bands of cordierite in some samples of the cordierite-bearing tuff can be attributed to this deformation. Chronologically, the cataclastic deformation, therefore, seems to post-date the growth of cordierite and pre-date the emplacement of pyrrhotite and chalcopyrite.

(6) The hydrothermal alteration involving silicification, chloritization, and sericitization took place later than the growth of the cordierite assemblages. This process also included the alteration of cordierite to chlorite and sericite. The hydrothermal activity was likely controlled by the assumed Gull Pond fault zone, as is indicated by the ore-bearing chloritic cordierite zone being flanked by the cordierite-anthophyllite zone; the latter is much less chloritized. A genetic association of the hydrothermal activity with the intrusion of the granite-diorite bodies seems plausible.

(7) A relatively minor deformation D_3 took place perhaps after the hydrothermal activity and before the emplacement of the sulphides. This deformation is believed to be responsible for the crenulation of the chlorite-2 acicules which were later on replaced by chalcopyrite (Figure 17). It also caused the bending of cordierite grains (Figure 12), the development of crenulations in S_1, and that of strain-slip schistosity S_2 (Figure 10). This deformation was perhaps not penetrative enough to

foliate the massive chlorite (chlorite-2) that forms a major part of the chloritic cordierite rock.

(8) The emplacement of sulphides can be ranked as the most important event of the Mineralization period. In the author's opinion, the sulphides possibly already existed close to their present position but during this event they were remobilized and emplaced along the assumed Gull Pond fault zone. Although a minor part of the remobilization and re-emplacement of sulphides took place during the contact metamorphism and metasomatism (Stage 4), the main phase of emplacement occurred later than the hydrothermal activity. The sulphides replaced quartz and chlorite of hydrothermal origin. The process of remobilization and re-emplacement could reasonably be related to the hydrothermal activity. The paragenesis and various other aspects of the sulphide mineralization have been dealt with in Chapter IV.

Post-mineralization Period

(9) The beginning of the Post-mineralization period was marked by the faulting of the ore body along several planes, four of which are shown in Fugure 7. These faults, referred to as "ore body faults" in this thesis, have been described in detail in Chapter II.

(10) Dykes of mafic, intermediate, and silicic composition were intruded along the ore body faults. The intrusions began with mafic types and ended with silicic dykes. Intermittent intrusions of compositionally different dykes along a single fault plane produced "composite" dykes.

(11) Solutions depositing silica and lime percolated through innumerable open spaces of different forms and sizes. This is represented by post-ore veins, up to 8 inches wide, filled with well developed crystals of quartz and calcite.

(12) The development of a northeasterly trending fault ("West Fault") resulted in a complete disruption of the dykes and some other rock units underlying the mine area (Figure 8). It raised the level of rhyolites west of the ore body, bringing them partly in direct contact with the latter.

(13) The ore body was subjected to a minor deformation D_4. The best evidence for this is the growth of deformation lamellae in pyrrhotite, especially lamellae crossing pyrrhotite grain boundaries (Figure 48). Apart from this, chlorite-1, which is usually massive,in places, shows a foliation parallel to the elongated streaks of sulphides.

Saussuritization and uralitization of the post-ore dykes, possibly in association with D_4, took place. This is suggested by the alteration of plagioclase and the development of secondary chlorite and hornblende in the diabase dykes.

(14) A mineralogical and textural "adjustment" between some adjoining minerals is suggested by the growth of reaction-rim chlorite (chlorite-3) around sulphides. Other aspects of chlorite-3 are discussed on page 40.

(15) The last notable geological event concerning the Gullbridge copper deposit was a close-spaced shearing of the ore body. The shear

planes are as closely spaced as 6 inches. In detail they show a random orientation but, in general, they strike from north to northeast. The shearing is manifested by the development of grooves and striations up to 2 millimeters deep (Figure 50). Chlorite-rich parts of the ore body seem to have yielded to this shearing to a higher extent than other parts. The absence of sulphides along these shear planes suggests that these are post-ore in age.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The mineralogy, petrography, and textures of the ore samples and those of the rocks occurring close to the ore body suggest that the rocks underlying the Gullbridge mine area were subjected to regional metamorphism, contact metamorphism and metasomatism, hydrothermal alteration, and polyphase deformation. At Mineral Point the restricted occurrence of the cordierite assemblages and particularly that of hydrothermal alteration and sulphide mineralization along a single zone suggests a probable structural control in the localization of the ore body. The most likely control is the fault recognized by Stoiber (Stoiber, 1940a) on the lake shore about 1800 feet southwest of Mineral Point that was assumed by him to pass through Mineral Point. Perhaps the same fault was assumed by Kalliokoski (Kalliokoski, 1955) to extend southwestward to the Southwest Shaft area. Whether the polyphase deformation suffered by the rocks underlying the mine area at Mineral Point was entirely accessory to the localization of the ore body or whether it exerted an important control on the shape and localization of economic mineralization through some unrecognized folding is not known, but the possibility should be investigated.

The chloritic cordierite rock is the most favourable rock for the occurrence of ore. The sulphides replaced chloritized cordierite and quartz. Despite rather non-conclusive evidence, the author proposes a modified volcanic exhalative origin for the ore body whereby the sulphides were remobilized and their emplacement was structurally controlled by the assumed Gull Pond fault zone at Mineral Point. It is suggested that the cordierite-andalusite and the cordierite-anthophyllite assemblages developed by subtractive metasomatism concurrently attended by contact metamorphism of faulted regionally metamorphosed basaltic flow rocks. In lieu of a detailed petrochemical investigation into this aspect of the assemblages, this conclusion, however, is speculative.

The following recommendations are made for any further study of the Gullbridge copper deposit.

1. A detailed mapping of the area around Mineral Point, especially to establish precisely the extent and nature of the contact metamorphism.

2. Detailed investigation of the Mineral Point - Southwest Shaft "belt" with the aim of: (a) establishing whether or not it is actually a fault zone; (b) comparing the mineralogy, petrography, and textures of the sulphide occurrences in Southwest Shaft area to the Mineral Point deposit; (c) obtaining further evidence to support or contradict the proposal that the rocks from which the cordierite assemblages formed were metabasalts.

3. A detailed structural study of the Mineral Point deposit to determine the extent, if any, to which "pre-ore" folding of favourable host rocks, or "post-ore" folding of mineralized rock units has influenced the shape and location of ore bodies.

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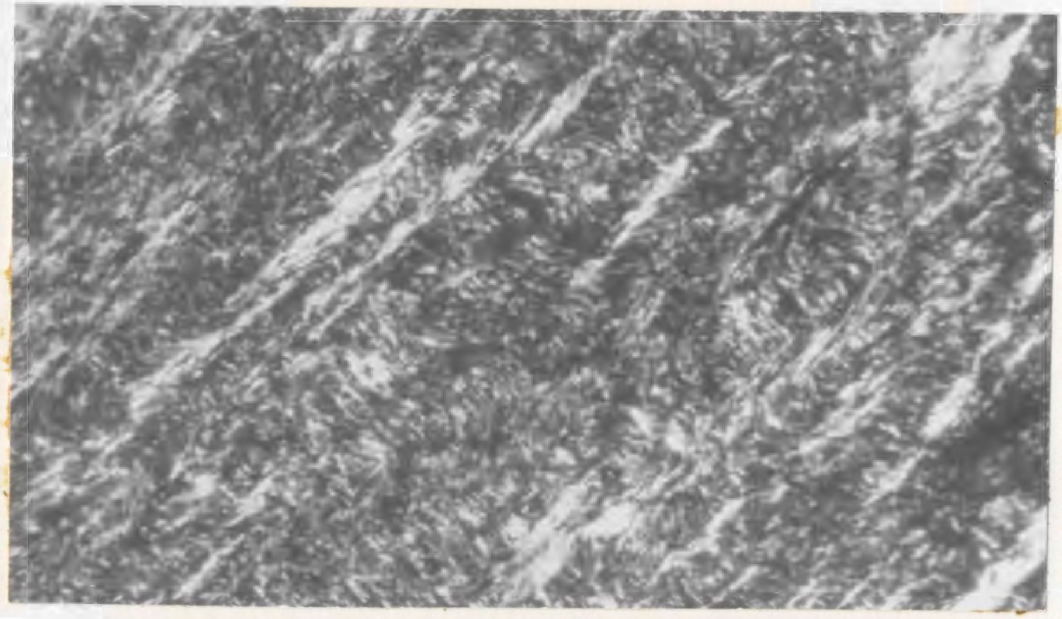


Figure 10: Photomicrograph of quartz-sericite phyllite showing the main schistosity S_1, which was crenulated by a later deformation that gave rise to the strain-slip schistosity S_2 (running northeast). Transmitted light, Crossed nicols, X60.

Figure 11: Growth of cordierite (C_O) over ilmenite-hematite trails (medium-gray specks) that probably represent S_1 within the ore zone. In the northwest corner of the microphotograph the elongated streaks of sulphide run parallel to the adjacent ilmenite-hematite trails. Transmitted plane polarized light, X25.

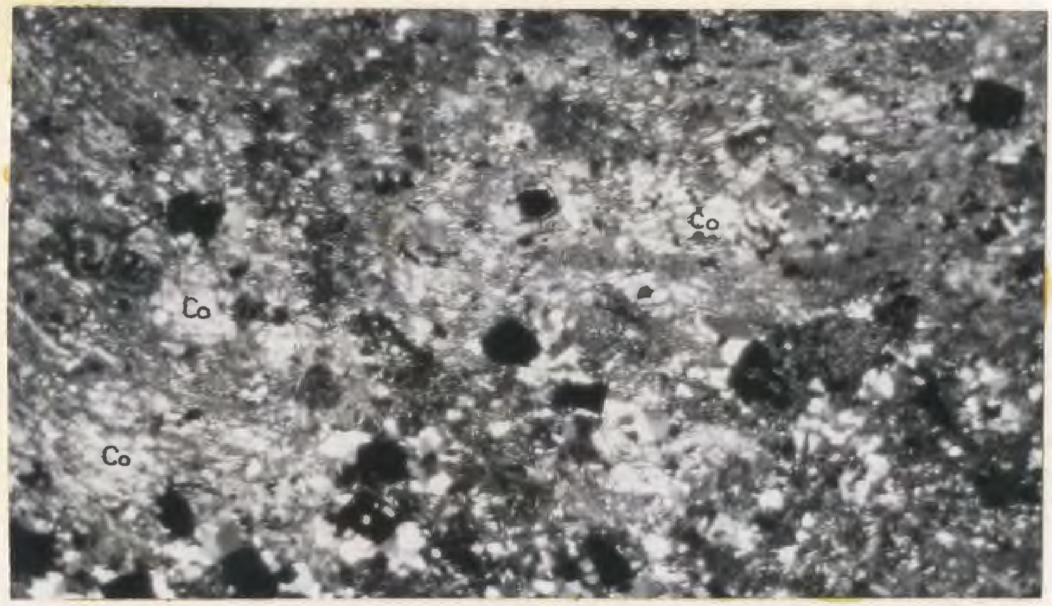


Figure 12: Crenulated patches and poorly defined bands of cordierite (Co) in cordierite-bearing silicic tuff. The banding is clearer on the western margin of the microphotograph. Transmitted light, Crossed nicols, X15.

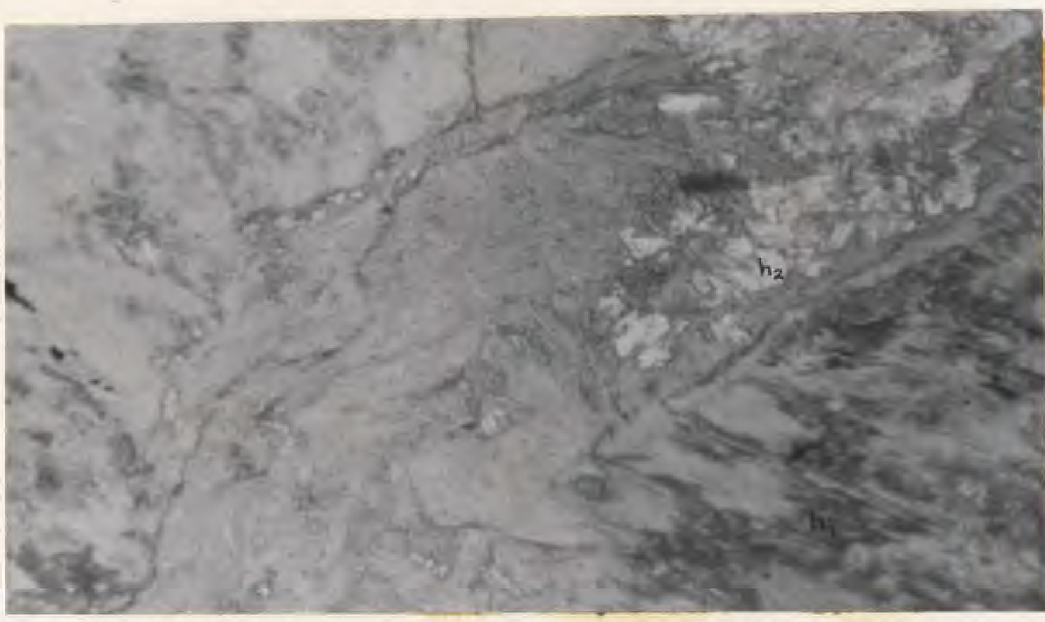


Figure 13: Greenstone showing whispy anhedral units of hornblende-1 (h_1) that define S_1 in the rock, and subhedral grains of hornblende-2 (h_2) that overgrew S_1. Transmitted plane polarized light, X15.

Figure 14: Non-amygdaloidal metabasalt containing laths of hornblende-2 (grayish white) and altered plagioclase (somewhat pitted) with diffused outlines. Transmitted plane polarized light, X15.

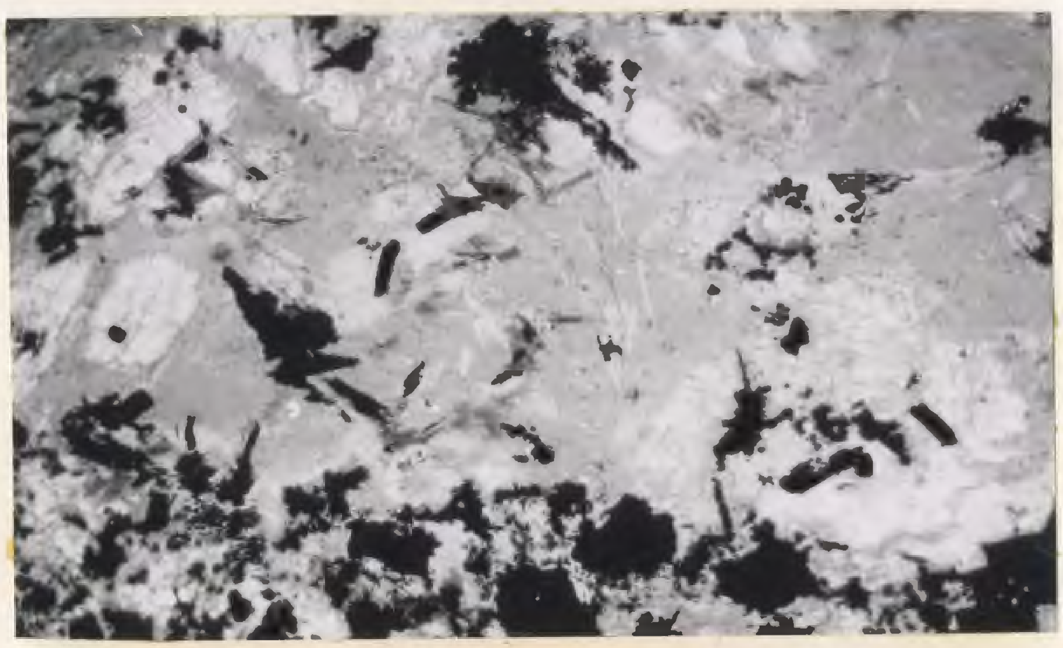


Figure 15: Chloritic cordierite rock showing the partly altered cordierite patches (grayish white) in a groundmass of massive chlorite (medium gray). Note that the sulphides (black) replace only chloritized parts of the cordierite grains. Transmitted plane polarized light, X15.

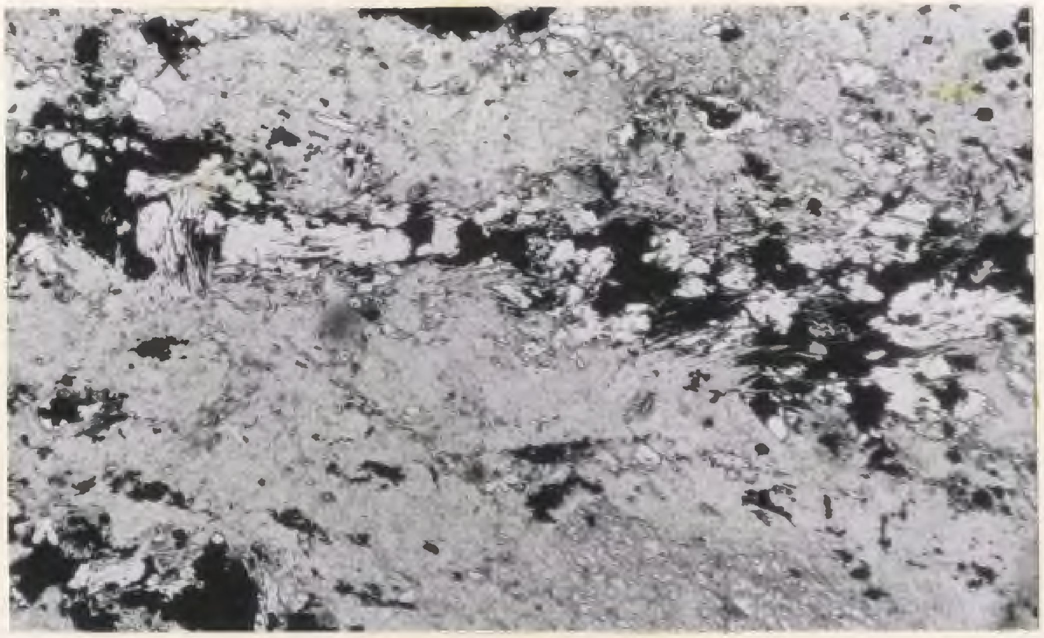


Figure 16: Crenulated acicules of chlorite-2 associated with sulphide bands (black). The chlorite acicules occur around the large patch of massive chlorite, which has a west-northwesterly elongation (lower part of the picture). Transmitted plane polarized light, X15.

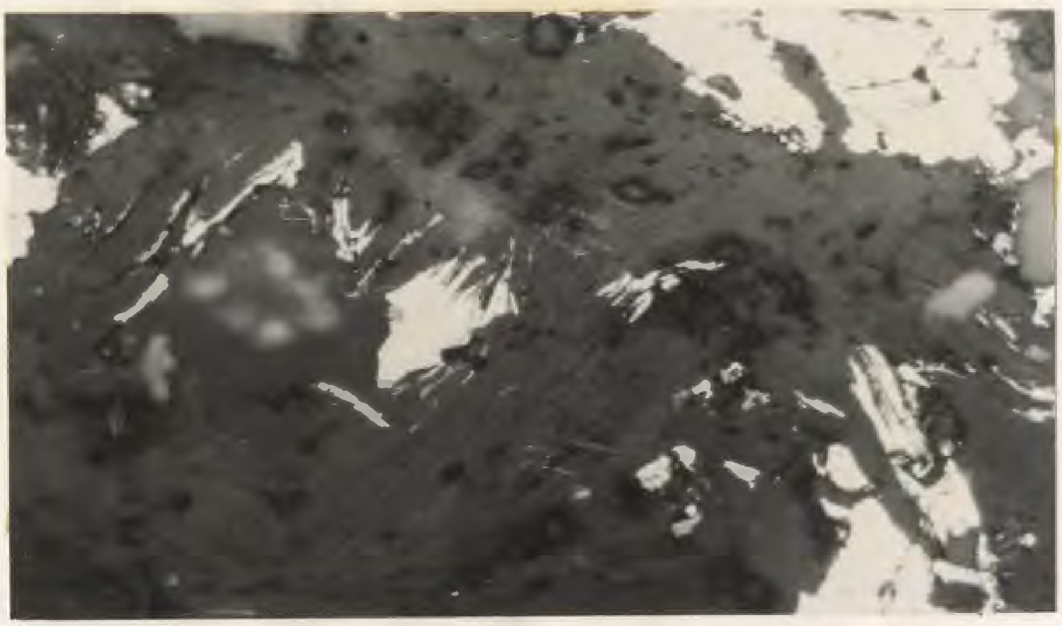


Figure 17: Crenulated acicules of chlorite-2 replaced by chalcopyrite (white). Reflected plane polarized light, X250.

Figure 18: Reaction-rim chlorite (chlorite-3) occurring at the contact of chloritized cordierite (grayish white) and sulphide (black). Transmitted plane polarized light, X45.

Figure 19: Crenulated silicic tuff. The darker laminae are richer in chlorite. White specks are pyrite. Length of specimen, 6 inches.

Figure 20: Cordierite-bearing silicic tuff. The discontinuous and slightly crenulated units (dark gray) consist of cordierite.

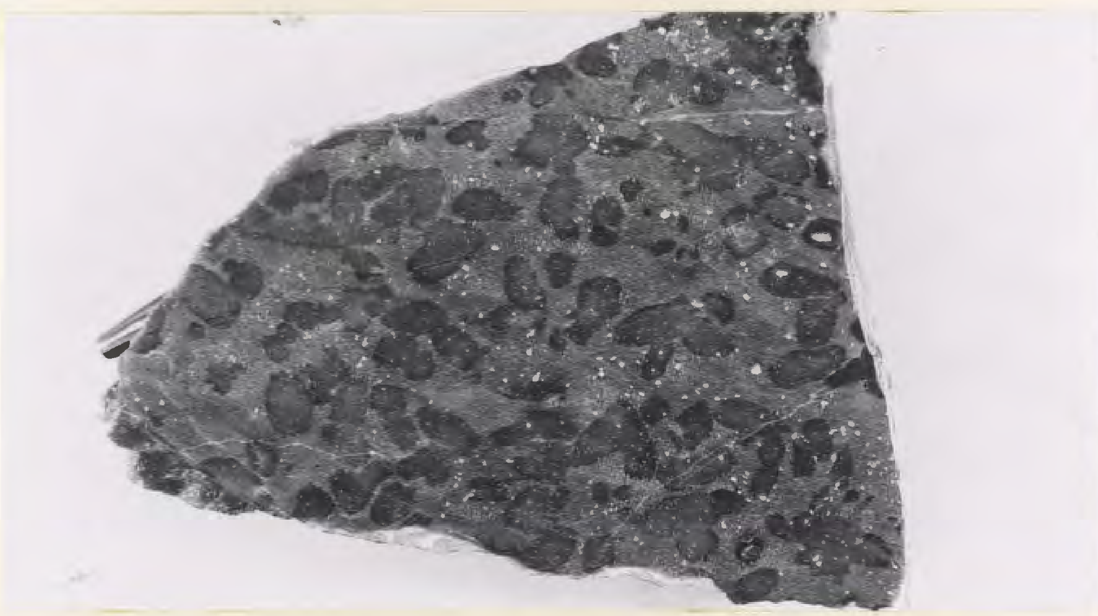


Figure 21: Cordierite-spotted silicic tuff. The randomly oriented cordierite porphyroblasts (dark gray) occur in a quartz-rich groundmass (medium gray). Length of specimen, 5 inches.

Figure 22: Lapilli tuff (?). Angular fragments of calcite and volcanic (?) rock occurring in a predominantly chloritic groundmass. The irregular veins are of calcite.

Figure 23: Spherulitic felsite dyke. The almost circular spherulites consist of feather-like units, the latter showing a micrographic texture. Transmitted light, Crossed nicols, X15.

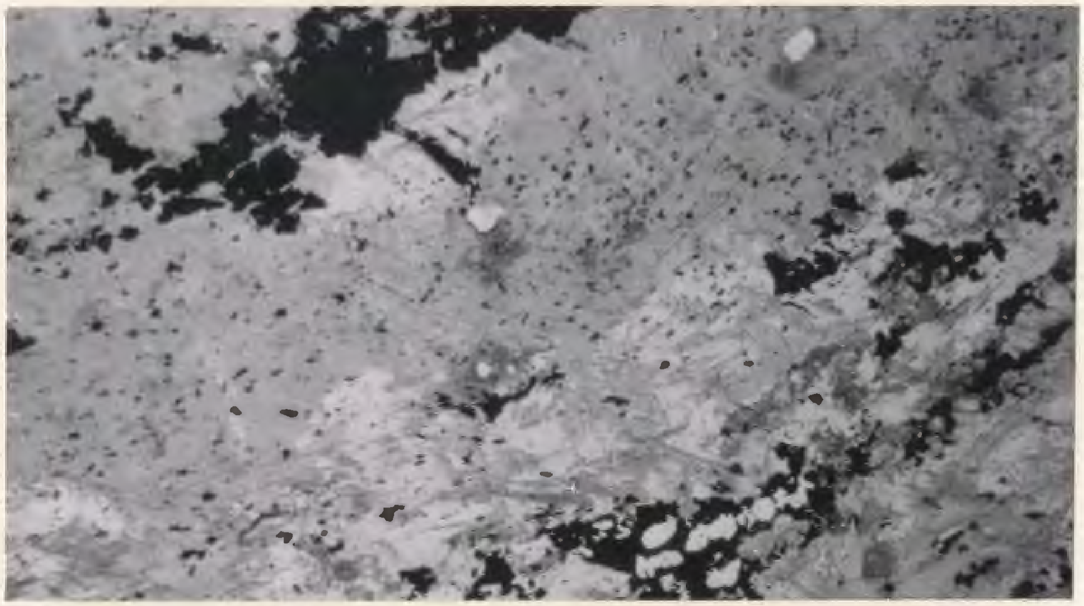


Figure 24: Cordierite-anthophyllite rock showing the growth of anthophyllite fibers (light gray, southeastern part) across northeast-trending ilmenite-hematite trails, the latter are the probable representatives of S_1. Note that the bands of sulphides run parallel to these trails. Transmitted plane polarized light, X20.

Figure 25: "Pinch and swell" structure shown by quartz (pitted white) in chloritic cordierite rock. The "necks" are filled with sulphides (black). Transmitted plane polarized light, X45.

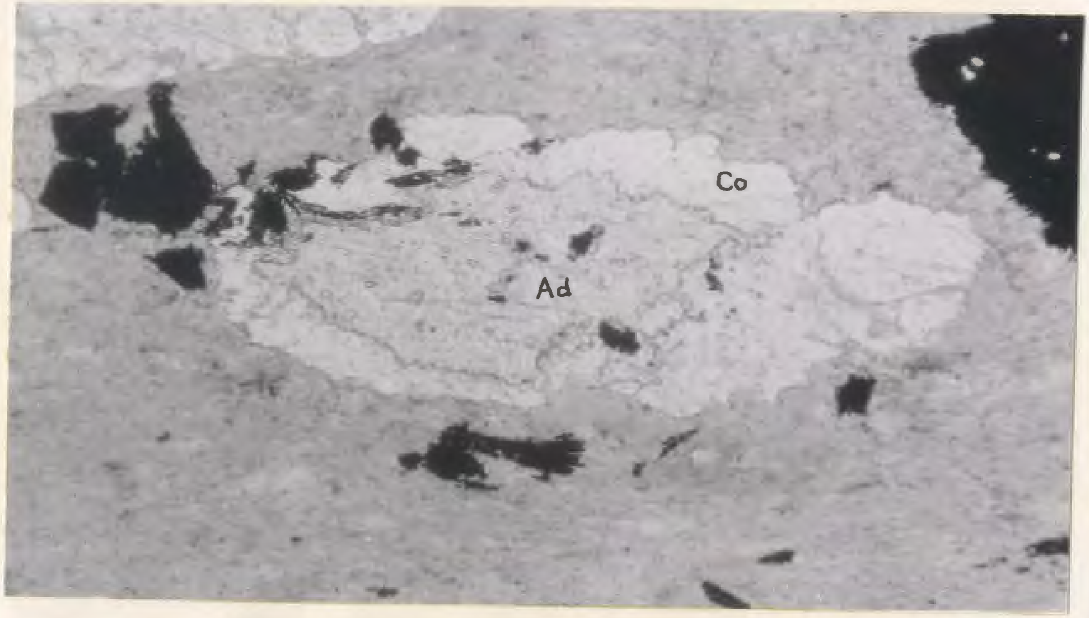


Figure 26: Andalusite (Ad) showing a corroded outline and occurring within cordierite (Co). Transmitted plane polarized light, X50.

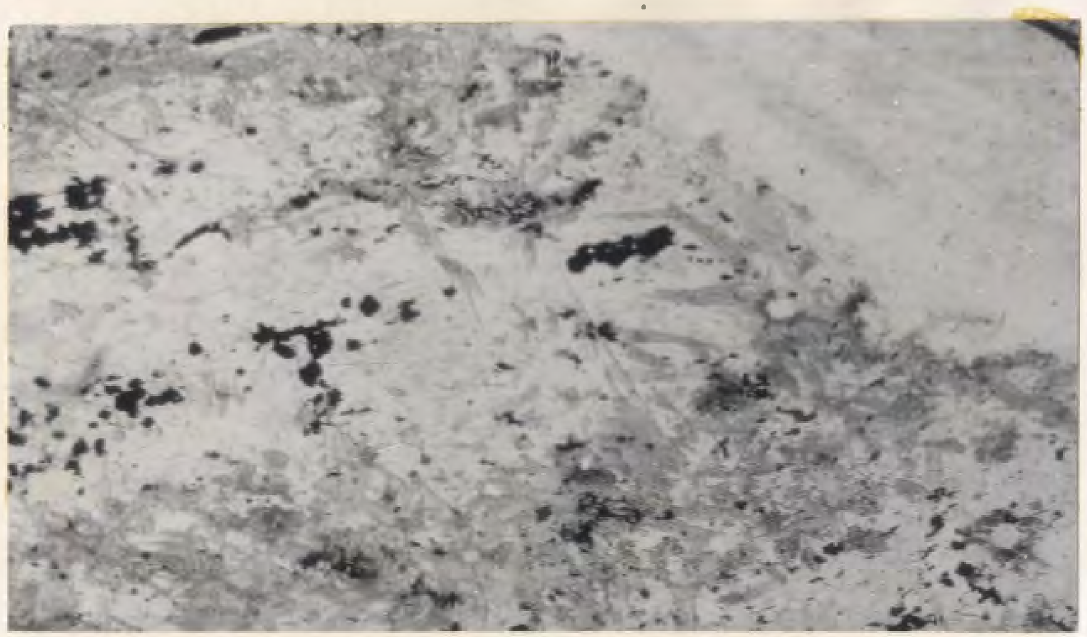


Figure 27: Anthophyllite fibers (medium gray) occurring subpoikilitically within cordierite grains (grayish white). Transmitted plane polarized light, X25.

Figure 28: Massive ore showing preferred orientation (running almost northeast). Dark and medium gray is gangue; grayish white is chalcopyrite and pyrrhotite. Length of specimen 4 inches.

Figure 29: Ribboned ore showing "ribbons" of sulphide (white) and gangue (medium and dark gray). Arrow indicates the direction of foliation which runs parallel to the 'ribbons'. Length of specimen, 6 inches.

Figure 30: Ore-bearing chloritic cordierite rock showing moderately bent lenticular units of sulphides (white). Specimen about natural size.

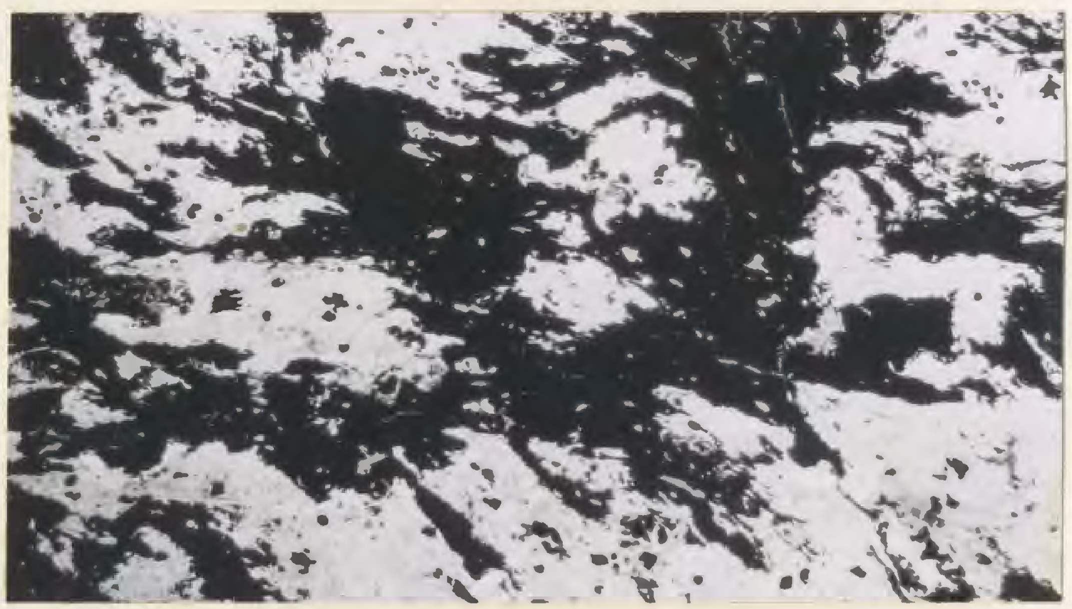


Figure 31: Elongated sulphide streaks (black) and chloritic groundmass (grayish white) giving rise to a schistose texture in the chloritic cordierite rock. Transmitted plane polarized light, X15.

Figure 32: Magnetite-2, almost completely replaced by some unknown gangue mineral, showing its overgrowth on the northwest-trending S_1 schistosity. The unreplaced lamellae (black) are probably of ilmenite. Transmitted plane polarized light, X60.

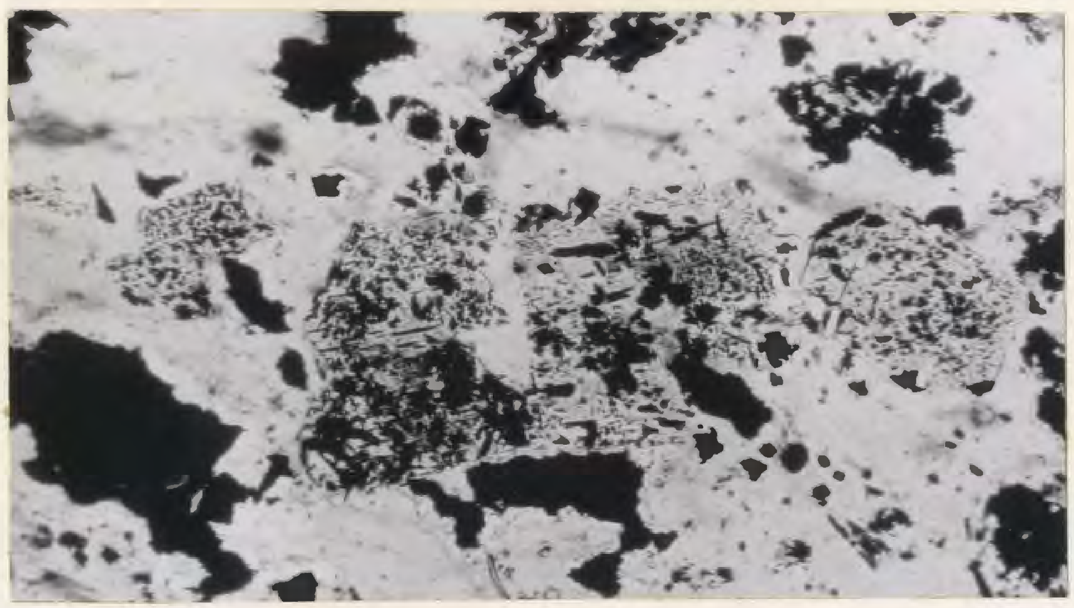


Figure 33: Some unknown mineral pseudomorphous after magnetite-2 (rhomb-shaped). The thin opaque lamellae are of ilmenite. Transmitted plane polarized light, X45.

Figure 34: Ilmenite lamellae occurring in magnetite-2 (medium gray). The latter is partly replaced by gangue. Reflected plane polarized light, X125.

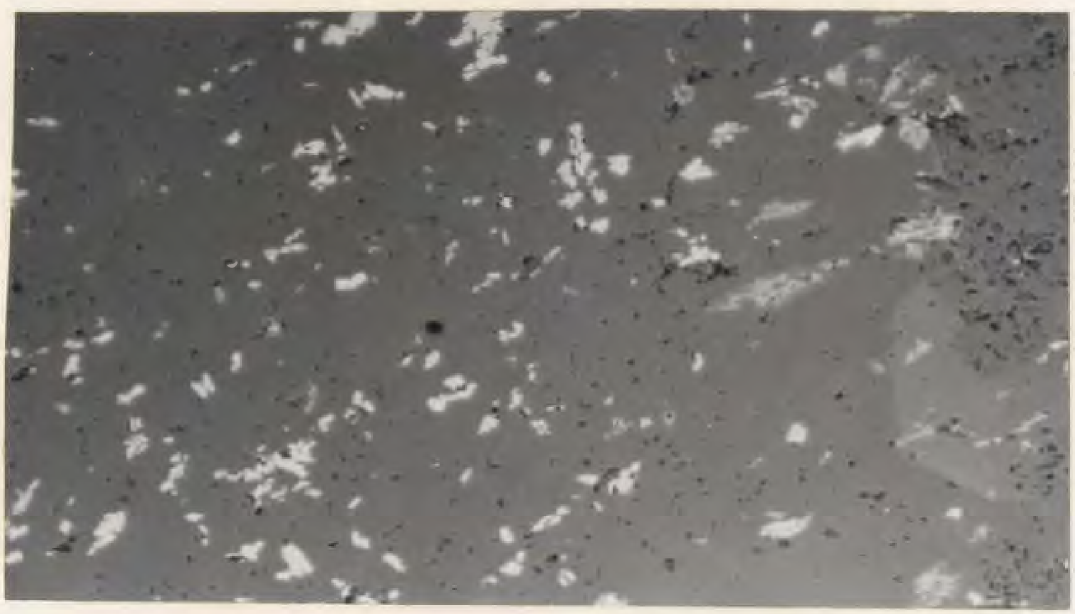


Figure 35: Very weakly defined trails of ilmenite-hematite (white) trending almost northeast. These are the probable representatives of S_1 within the ore zone. Reflected plane polarized light, X125.

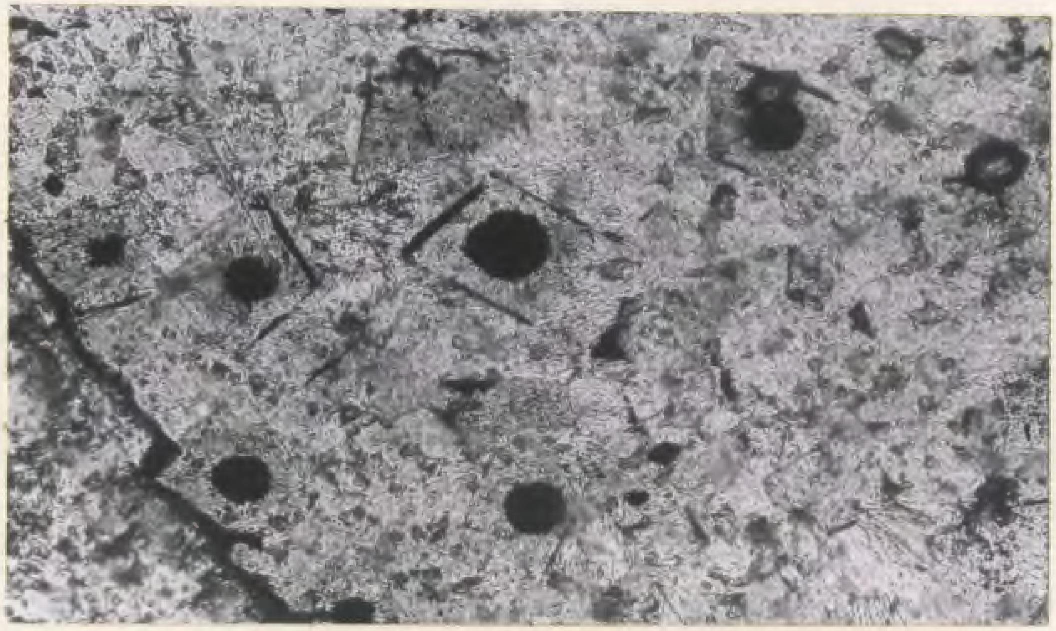


Figure 36: Rhomb-shaped pseudomorphs of some unknown gangue mineral after magnetite-2. The circular opaque mineral in the centre of the pseudomorphs is possibly mineral "X". Transmitted plane polarized light, X150.

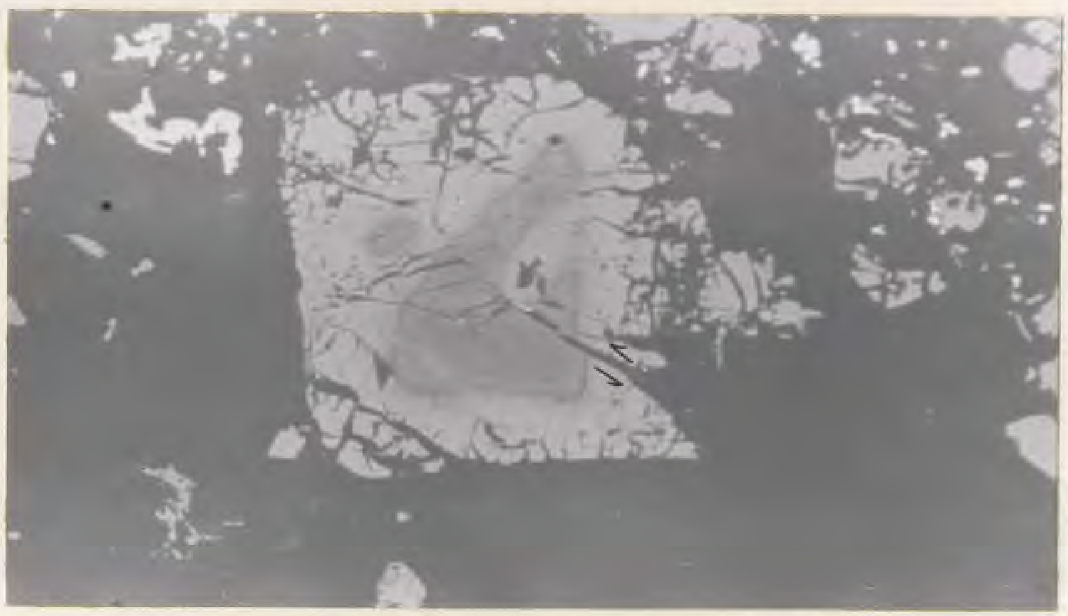


Figure 37: Disrupted grain of magnetite-2 (light gray) containing islands of mineral "X" (medium gray). Arrows indicate the direction of relative movement during disruption. Reflected plane polarized light, X200.

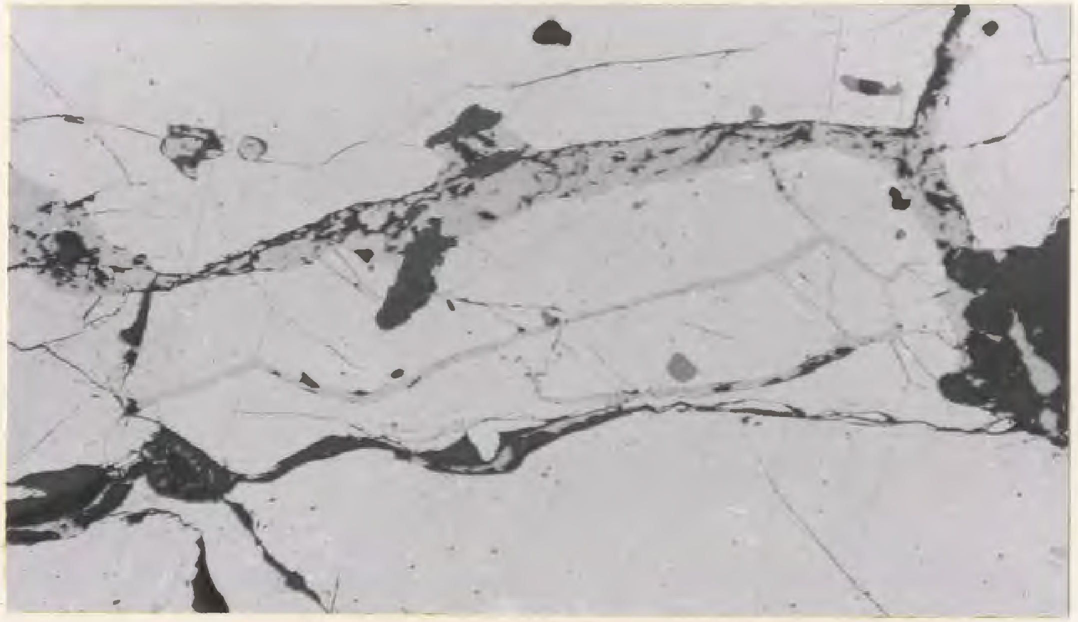
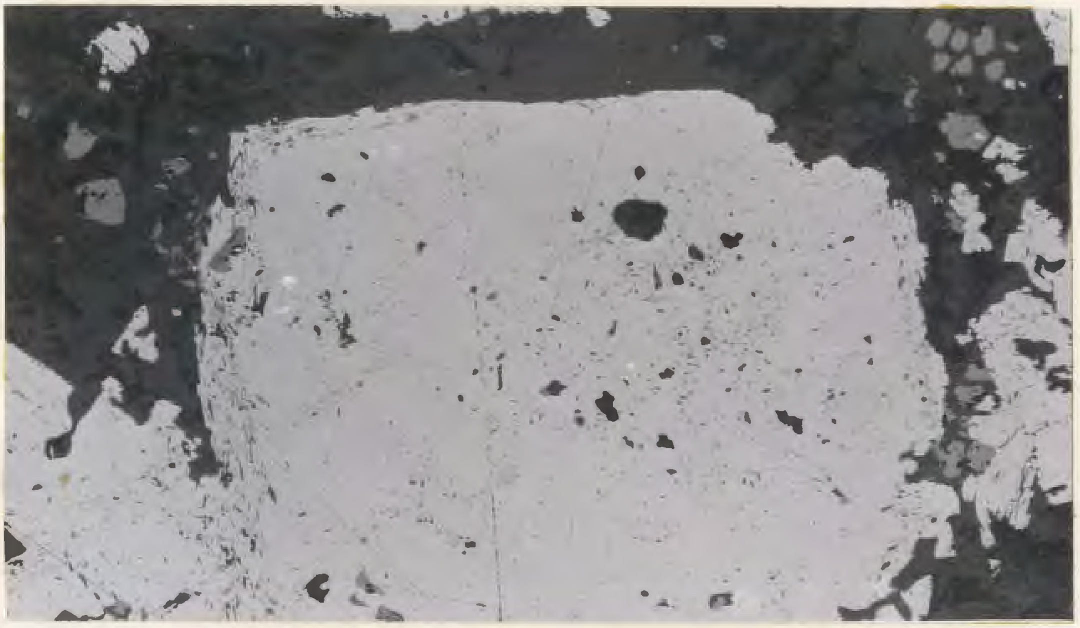


Figure 38: Pyrite-2 (grayish white) fractured by cataclastic deformation. The fractures are filled with chalcopyrite (light gray). Reflected plane polarized light, X125.

Figure 39: Pseudomorphs of pyrite-3 (black) after anthophyllite. Transmitted plane polarized light, X50.



igure 40: A square-shaped grain of pyrite-2. Pyrite-3, which grew through the replacement of anthophyllite, occurs along the left and right margins of this grain. Reflected plane polarized light, X200.

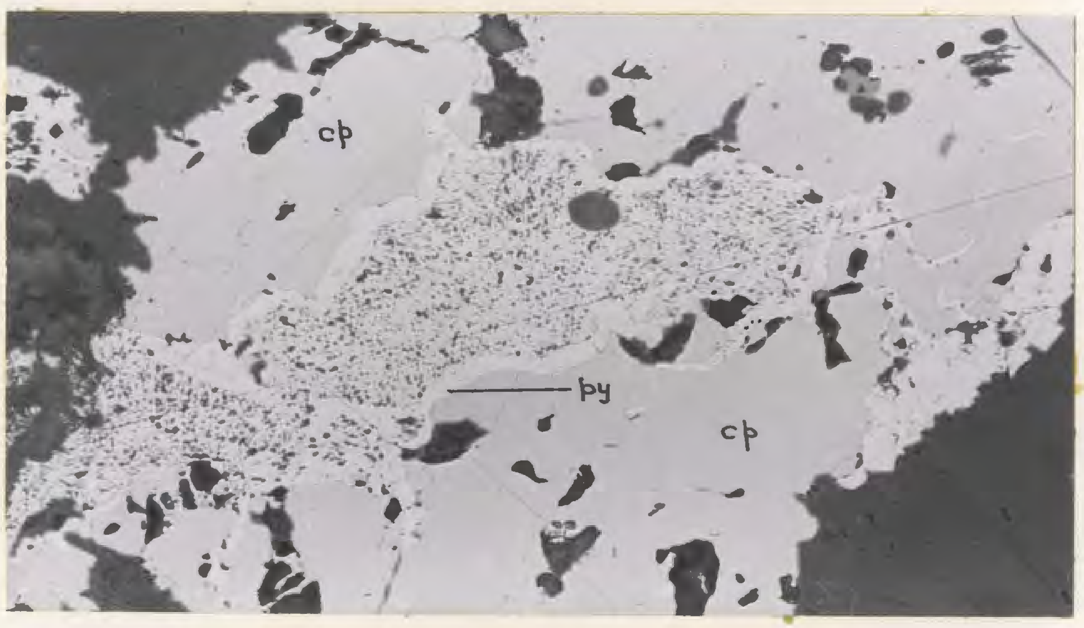


Figure 41: Pyrite-4 (pitted surface) surrounded by a thin rim of pyrite-2(?) (py). The whole grain occurs in a groundmass of chalcopyrite (cp). Reflected plane polarized light, X250.

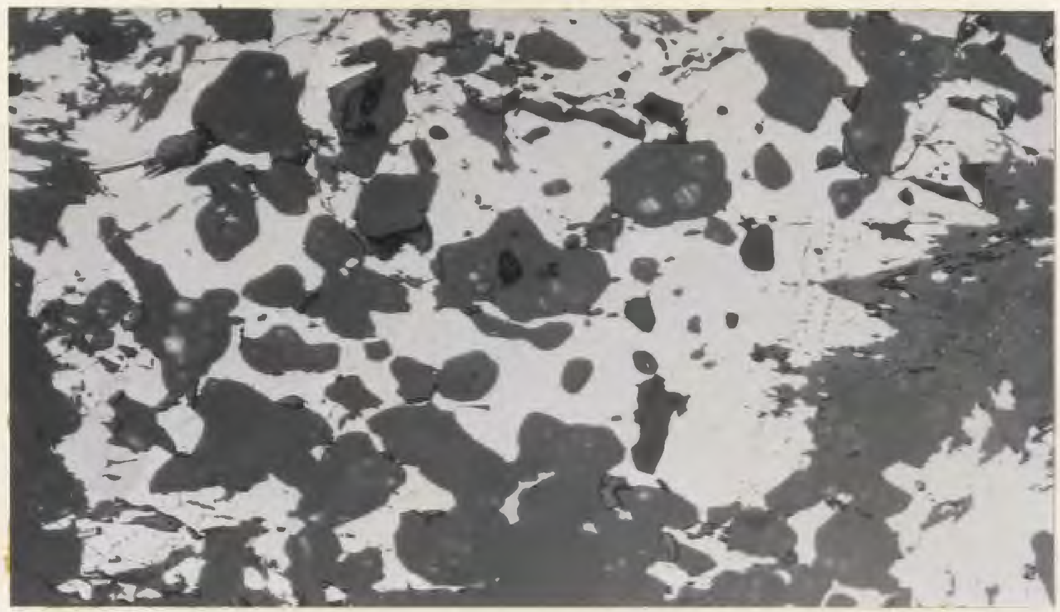


Figure 42: Pyrrhotite (white) filling intergranular spaces among quartz grains (dark gray). Reflected plane polarized light, X125.

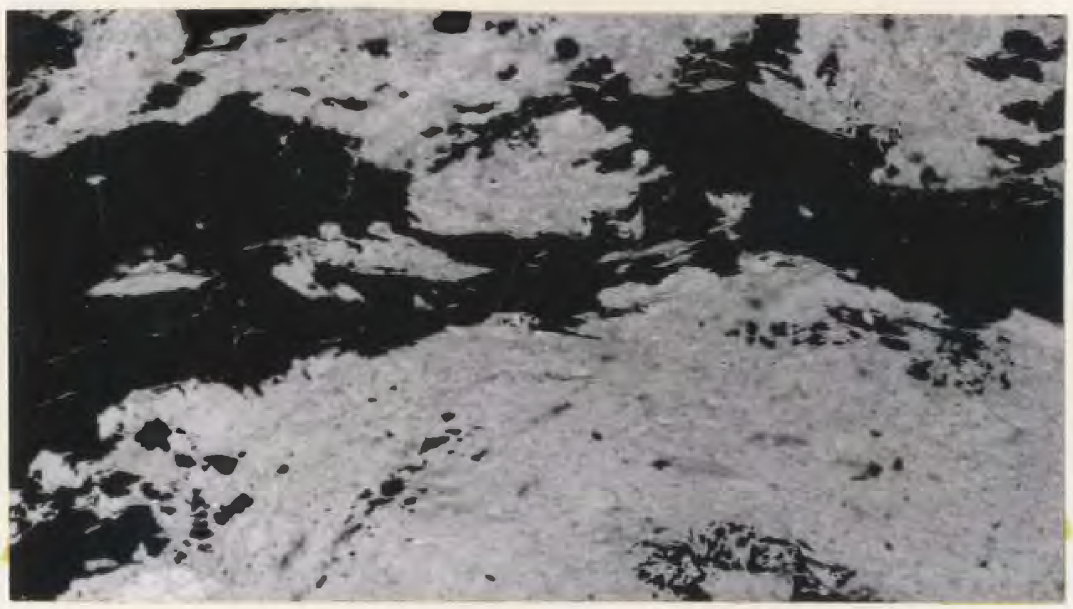


Figure 43: Massive chlorite (light gray) foliated parallel to the elongated streaks of sulphides (black). Transmitted plane polarized light, X45.

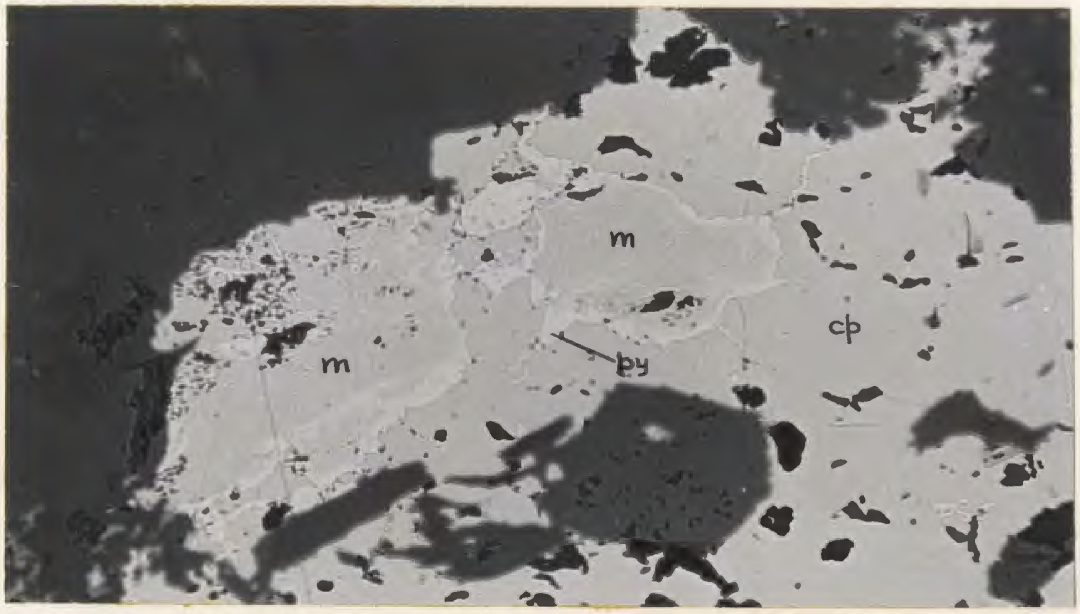


Figure 44: Irregular patches showing a myrmekitic intergrowth (m) and occurring in a groundmass of chalcopyrite (cp). The patches are surrounded by a pyrite rim (py) of variable width. Reflected plane polarized light, X200.

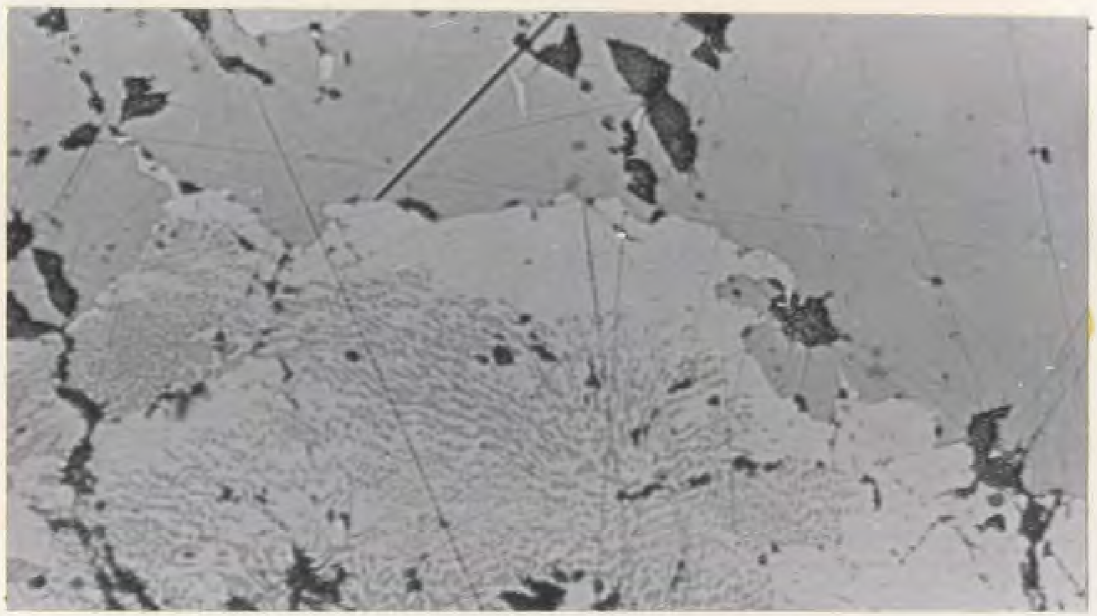


Figure 45: Detailed view of the marginal portion of the myrmekitic intergrowth (Figure 44). The medium gray "worms" are chalcopyrite and the white is pyrite. Reflected plane polarized light, X1000.

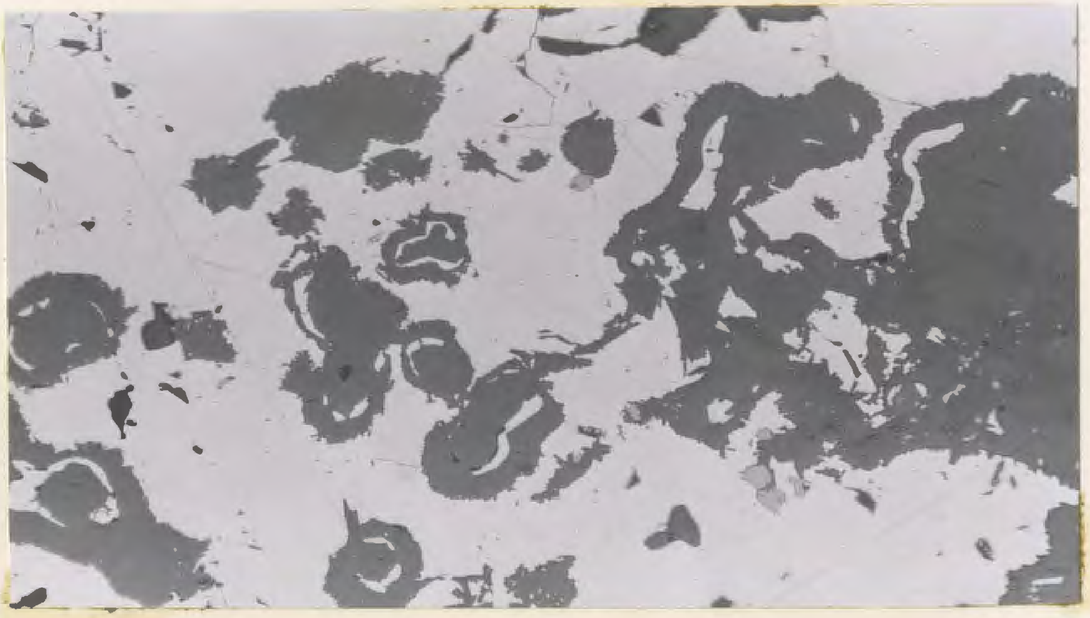


Figure 46: Mutual boundaries (?) texture between sulphides (chalcopyrite, pyrrhotite) and silicates (dark gray) in a sample that occurs within 3 feet of the contact of a post-ore diabase dyke. Reflected plane polarized light, X125.

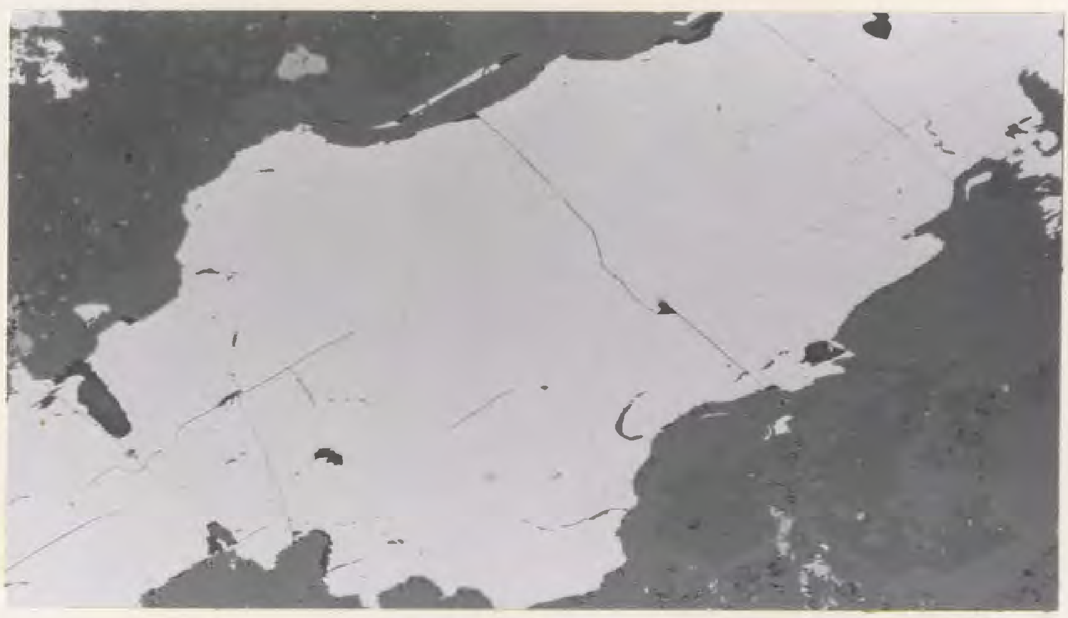


Figure 47: Exolved (?) spindles of chalcopyrite (trending northeast) in pyrrhotite. Reflected plane polarized light, X125.

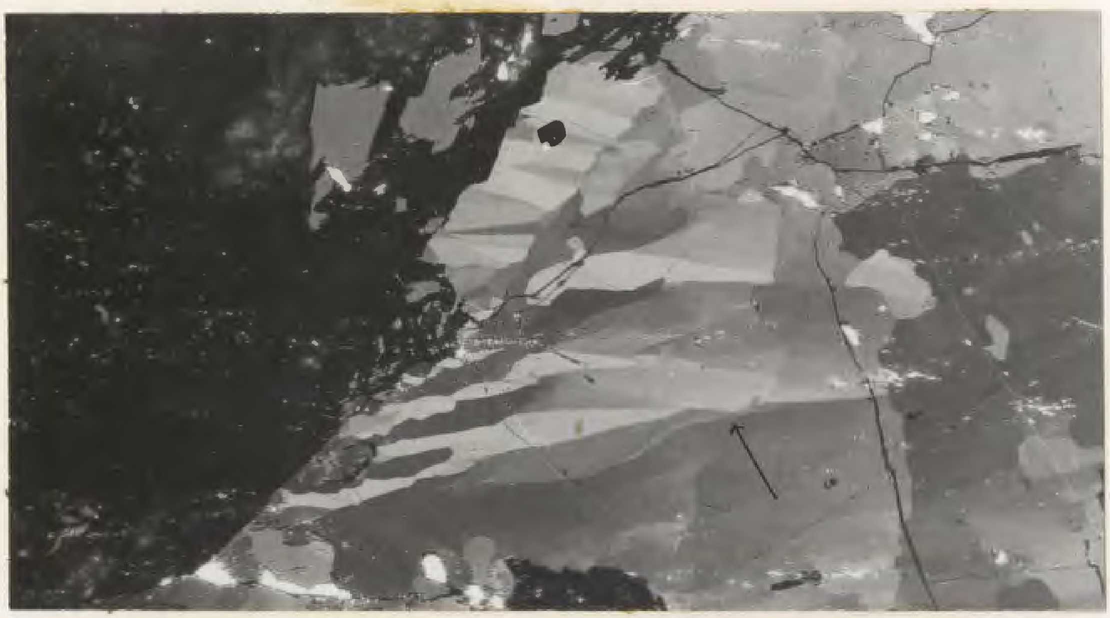


Figure 48: Deformation lamellae (grays of various shades) in pyrrhotite that have almost an east-west trend. The grain boundaries of pyrrhotite grains run roughly towards north-northeast. Arrow indicates the crossing of pyrrhotite grain boundary by the lamellae. Reflected light, crossed nicols, X125.

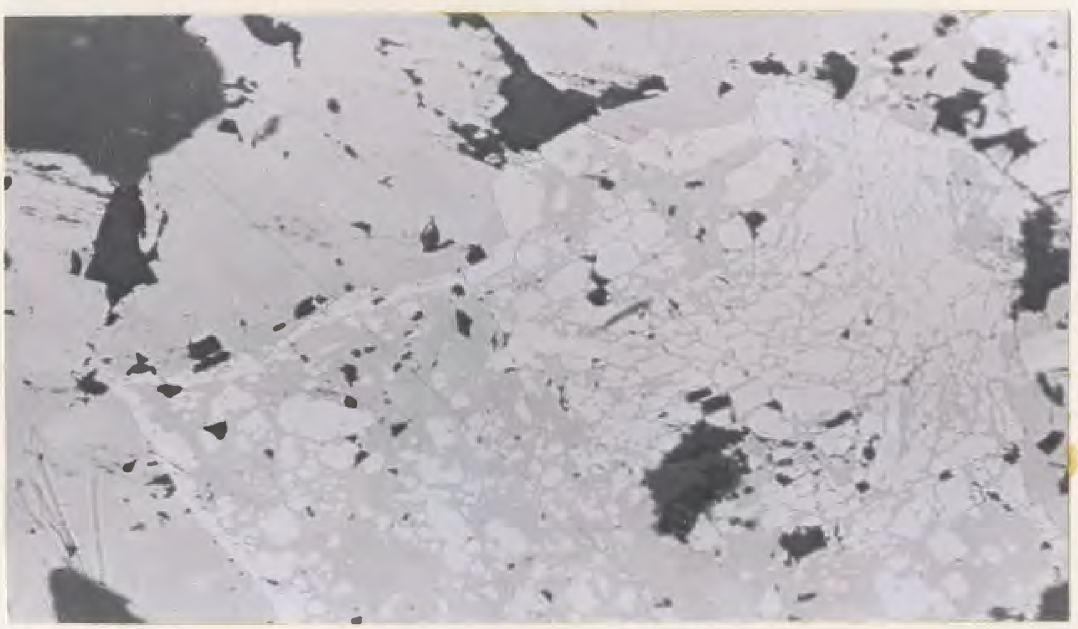
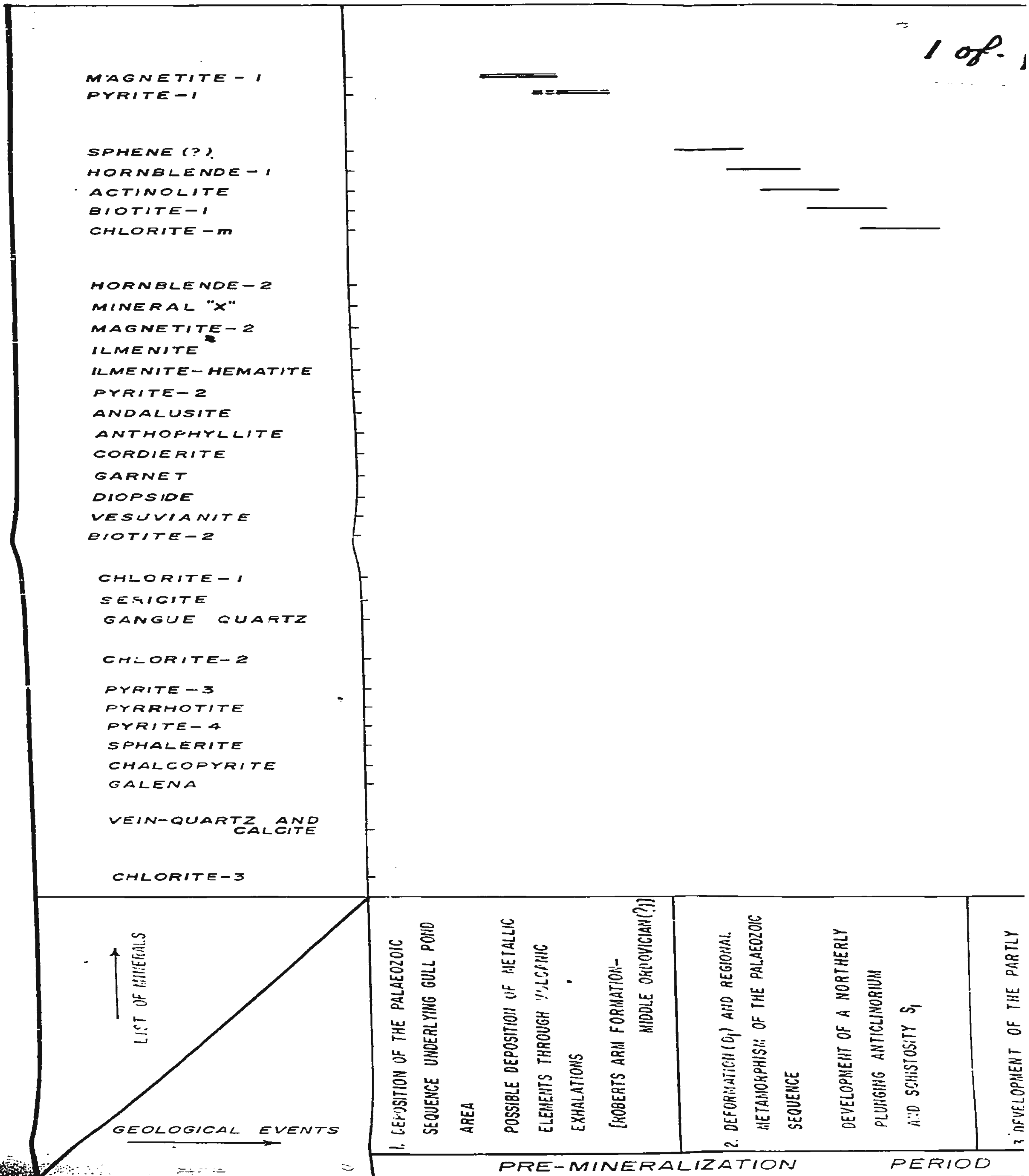


Figure 49: Remnant segments of large pyrite-2 crystal (grayish white) that was replaced by chalcopyrite and pyrrhotite (light gray). Reflected plane polarized light, X125.

Figure 50: Striations developed on chloritic cordierite rock due to a late stage close-spaced shearing. Length of specimen, 6 inches.


1 of.
MAGNETITE-1
PYRITE-1
SPHENE (?)
HORNBLENDE-1
ACTINOLITE
BIOTITE-1
CHLORITE-m
HORNBLENDE-2
MINERAL "X"
MAGNETITE-2
ILMENITE
ILMENITE-HEMATITE
PYRITE-2
ANDALUSITE
ANTHOPHYLLITE
CORDIERITE
GARNET
DIOPSIDE
VESUVIANITE
BIOTITE-2
CHLORITE-1
SERICITE
GANGUE QUARTZ
CHLORITE-2
PYRITE-3
PYRRHOTITE
PYRITE-4
SPHALERITE
CHALCOPYRITE
GALENA
VEIN-QUARTZ AND CALCITE
CHLORITE-3
LIST OF MINERALS
GEOLOGICAL EVENTS
1. DEPOSITION OF THE PALAEOZOIC SEQUENCE UNDERLYING GULL POND AREA
POSSIBLE DEPOSITION OF METALLIC ELEMENTS THROUGH VOLCANIC EXHALATIONS
(ROBERTS ARM FORMATION- MIDDLE ORDOVICIAN(?))
2. DEFORMATION (D_1) AND REGIONAL METAMORPHISM OF THE PALAEOZOIC SEQUENCE
DEVELOPMENT OF A NORTHERLY PLUNGING ANTICLINORIUM AND SCHISTOSITY S_1
3. DEVELOPMENT OF THE PARTLY
PRE-MINERALIZATION PERIOD

PAR

TABLE III

PARAGENESIS AND PROGRESSIVE SEQU

ERIOD

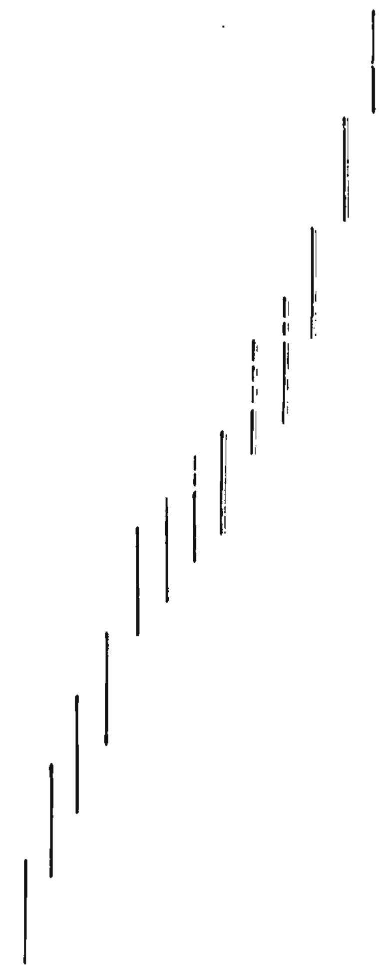
AND SCHISTOSITY S_1

3. DEVELOPMENT OF THE PARTLY DEFINED GULL POND FAULT ZONE

MINERALIZATION

4. INTRUSION OF GRANITE-DIORITE BODIES, ACCOMPANIED BY CONTACT METAMORPHISM & METASOMATISM

GROWTH OF CORDIERITE ASSEMBLAGES AND POSSIBLE INITIATION OF REMOBILIZATION AND EMPLACEMENT OF SULPHIDES



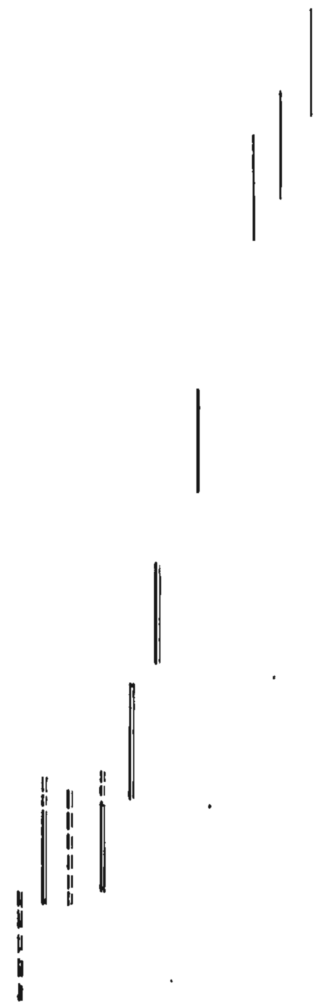
5. CATACLASTIC DEFORMATION (D_2)

LE III

SEQUENCE OF GEOLOGICAL EVENTS

ZATION | PERIOD

5. CATACLASTIC DEFORMATION (D_2)	
6. HYDROTHERMAL ALTERATION	
7. DEFORMATION (D_3) GIVING RISE TO STRAIN-SLIP SCHISTOSITY S_2	
8. MAIN STAGE OF REMOBILIZATION OF SULPHIDES AND THEIR EMPLACEMENT ALONG THE ASSUMED GULL POND FAULT ZONE	
9. DEVELOPMENT OF ORE BODY FAULTS	



ENTS

POST-MINERALIZATION PERIOD

9. DEVELOPMENT OF ORE BODY FAULTS

10. INTRUSION OF DYKES ALONG THE ORE BODY FAULTS

11. PERCOLATION OF SILICA- AND LIME-BEARING SOLUTIONS

12. DEVELOPMENT OF WEST FAULT

13. MINOR DEFORMATION (D_4)

SAUSSURITIZATION & URALITIZATION OF POST-ORE DYKES

14. MINERALOGICAL AND TEXTURAL "ADJUSTMENTS"

15. CLOSE-SPACED SHEARING OF THE ORE BODY

1 of

LEGEND

PALÆOZOIC

DEVONIAN

- **17** — Basic intrusions: 17a, gabbro, diabase; 17b, pyroxenite; 17c, peridotite; may be in part older than 6, 15, and 16
- **15 / 16** — 15. Quartz diorite, diorite, gabbro; minor granite and granodiorite. 16. Granite, granodiorite, minor quartz diorite and diorite. Twin Lakes diorite complex may be older than 7

SPRINGDALE GROUP (6-14)

- **14** — Amygdaloidal and vesicular basic lava with abundant intrusions of basalt and coarsely porphyritic gabbro
- **13** — Reddish or purplish, flow-layered, spherulitic, rarely porphyritic, acidic lava; minor flow-breccia and tuff
- **12** — Basic, amygdaloidal and vesicular lava; minor acidic lava, tuff, and agglomerate
- **11** — Flow-layered, spherulitic, acidic lava with abundant flow-breccia
- **10** — Porphyritic, massive, acidic lava; minor tuff, agglomerate, and flow-breccia
- **9** — Basic lava, minor agglomerate and tuff; 9a, red sandstone, shale, and conglomerate. 9b, basic agglomerate
- **8** — Latite and quartz latite
- **7** — Acidic and basic agglomerate and tuff, some basic conglomerate and basic lava
- **6** — Red, arkosic sandstone with thin layers of conglomerate

ORDOVICIAN

MIDDLE ORDOVICIAN (?)

BADGER BAY 'SERIES' (1-5)

- **5A / 5B** — 5A, ROBERTS ARM FORMATION: predominantly basaltic pillow lava, some undifferentiated volcanic rocks and tuff. 5B, predominantly rhyolite, latite, tuff, tuffaceous shale, minor greywacke. 5Aa and 5Ba, pyritic schists derived from 5A and 5B
- **4** — CRESCENT LAKE FORMATION: grey, green, and red tuffaceous shale, rhyolite tuff, and chert, greywacke, undifferentiated basalt and rhyolite. 4a, hornfelsic rocks
- **3** — Basaltic pillow lava
- **2** — Greywacke with some slate, minor conglomerate and basic lava. 2a, metamorphosed sedimentary rocks; 2b, basalt
- **1** — Greywacke conglomerate, minor greywacke and slate

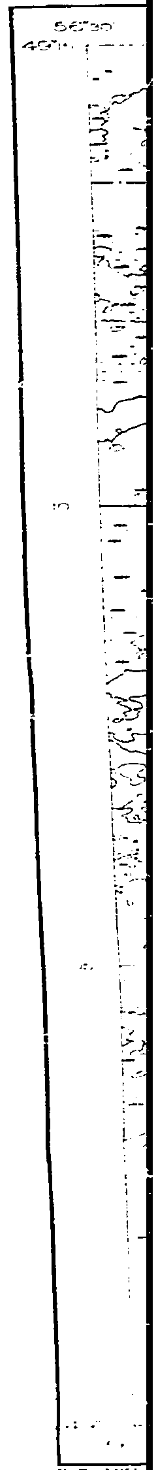
Outcrop, area of outcrop
Bedding (inclined, vertical, overturned)
Bedding (direction of dip known, upper side of bed unknown)
Schistosity, gneissosity (inclined, vertical, dip unknown)
Fault (defined, approximate, assumed)
Axis of anticline
Synclinal axis
Mineral prospect or occurrence ×

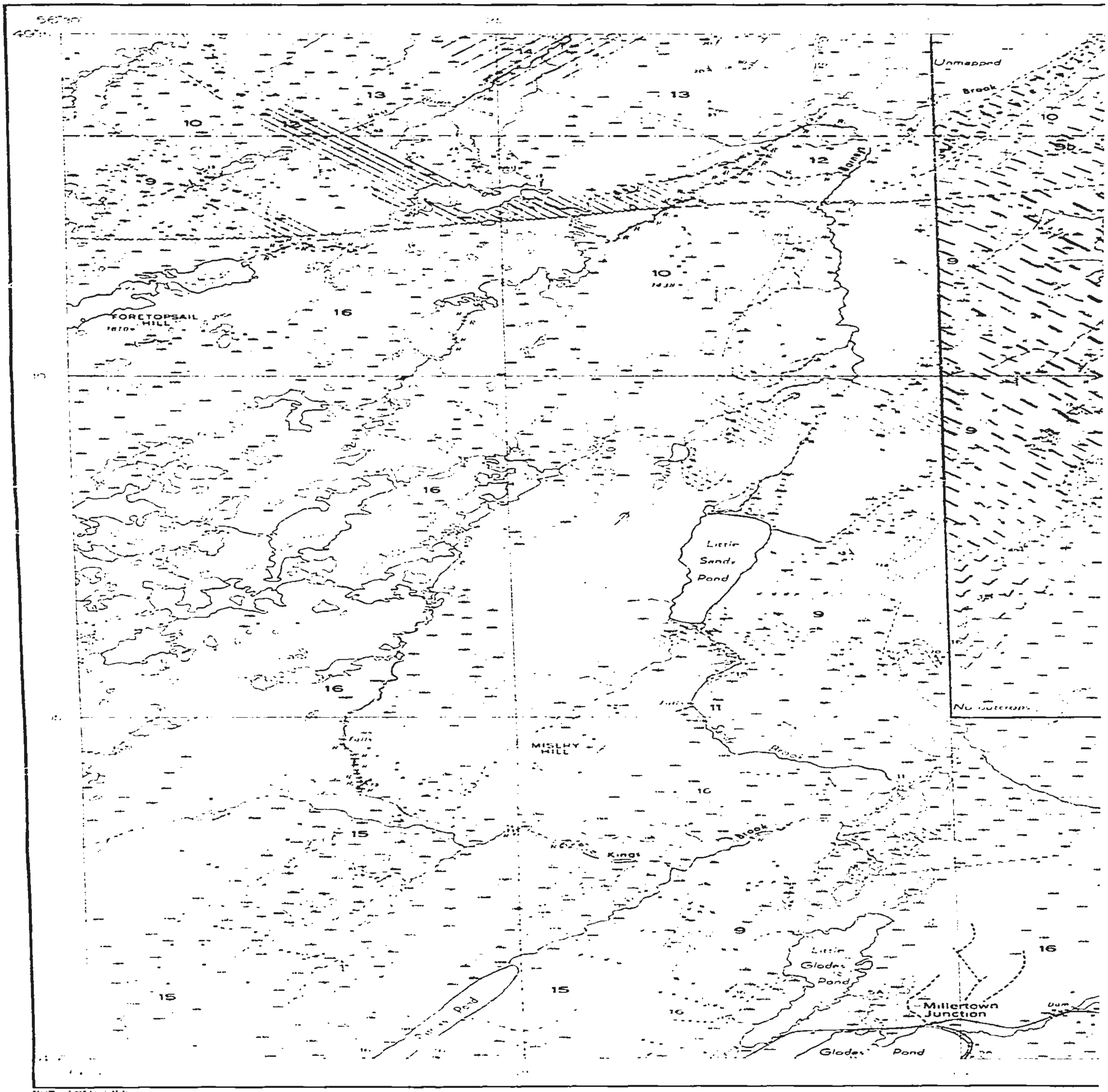
Geology of the granitic rocks east of Badger-Halls Bay road by J. Hayes, 1947 and 1948 for the Geological Survey of Newfoundland. Geology by J. Kalliokoski 1950, 1951, 1952

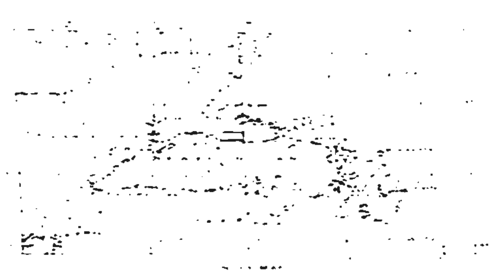
Descriptive notes by J. Kalliokoski

Cartography by the Geological Cartography Division, 1954

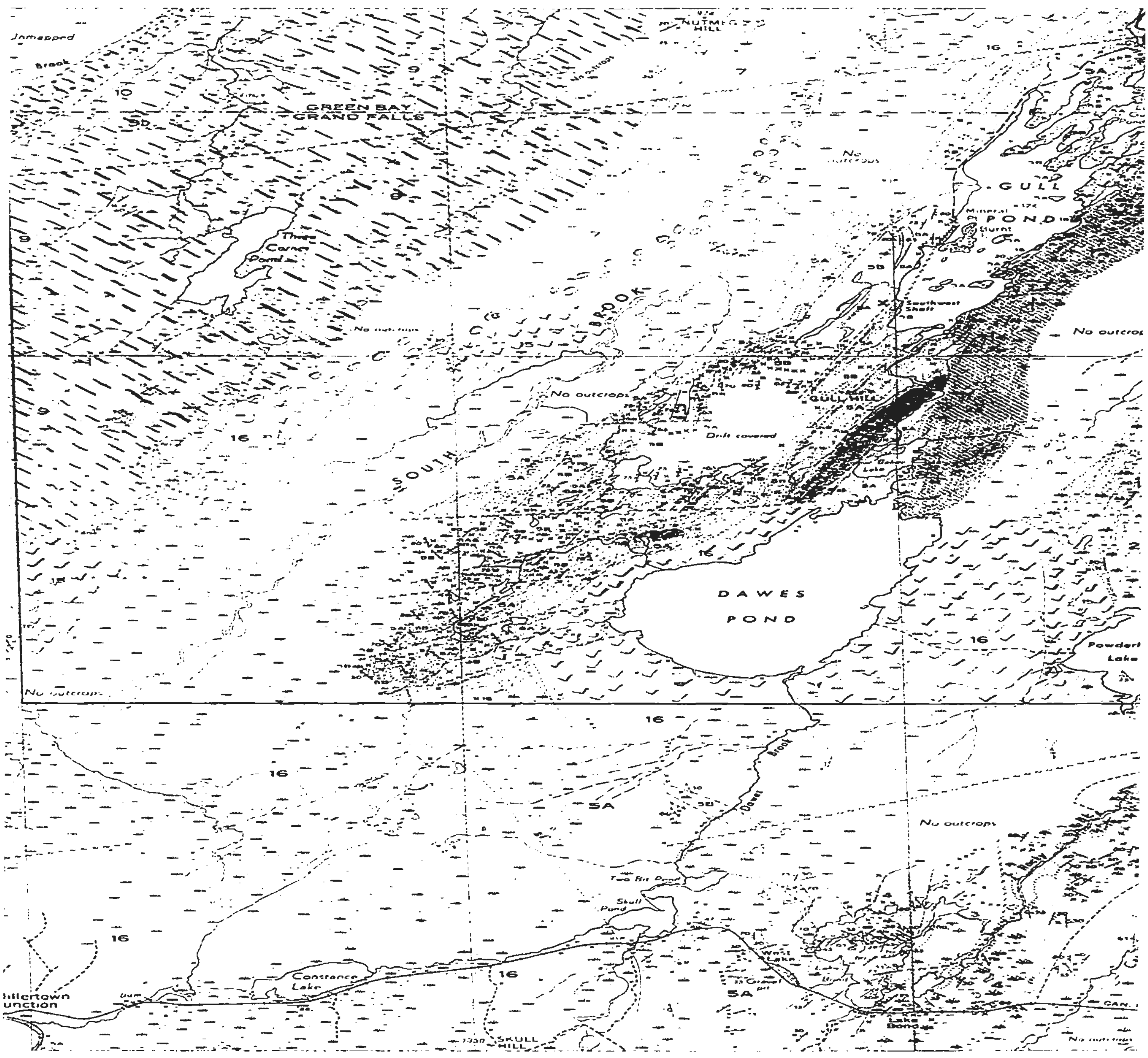
Approximate magnetic declination, 29° 32' West




Unmapped
Brook
FORETOPSAIL HILL
Little Sandy Pond
Falls
MISERY HILL
Brook
Kings
Little Glodes Pond
Millertown Junction
Glodes Pond
Pond
Dam
No outcrops



CANADA
DEPARTMENT
OF
MINES AND TECHNICAL SURVEYS
GEOLOGICAL SURVEY OF CANADA



PRELIMINARY MAP 54-4

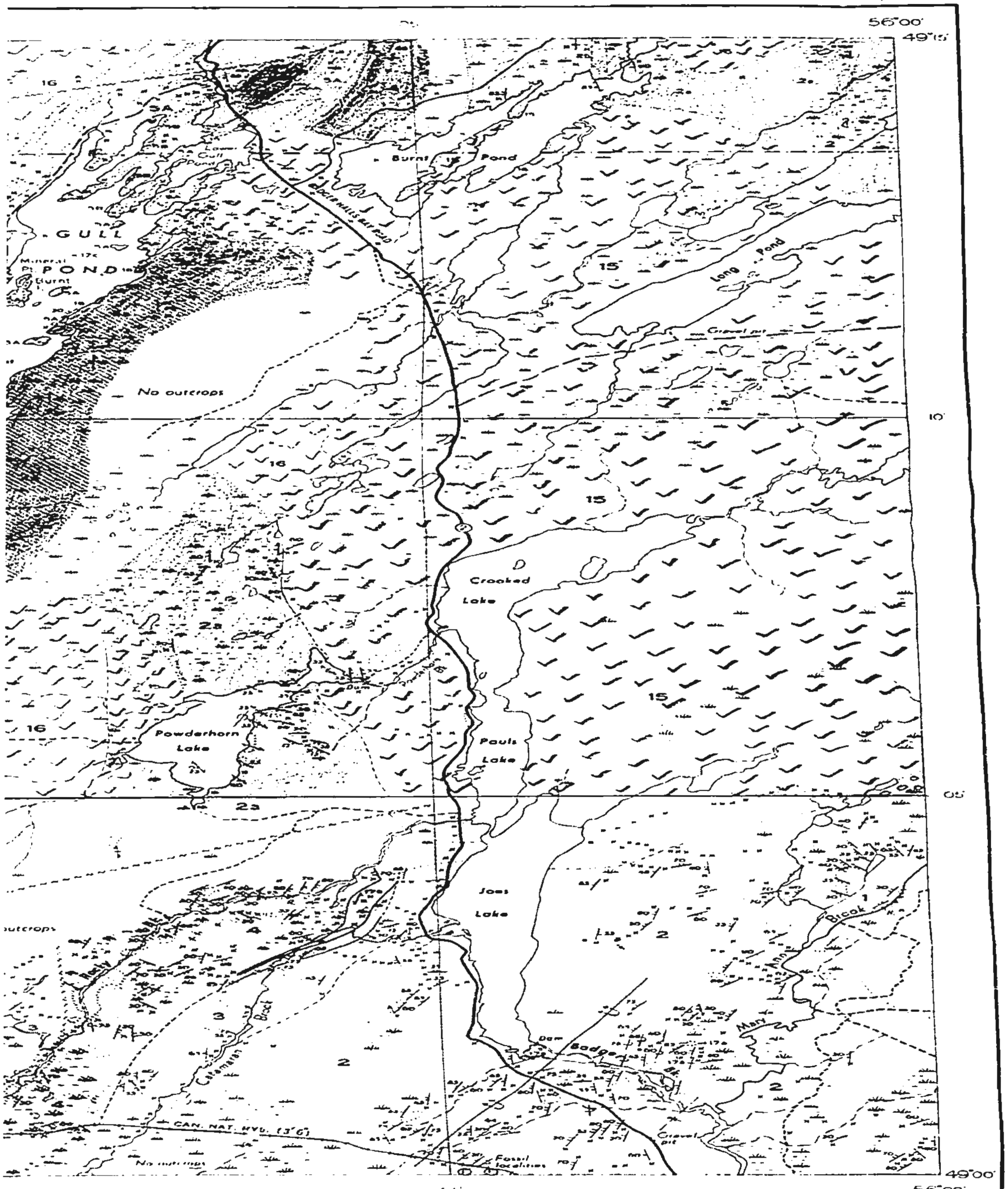
GULL POND
NEWFOUNDLAND

Scale: One Inch to One Mile = $\frac{1}{63,360}$

Miles

FIGURE 2

SHEET 12 H/1



Printed by the Surveys and Mapping Branch

LEGEND

Main highway
Other roads
Trail or portage
District boundary
Intermittent stream
Rapids
Marsh
Sand or gravel
Height in feet above mean sea-level 974

Air photographs covering this map-area may be obtained through the National Air Photographic Library, Topographical Survey, Ottawa, Ontario

DES

The land surface of this [illegible] ... can b[illegible] ... and areas. The [illegible] ... has a relat[illegible] ... and knobs ... north over v[illegible] ... similar volcan[illegible] and South Brook has an[illegible] ... Millertown Ju[illegible] ... Burnt Pond and C[illegible] ... along Bad[illegible] ... Southwes[illegible] of numerous parallel ...

The glacial cover consis[illegible] ... utilized for railroad ... deposits of sand and grav[illegible] was found in the map-area[illegible]

With the exception of B[illegible] west of Gull Pond all stre[illegible] canoe. Thus, away from roa[illegible] only by foot.

The oldest succession in[illegible] ... and volcanic orig[illegible] (1) consists predominantly ... greywacke and slate. Over[illegible] formation (2) of greywacke[illegible] slate, conglomerate, mino[illegible] Powderhorn Lake the form[illegible] ... porphyroblasts of biot[illegible] ... of the rocks to t[illegible] been altered to locally spo[illegible] succession of basaltic pillo[illegible]

The Crescent Lake forma[illegible] with some chert and greyw[illegible] flows of rhyolite, form an[illegible] apparently are interbedded[illegible] formation (5A) southwest [illegible] occurrences of tuffaceous r[illegible] strata or whether they repre[illegible] by faulting and tight folding[illegible]

Roberts Arm formation [illegible] pillowed basalt, with mino[illegible] Here the name Roberts A[illegible] volcanic assemblage, the [illegible] that is composed primarily[illegible] quantities of acidic volcani[illegible] agglomerate (5B), similar [illegible] formation (4).

Overlying the Badger B[illegible] members of the Springdal[illegible] correlated with similar roc[illegible] possible Devonian age has [illegible] Springdale and Ordovician[illegible]

The lowermost beds (6) [illegible] granitic rocks, and the c[illegible] lithologically similar to the[illegible] the Hodges Hill granite, out[illegible] Except for a few thick be[illegible] debris in the overlying for[illegible] conglomerate formation ([illegible] Springdale map-units of t[illegible]

Basic volcanic rocks (9,[illegible] They are dark green, grey, [illegible] amygdaloidal but rarely po[illegible] agglomerate are interlayer[illegible] and gabbro has intruded th[illegible] of Little Gull Pond, the v[illegible] are grey to greenish grey [illegible] the Springdale group is bas[illegible]

The rhyolite (11) south [illegible] layered and spherulitic rhy[illegible]

The coarse intrusive ro[illegible] gabbro and range in colou[illegible] of the intrusions are com[illegible] pink weathering, medium-[illegible] minerals increase in abund[illegible] the composition of the roc[illegible] bodies, and in irregular are[illegible] diorite to gabbro in compo[illegible] to poikilitic in texture, and [illegible] are common in the more b[illegible] a few inches or feet in [illegible] hornblende, and biotite [illegible] elongate masses with a mo[illegible] recrystallized blocks of vol[illegible]

Sill-like masses of diaba[illegible] island in the southeastern [illegible] abundant, microscopic gr[illegible] large body of massive, da[illegible] the northeast part of Daw[illegible] peridotite (17c), containing[illegible] a small island on Gull Pon[illegible]

Dykes of diabase, ande[illegible] map, are the youngest roc[illegible] east side of Powderhorn La[illegible]

The Ordovician rocks ap[illegible] plunging anticlinorium th[illegible] verse and strike faults an[illegible] observed, but extensive s[illegible] presence is strongly susp[illegible] types (3, 4) near Lake Bond[illegible] formation (3), and also th[illegible] geological contacts near [illegible] important strike fault in t[illegible] Pond, passing through M[illegible] control on the localization[illegible] the adjoining rocks have [illegible] is situated northwest of [illegible] extends across the map-[illegible] north of Burnt Pond on the[illegible] moved east in relation to[illegible] along which Mineral Point[illegible] located, terminates at the[illegible] miles to the east where a [illegible] on the north side of the fa[illegible]

The rocks of the Springd[illegible] plunging syncline.

The most important mi[illegible] and consists of two pyr[illegible] corderitic rocks near a [illegible] exploration at Mineral Poi[illegible] containing 1.62 per cent [illegible] along the Mineral Point st[illegible] the shear zone northwest [illegible] northwest shore of Powde[illegible]

[1]Espenshade, G. H.: G[illegible] Area, Nfld. [illegible]

[2]MacLean, H. J.: Geo[illegible] G[illegible]

[3]Twenhofel, W. H.: T[illegible]

[4]Hayes, John Justi[illegible]

PRE

END

o, diabase: 17b, pyroxenite: 17c, peridotite;
6, 15, and 16

e, gabbro; minor granite and granodiorite
minor quartz diorite and diorite.
t may be older than 7

14)
r basic lava with abundant intrusions of basalt
gabbro

layered, spherulitic, rarely porphyritic, acidic
and tuff

esicular lava; minor acidic lava,

acidic lava with abundant flow-breccia

lava; minor tuff, agglomerate, and flow-breccia

erate and tuff; 9a, red sandstone, shale,
asic agglomerate

erate and tuff; some basic conglomerate and basic lava

ith thin layers of conglomerate

1-5)
FORMATION: predominantly basaltic pillow lava;
lcanic rocks and tuff
te, latite, tuff, tuffaceous shale; minor greywacke;
chists derived from 5A and 5B

RMATION: grey, green, and red tuffaceous shale,
greywacke; undifferentiated basalt and rhyolite;

ate; minor conglomerate and basic lava;
imentary rocks; 2b, basalt

e; minor greywacke and slate

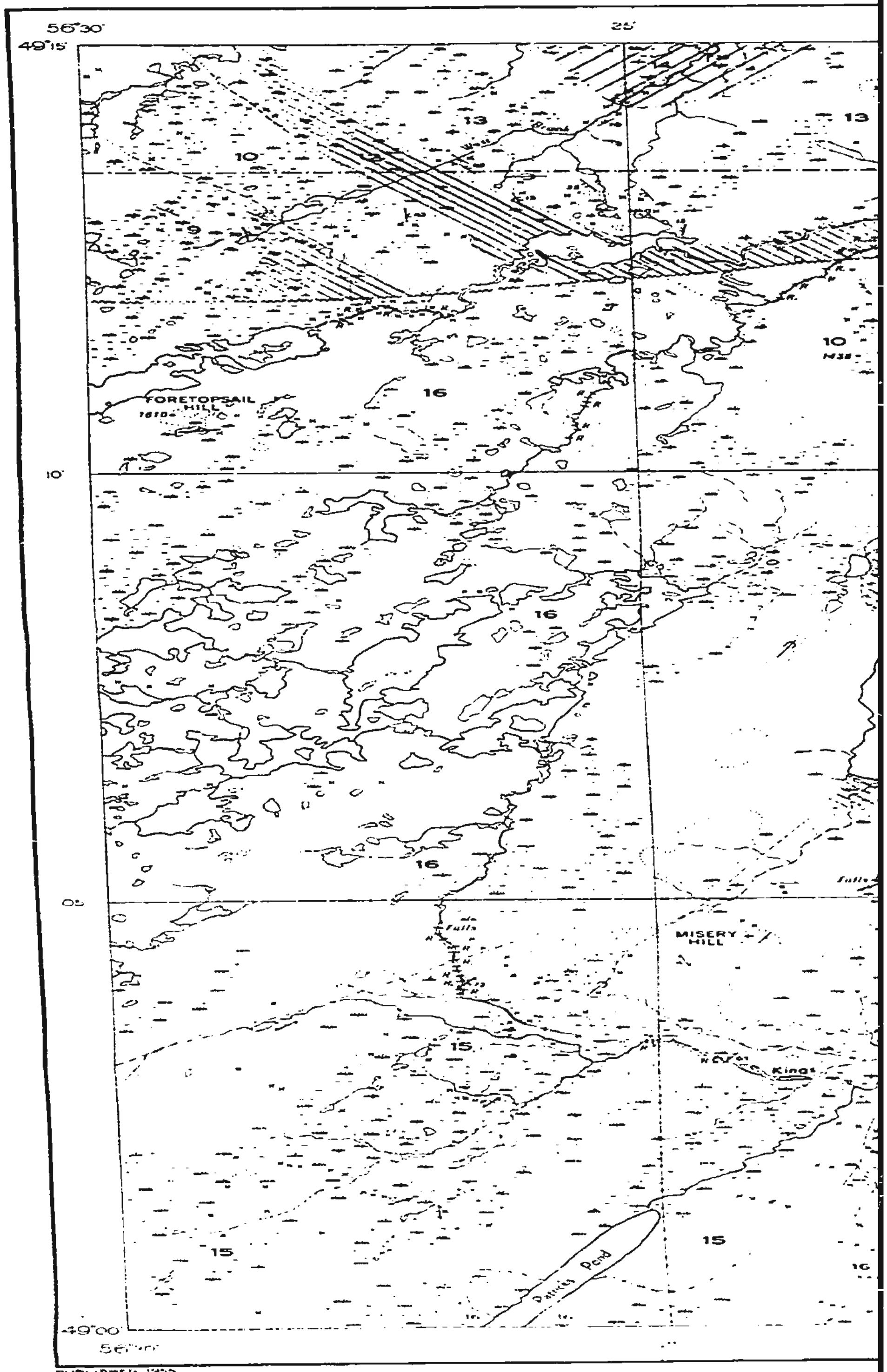
r side of bed unknown)
al, dip unknown)

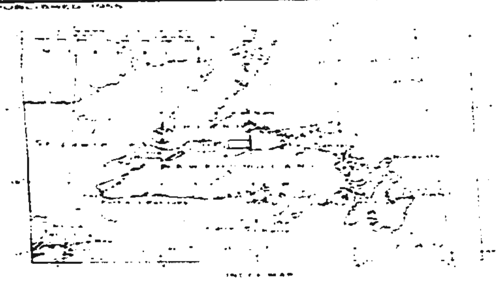
east of Badger-Halls Bay road by
1948 for the Geological Survey of
by J. Kalliokoski 1950, 1951, 1952

otes by J. Kalliokoski

gical Cartography Division, 1954

ic declination, 29° 32' West





2 of 2

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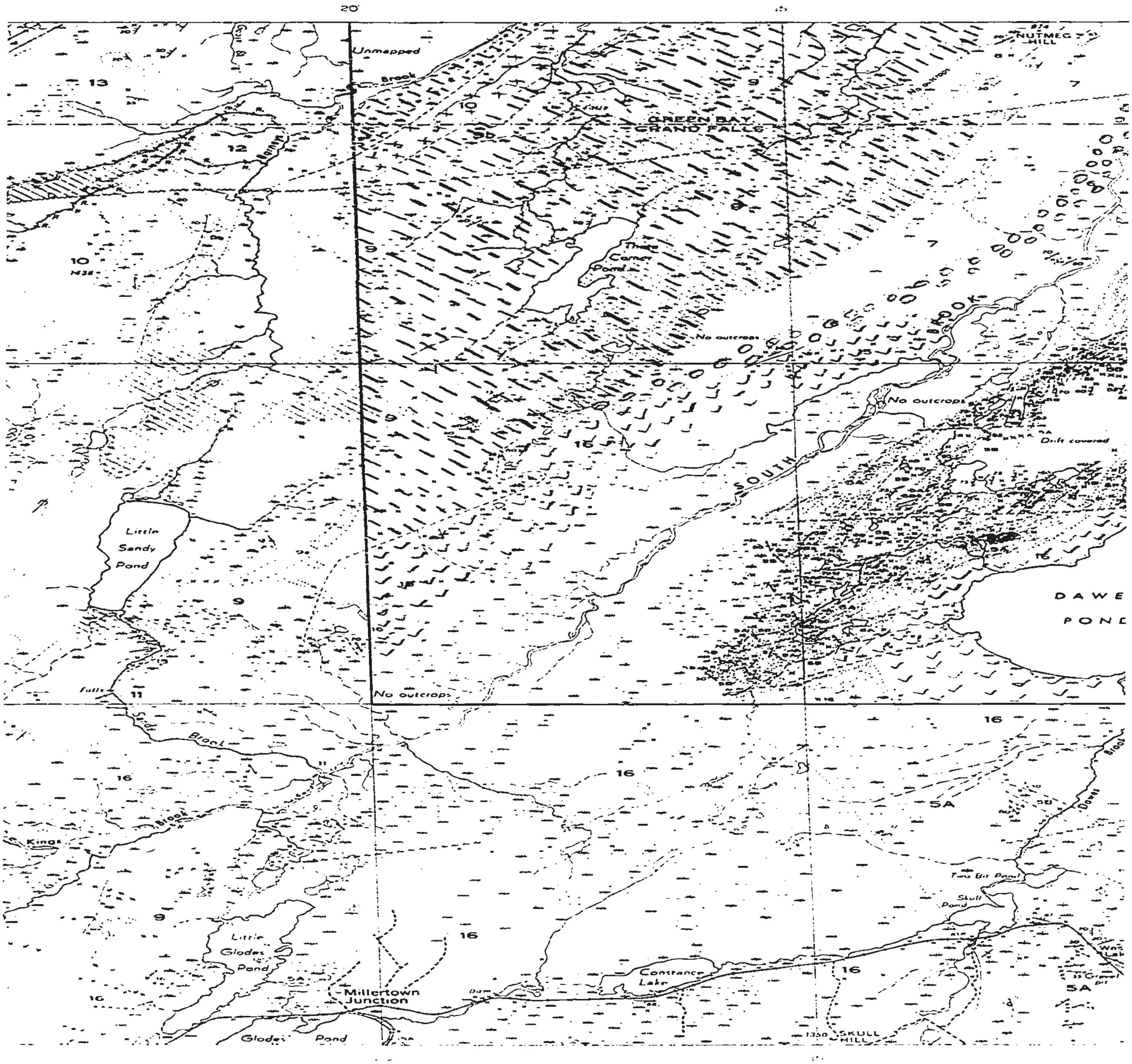


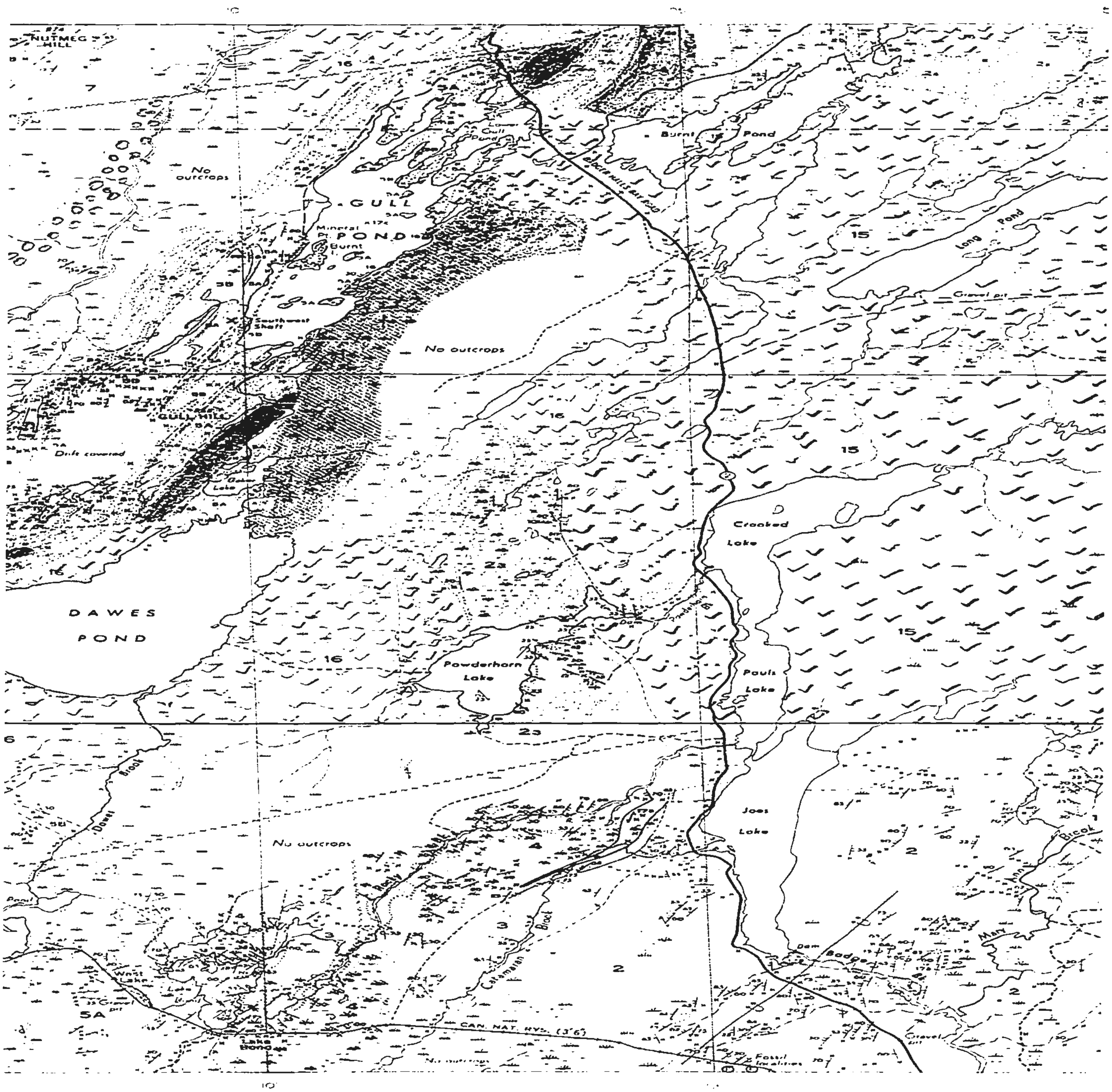
PRELIMINARY MAP 54-4

GULL POND
NEWFOUNDLAND

Scale: One Inch to One Mile = 1/63,360

FIGURE 2

SHEET 12



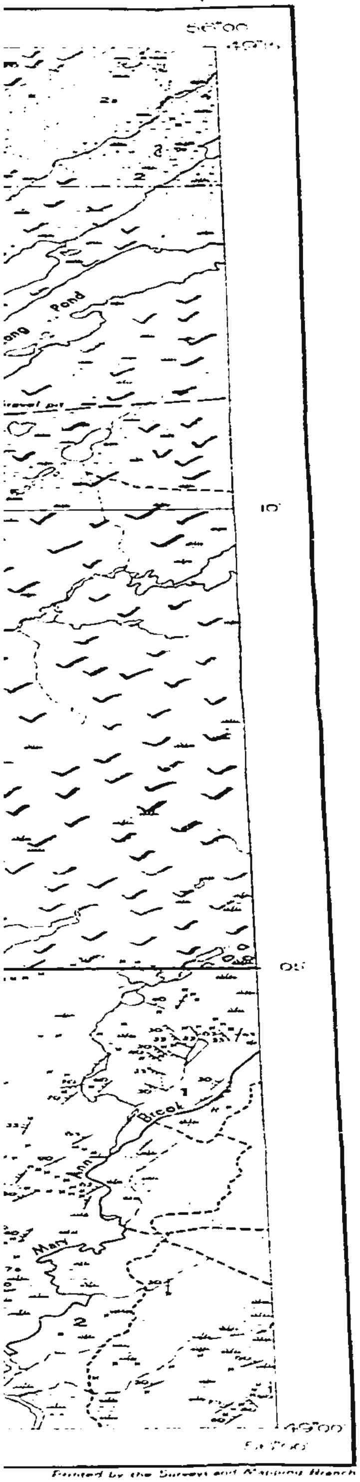
Printed by the Surve

LEGEND

Main highway
Other roads
Trail or portage
District boundary
Intermittent stream
Rapids
Marsh
Sand or gravel
Height in feet above mean sea-level

Air photographs covering this map-are
through the National Air Photo
Topographical Survey, Ottaw

SHEET 12 H/1



Printed by the Surveys and Mapping Branch

LEGEND

...above mean sea-level

...s covering this map-area may be obtained
...e National Air Photographic Library,
...aphical Survey, Ottawa, Ontario

DESCRIPTIVE NOTES

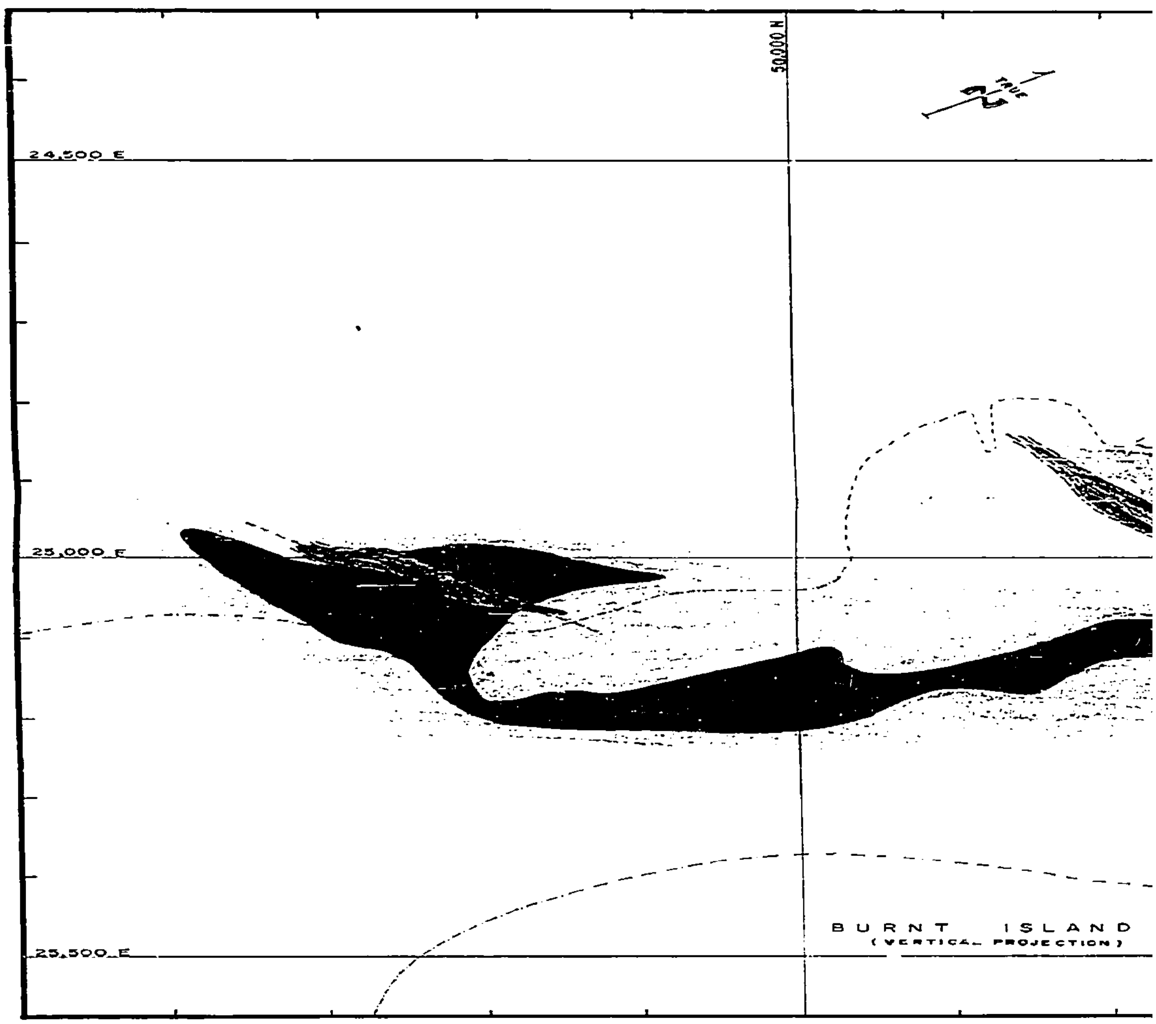
[illegible]

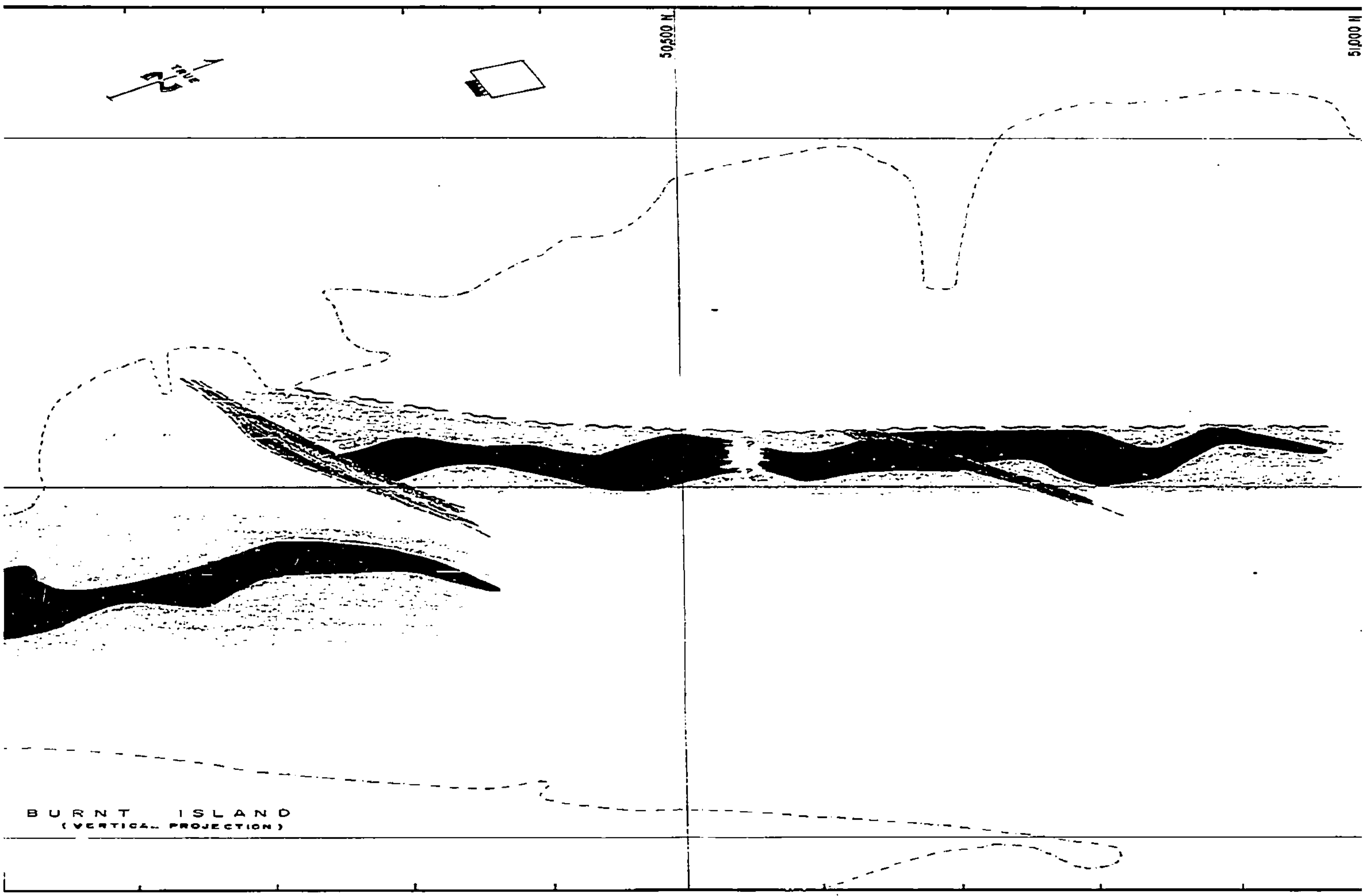
[illegible]

PRELIMINARY MAP 54-4
GULL POND
NEWFOUNDLAND

SHEET 12 H/1

1 of 1


50,000 N
24,500 E
25,000 E
25,500 E
BURNT ISLAND
(VERTICAL PROJECTION)


50,500 N
51,000 N
BURNT ISLAND
(VERTICAL PROJECTION)

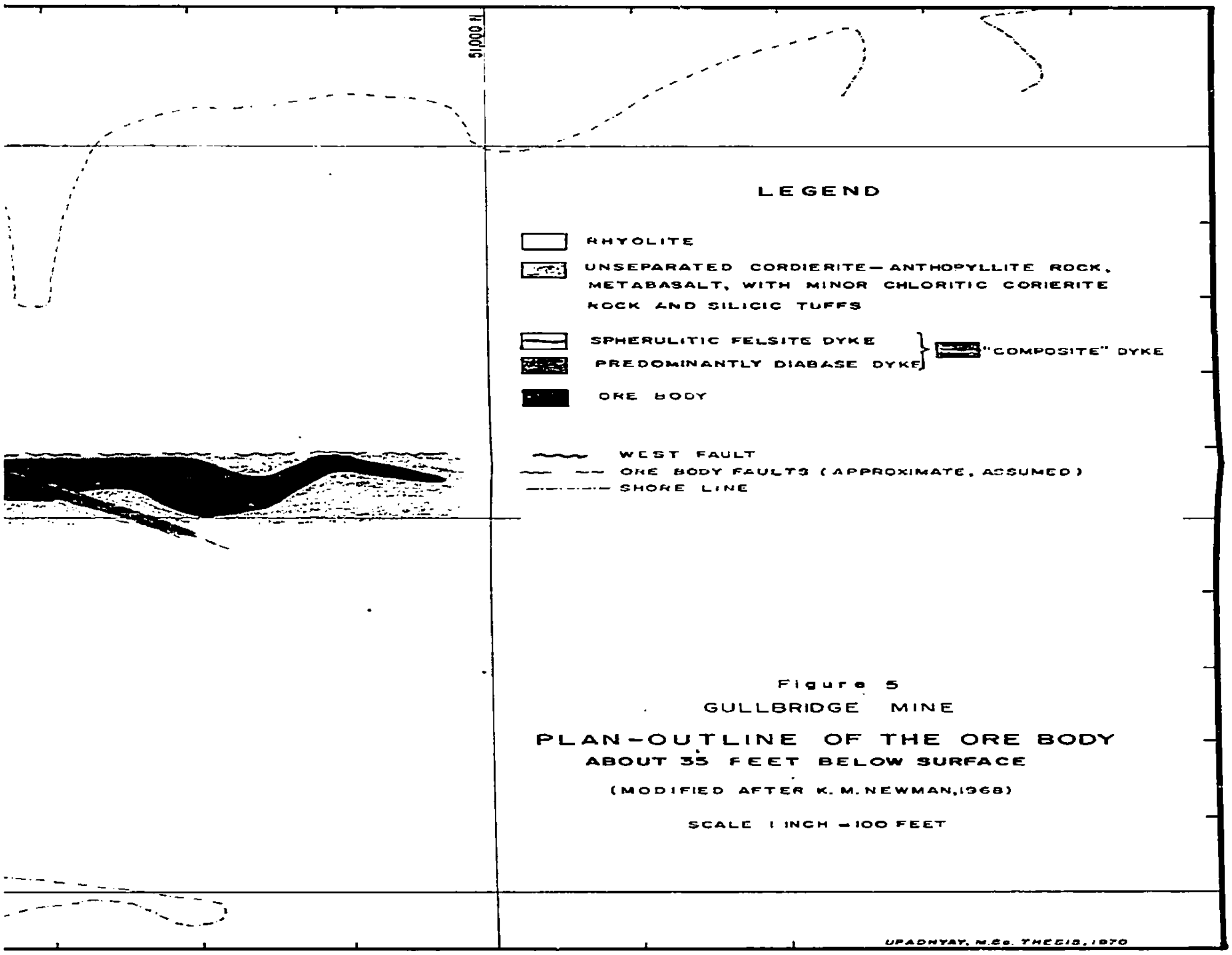
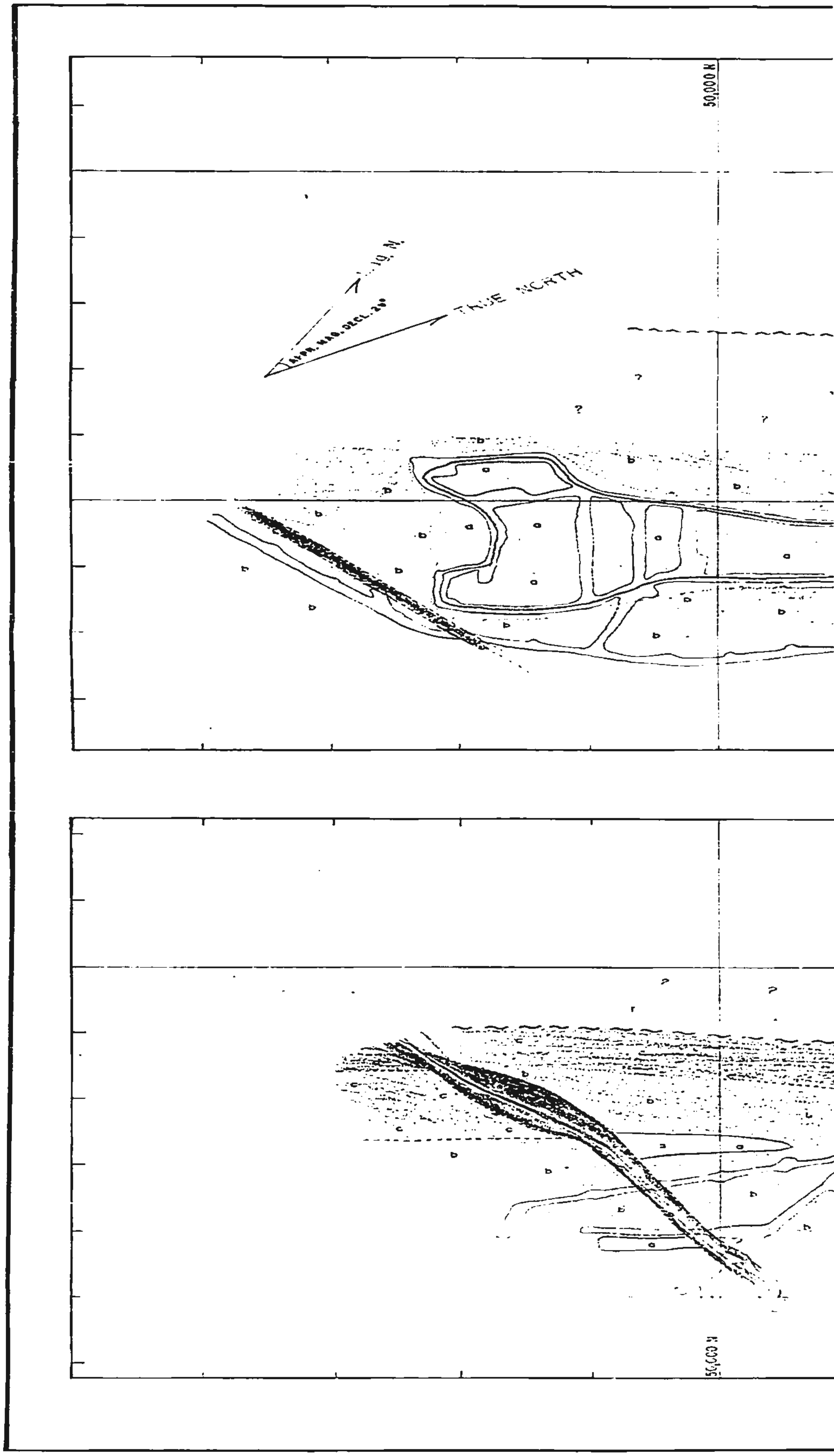
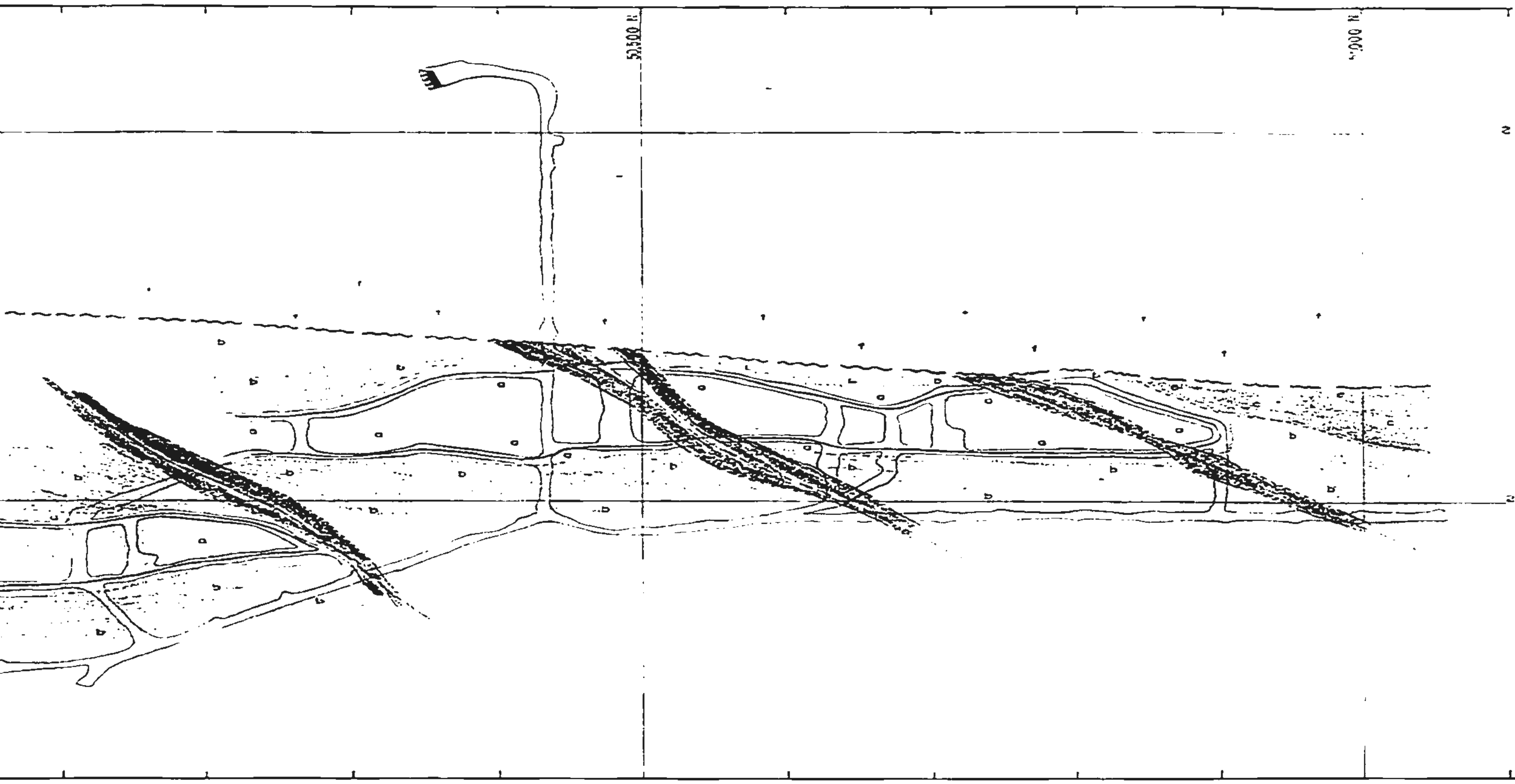


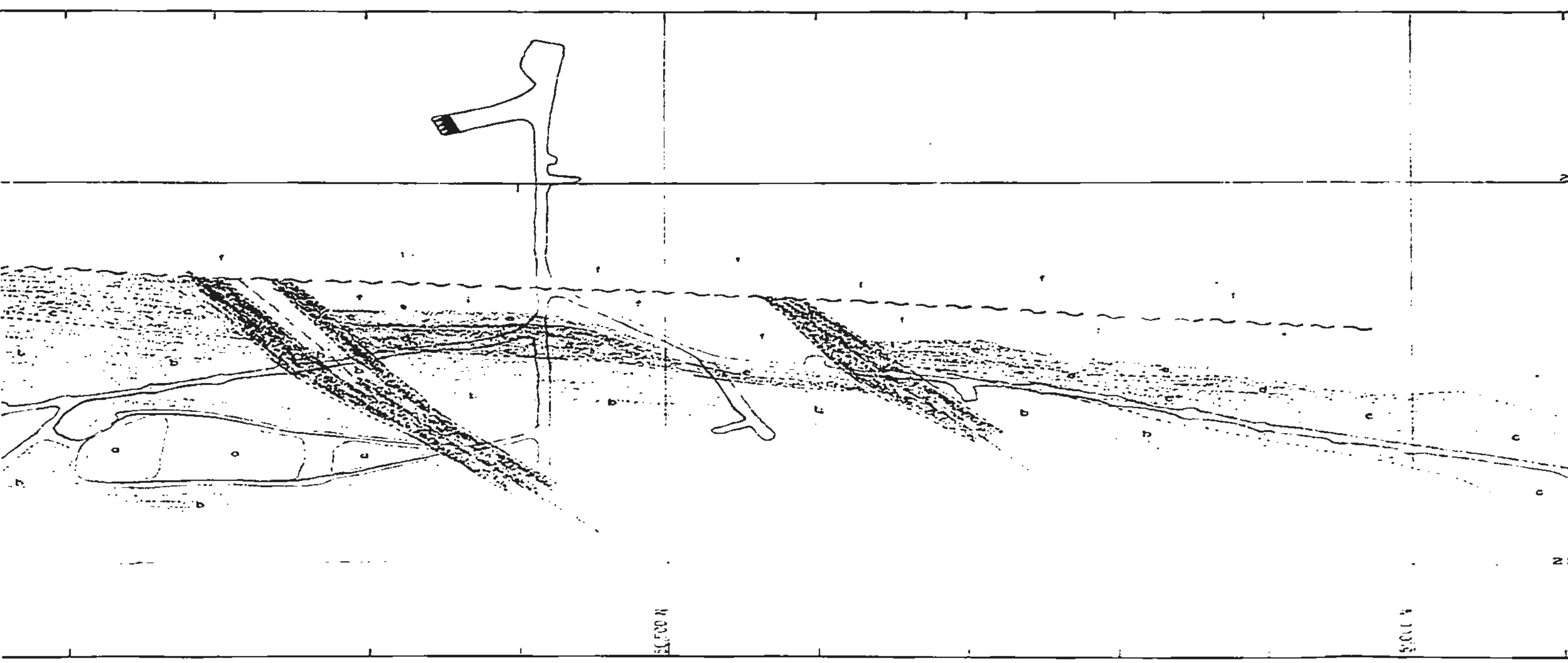
Figure 5
GULLBRIDGE MINE
PLAN–OUTLINE OF THE ORE BODY
ABOUT 35 FEET BELOW SURFACE
(MODIFIED AFTER K. M. NEWMAN, 1968)
SCALE 1 INCH = 100 FEET

1 of 1

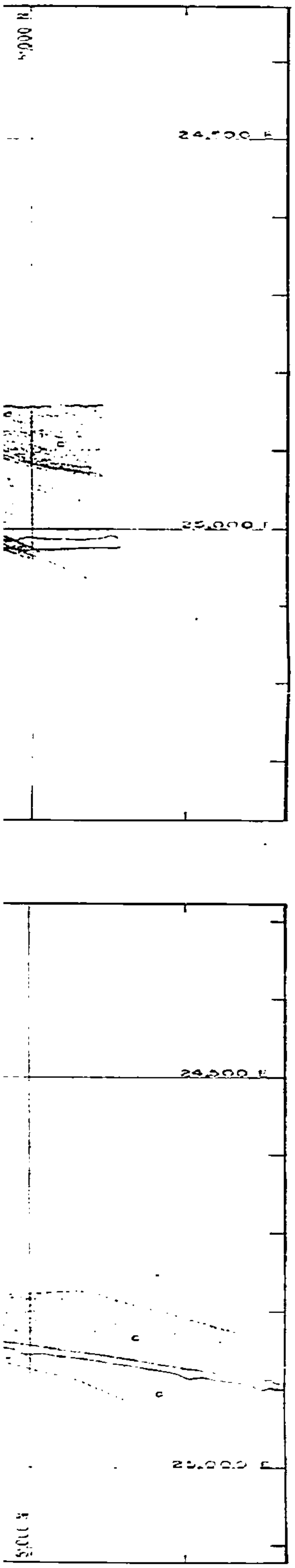




(A) 250 LEVEL



(B) 550 LEVEL



LEGEND

- RHYOLITE
- QUARTZ-SERICITE PHYLLITE
- IRON FORMATION
- METABASALT
- CORDIERITE-ANTHOPHYLLITE ROCK
- CHLORITIC CORDIERITE ROCK

- SPHERULITIC FELSITE DYKE
- PREDOMINANTLY DIABASE DYKE

"COMPOSITE" DYKE

- DRIFT
- OUTLINE OF THE ORE BODY
- GEOLOGICAL BOUNDARY (DEFINED, APPROXIMATE, ASSUMED)
- WEST FAULT (DEFINED, APPROXIMATE)
- ORE BODY FAULTS (DEFINED, ASSUMED)

NOTE: THE AVERAGE DIP OF THE VARIOUS ROCK UNITS IS 80° NORTHWEST

Figure 6

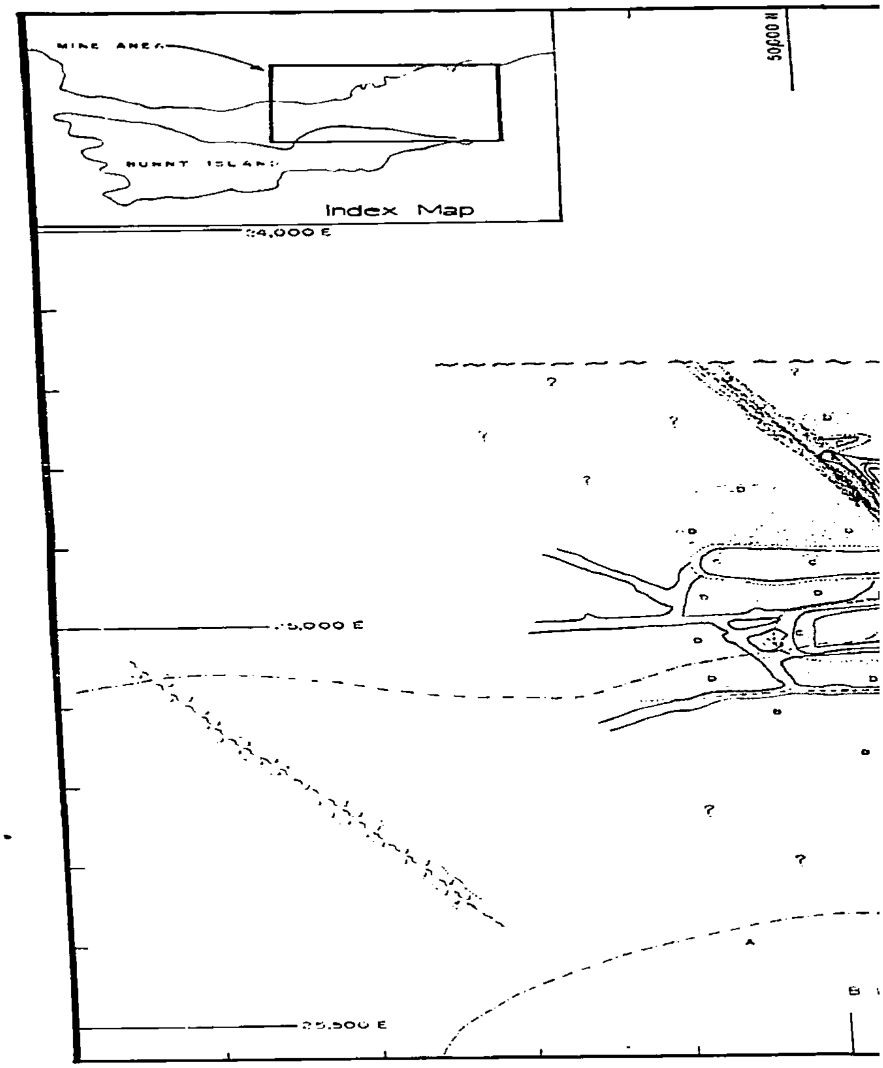
GULL BRIDGE MINE

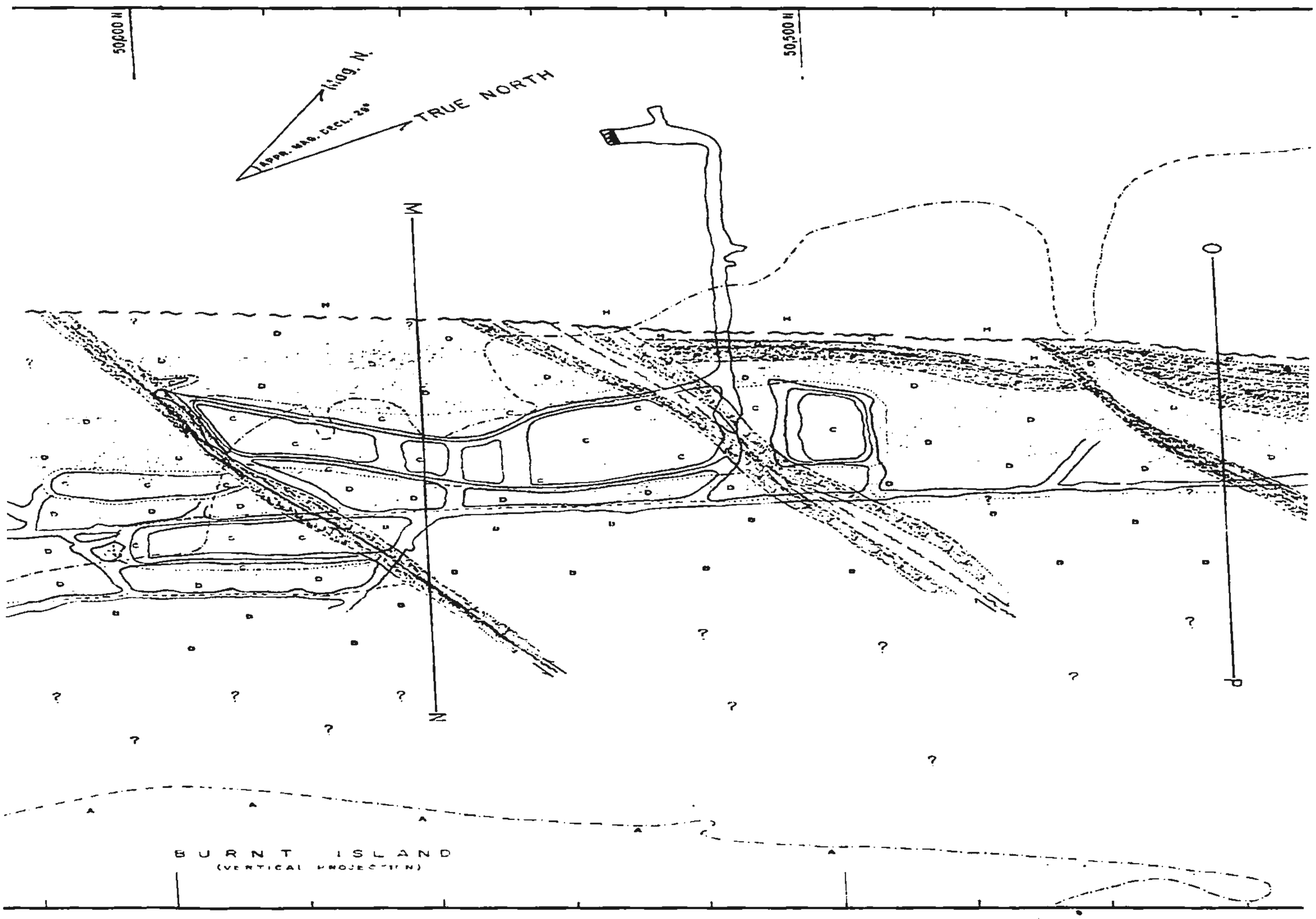
GENERALIZED GEOLOGICAL PLANS OF 250 AND 550 LEVELS

(Modified after K. M. Newman, 1968)

SCALE

UPADHYAY, M.Sc. THESIS, 1970


MINE AREA
BURNT ISLAND
Index Map
50,000 N
24,000 E
25,000 E
25,500 E


50,000 N
50,500 N
Mag. N.
TRUE NORTH
M
N
O
P
BURNT ISLAND
(VERTICAL PROJECTION)

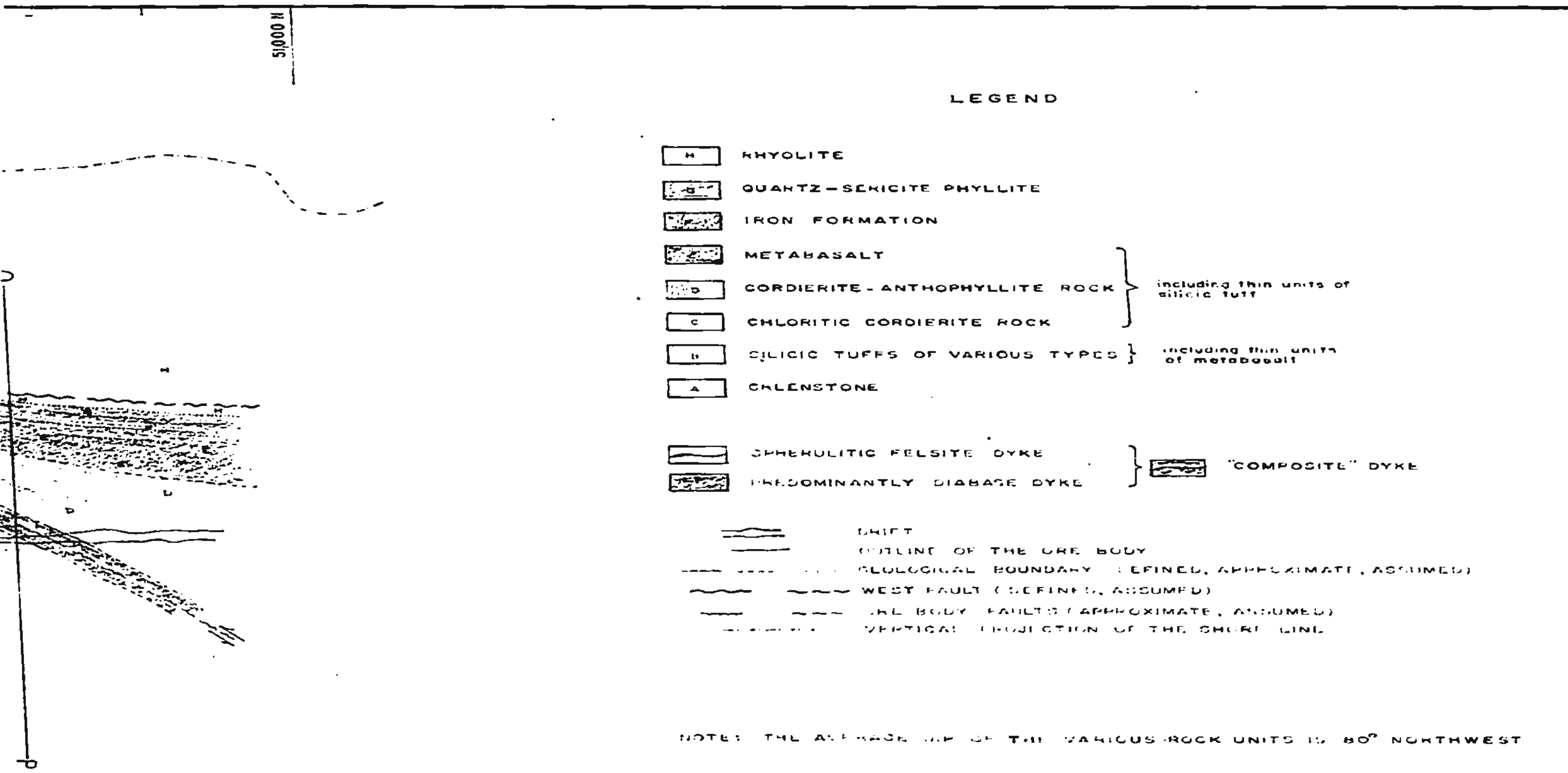


Figure 7

GULLBRIDGE MINE

GENERALIZED GEOLOGICAL PLAN OF THE MINE AREA AT 4

(MODIFIED AFTER K. M. NEWMAN, 1960)

Scale of feet

0 100

UPADHYAY,

CK } including thin units of silicic tuff

ES } including thin units of metabasalt

} "COMPOSITE" DYKE

BODY
(DEFINED, APPROXIMATE, ASSUMED)
D, ASSUMED)
APPROXIMATE, ASSUMED)
N OF THE SHORE LINE

ARIOUS ROCK UNITS IS 80° NORTHWEST

7
E MINE
OF THE MINE AREA AT 400 LEVEL

A, NEWMAN, 1968)

eet

100

UPADHYAY, M. Sc. THESIS, 1970