GEOLOGY OF A SULFIDE DEPOSIT IN LOWER PRECAMBRIAN
METAVOLCANIC-METASEDIMENTARY ROCKS NEAR BIRCHDALE,
KOCCHICHING COUNTY, MINNESOTA

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WILLIAM HAROLD LISTERUD

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ABSTRACT

The Birchdale area lies near the southern edge of the Superior Province of the Canadian Shield. The rocks are felsic-intermediate metatuffs, metasediments, granite, and mafic intrusives. The rocks are part of a northwest dipping, northeast trending monocline which is on the southern margin of a small granitic pluton, the Birchdale Granite. The greenstone rocks have been metamorphosed twice, first to upper greenschist or lower amphibolite facies during the regional metamorphism, and then to albite-epidote hornfels facies as a result of the intrusion of the Birchdale Granite. The two metamorphic events have obscured much of the original textures and structures of the rocks and made the origin of the sulfides more difficult to determine.

The sulfides of the Birchdale anomaly area are pyrrhotite, pyrite, chalcopyrite, sphalerite, pentlandite, and marcasite. The main sulfide horizon is in a series of interbedded metatuffs and graphitic metasediments, although disseminated sulfides are found throughout the section. Pyrrhotite is the principal sulfide, with only minor amounts of the other phases. The main sulfide horizon thickens, increases in sulfide content, and increases in graphitic material northeastward along strike. Trace element work shows apparent increases in cobalt and nickel, and an enrichment of copper over zinc northeastward. The sulfides appear to be syngenetic, based on their position in the sequence and their relationships with the enclosing rocks. The sulfides now show mineralogy, textures, and structures related to the metamorphic episodes.
INTRODUCTION

Purpose

The purpose of this investigation of the Birchdale anomaly area, Koochiching County, Minnesota, is to provide a better understanding of the geology and the potential for economic sulfide mineralization. Specific objectives were to determine the rock types present, the stratigraphy, the sulfide mineralogy and genesis, and to find possible ore indicators. Drilling by two companies has intersected uneconomic amounts of copper-nickel and copper-zinc sulfides.

Location

The Birchdale anomaly is a geophysical feature, located four miles south of the Canadian border and three miles south of the small town of Birchdale, in sections 15, 16, and 21, T.159N., R.27W., Koochiching County (Figure 1). The area is approximately 31 miles west of International Falls and 23 miles east of Baudette. Access to this area is by the sectionline road leading south from Birchdale.

Methods of Study

Work included geological mapping, logging and sampling of the cores from seven drill holes, preparation of some samples for thin and polished sections, and atomic absorption analysis. The outcrop area was
INTRODUCTION (Continued)

mapped on a topographic base map at a scale of
1" = 500'. All outcrops were visited and examined.
FIGURE 1: General Location Map

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Two hundred samples from outcrops and drill cores were collected. Sixty-nine thin sections and 178 polished sections were prepared from these samples. In addition, 41 thin sections prepared for R. W. Ojakangas of the Minnesota Geological Survey and 49 thin sections from the collection of the Exxon Corporation were examined. A few thin sections were polished for opaque mineral determinations. Microscope work consisted of studying relic textures and structures, and the determination of mineralogy in order to determine the original rock types. Opaque mineralogy, relative abundances, interrelationships of sulfides, and sulfide-host rock relationships were determined using reflected light. Several polished sections were etched in saturated chromic acid, using a method described by Arnold (1966), to determine amounts and relationships of monoclinic and hexagonal pyrrhotites.

Sixteen samples were selected and prepared for analysis by atomic absorption. Elements determined were copper, zinc, nickel, cobalt, and manganese. Analyses were done by A. Klaysmat of the Minnesota Department of Natural Resources, at Hibbing, Minnesota. The samples were selected from a correlative horizon, in four cores, and the entire section in core R-2-1. Five grams of the pulverized rock were dissolved in a beaker, by heating
with 25 ml HCl for 15 minutes, adding 15 ml HNO₃ and heating for 10-15 minutes, and adding 3-5 ml HF and heating for 5 minutes. The liquid was transferred to a volumetric flask and diluted to 100 ml with deionized water. The liquid was then filtered through #40 Whatman filter paper and the analysis completed. Digestion was not complete in any sample, but very nearly so in every sample.

Thin section heels and about 50 cut samples were etched in hydrofluoric acid and stained for potassium feldspar with a saturated solution of sodium cobaltinitrite, using the method described by Chayes (1952) and Rosenblum (1956). The cut samples were also stained for calcium feldspar, using the food dye amaranth, after a method described by Laniz, Stevens and Norman (1964). The etching of sawed and polished slabs gave useful information concerning obscure textures and structures.

The field work and most of the sample collecting and preparation were completed during the summer of 1972. The examination of samples and drill cores and the tabulation of data continued through 1973. The drill cores studied in this project are stored by the Minnesota Department of Natural Resources, Division of Waters, Soils and Minerals, in Hibbing, Minnesota.
Previous Work

Interest in the general Birchdale area began on the Canadian side of the Rainy River with the mapping of the Emo Area by Fletcher and Irvine in 1955. This work showed the occurrence of a complex series of Early Precambrian mafic volcanic, felsic-intermediate volcanic, and sedimentary rocks with a general northeast trend. Intruding these rocks are bodies of granitic and mafic rocks, and northwest trending quartz diabase dikes. In 1961, Goldich published K-Ar date for the Birchdale Granite of 2.4 b.y., but did no mapping in the area.

In the 1960's several companies explored the Minnesota continuation of the greenstone belt for sulfide deposits. Two of the most active companies were Ridge Mining Company and the Exxon Corporation. These companies covered much of the region with geological mapping, airborne geophysical surveys, and ground geophysical surveys in the Birchdale anomaly area. In 1967, Ridge Mining Company drilled three holes, S-43-1, S-43-2 and S-43-3, on the property of Myron Smart in the southeast corner of Section 16, T.159N., R.27W., in the central portion of the Birchdale anomaly. In 1969 and 1970, Exxon drilled four holes on this anomaly, two on each end (R-2-1, R-2-1A, R-2-2 and R-2-3). Figure 4 shows the locations of these holes. Drill cores
from these seven holes furnished a major portion of
the information for this study.

During the summer of 1969, 1971 and 1972, R. W.
Ojakangas, working for the Minnesota Geological Survey
and with support from the Minnesota Department of Natu-
ral Resources, mapped the area south of the Rainy River,
shown in Figure 2. Using the work of Fletcher and Ir-
vine in the Emo area, the sparse outcrop data, air
photographs, and data from drill cores, he produced a
map of the Birchdale-Indus area (Ojakangas, 1972b).
This mapping furnished the basic framework information
for a study of the Birchdale anomaly area (Figure 4).
Other work includes a soil geochemical study of the
Birchdale area begun in 1972 by the Minnesota Depart-
ment of Natural Resources.
Acknowledgments

The writer would like to express his appreciation to Dr. Ralph W. Marsden and Dr. Richard W. Ojakangas who served as advisors for this project for their advice, constructive criticism, and encouragement during all phases of the project. I also acknowledge, with thanks, the assistance of Dr. James A. Grant and the geology faculty at the University of Minnesota, Duluth. Special thanks go to Dr. Paul K. Sims and the Minnesota Geological Survey, Bear Creek Mining Company, and the Minnesota Department of Natural Resources for financial assistance and support of this project. Also deserving acknowledgments are my wife, Roxine, who supported and encouraged me during this study, and Margaret Lawson who typed this thesis.
REGIONAL GEOLOGY

Introduction

The region (Figure 2) is located near the southern edge of the exposed portion of the Canadian Shield in the Superior Province. All of the bedrock in the area is Precambrian in age. Rock exposures increase from practically none in the area five miles or more south of the Rainy River to fairly common north of the Rainy River in the Emo area. Generally, local relief increases northward from very little in the south to a maximum of about 75 feet in the northern part of the Emo area. The overburden generally thickens southward and consists of glacial tills, outwash and lake silts from Glacial Lake Agassiz. Ackroyd, Walton and Hills (1967) report that the glacial deposits in the southern portion of the region are generally less than 100 feet thick.

The region has been mapped by Fletcher and Irvine on the Canadian side of the Rainy River (Emo area), and by Ojakangas in Minnesota (Birchdale-Indus area). Figure 2 is a composite of their maps. Ojakangas published only a preliminary geologic map (1972b); therefore, descriptions of rock units in the region are after those of Fletcher and Irvine (1955). The rocks studied by this writer occur in the felsic-intermediate volcanics and sediments unit of Ojakangas and are described later.
Stratigraphy

The rocks in the region are Early Precambrian in age with the possible exception of the quartz diabase dikes that may be Middle Precambrian in age. The stratigraphic column of the region is shown in Figure 3. Thicknesses of the various units, or the total thickness are not known.

Biotite and Hornblende Schists

The only outcrops of siliceous tuffs and biotite and hornblende schists in this area are north of the Rainy River (Figure 2), however, they are equivalent to the biotite schists of Ojakangas which are projected in the area from the east (Southwick and Ojakangas, 1973). The age relationships of these rocks with other rock units is not clear. Fletcher and Irvine accepted the work done on these rocks by Lawson (1888) in the Rainy Lake region, which indicated that rocks similar to these were older than the other greenstone belt rocks.

The siliceous tuff is a greenish-gray color, is generally well-bedded, and is composed mainly of plagioclase and quartz with traces of biotite and hornblende. The biotite and hornblende schists are thin-bedded, a dark gray color, and are composed of plagioclase, quartz, hornblende and biotite.
Carpenter Sediments

The Carpenter sediments of Fletcher and Irvine are hornblende schists and garnetiferous hornblende schists. These schists are thin-bedded with local clots of red garnets and hornblende along bedding planes. They are well banded with alternating units of dark gray and light brown colors. This rock is composed of about 40% hornblende, 25% quartz, 20% plagioclase, and 15% diopside. Biotite and garnet are minor constituents, but locally important.

Dobie and Tait Volcanics

The Dobie and Tait volcanics of Fletcher and Irvine are felsic-intermediate and mafic volcanics. The felsic-intermediate volcanic rocks are: dacite, dacite porphyry, rhyolite, intermediate agglomerate, and tuffs. These rocks correspond to the felsic-intermediate volcanics and sediments of Ojakangas. The mafic volcanics in the Dobie and Tait unit consist of basalt, pillow basalt, basalt porphyry, amygdaloidal and vesicular basalt, and basic tuff and sediment. These rocks probably correspond to the mafic volcanic unit of Ojakangas, although he also includes metagabbro in his unit. Some of the sediments included by Ojakangas may correspond to the sedimentary units of Fletcher and Irvine, but poor exposure prohibits differentiation.
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<td>Quartz Diabase Dikes</td>
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<td>Carpenter Sediments</td>
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<td>Siliceous Tuff, Biotite and Hornblende Schists</td>
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1 After Ojakangas (1972b)
2 After Fletcher and Irvine (1955)
These volcanics crop out on both sides of the Rainy River in several bands separated by intrusive units. Each band has the same rock types present but in varying proportions.

The dacites are light greenish-gray when fresh and weather to a light buff color. They vary from aphanitic to porphyritic, with phenocrysts of quartz and plagioclase in the porphyritic units. Compositionally, they average about 45% each of quartz and plagioclase (oligoclase) with 10% of muscovite, biotite, chlorite, and hornblende. Rhyolites are usually thin-bedded and are interbedded with tuff. They resemble the dacites in hand specimens but contain abundant potassium feldspar.

The intermediate agglomerates are composed of dacite fragments up to a foot long in a matrix of volcanic rock fragments and tuffaceous material. The matrix is usually more mafic than the dacite fragments, darker in color, and commonly is more easily weathered, leaving the fragments standing in relief. The agglomerates are often interbedded with the dacite. The tuffs occur as thin units between flows and are generally rhyolitic in composition, light-colored, fine-grained, and thin-bedded.

The basaltic rocks in this unit are generally fine-
grained and massive, but pillowed, amygdaloidal, vesicular, and porphyritic types are common. The pillowed basalts are useful top indicators. The plagioclase composition is generally unknown due to alteration, but some of the larger phenocrysts are bytownite. Mineral assemblages and textures vary from a felty mat of amphibole in a matrix of plagioclase and epidote, to a granular hornblende, augite, hypersthene, and plagioclase rock. In part at least, the rock type depends on the metamorphic grade.

The mafic sediments, tuffs, and agglomerates are usually interbedded with the flows. The sediments and tuffs are irregularly bedded, fine-grained, and composed of hornblende, diopside, plagioclase and quartz. They are schistose, and locally garnetiferous. The agglomerates are composed of fragments of porphyritic and fine-grained, massive basalt in a matrix of tuffaceous material. These rocks are a dark greenish-gray color.

Mather Sediments

The Mather sediments of Fletcher and Irvine apparently do not constitute a separate unit in Minnesota. Exposures two miles south of the international border, on strike with the Mather sediments, consist of different lithologies, dominantly felsic-intermediate tuffs.
(Ojakangas, 1974, personal communication). The Mather sediments in Canada consist of graywackes, conglomerates, and iron formations, in three belts. The southernmost belt can be traced into Minnesota along an anomalous magnetic high. The prominent magnetic high, caused by magnetic iron formations, has been drilled on both sides of the border.

The graywacke is fine-grained with irregular and graded bedding. It is dark gray and greenish-gray when fresh, and weathers to a sandy-textured, grayish-brown color. A spotted appearance is common due to poikilitic biotites. The composition is generally 25% quartz, 45% plagioclase, 30% biotite, and minor hornblende, garnet, and accessory minerals. Potassium feldspar is common as an alteration product along fractures. The conglomerate is minor and occurs near the base of the unit. It consists of rounded cobbles and pebbles of quartzite, granite, and dacite in a matrix of graywacke.

The iron formation occurs in several bands in the region. They do not crop out, but have been defined by magnetic anomalies and diamond drilling. They are usually 35-40 feet thick, and "... consist of garnetiferous mica and hornblende sedimentary schists with disseminations and tiny bands of finely granular magnetite". (Page 12, Fletcher and Irvine, 1955). Pyrite and hema-
tite are rarely found but Fletcher and Irvine believe the magnetite to be the result of recrystallization of hematite.

**Basic Intrusives**

The basic intrusives described by Fletcher and Irvine have not been observed to crop out in the Minnesota portion of the region. They are norites, hypersthene gabbros, diabasic gabbros, hornblende diorite, and gabbros. These rocks are usually found associated with granitic rocks of the area.

Norite, hypersthene gabbro, and diabasic gabbro occur as a large body in Dobie Township in a belt around a granitic body. The diabasic gabbro is coarse-grained and is composed of 70% augite and 10% hypersthene. This rock forms the central part of the intrusive. Hypersthene gabbro appears to partially enclose the diabasic gabbro, is medium-grained, and is composed of 50% labradorite, 30% augite, and 20% hypersthene. The texture is equigranular. The norite is fine to medium-grained and occurs only on the southern margin of the intrusive. It is 75% hypersthene with minor labradorite, enstatite, olivine. Associated with this phase are small, currently uneconomic bodies of massive and disseminated pyrrhotite and pentlandite. Another large hypersthene gabbro intrusive is found in Carpenter
and Lash Townships; it is fine to medium-grained, greenish-gray in color, and composed of labradorite, hypersthene, and augite. Several smaller, dark gray to greenish-black, fine to medium-grained, and equigranular, hornblende diorite and hornblende gabbro bodies occur scattered throughout the region.

Granitic Intrusives

Granitic intrusives are found in both the Emo and Birchdale-Indus areas and are more common in the Emo area than in the Birchdale-Indus area (Figure 2). The rock types include granodiorites, monzonites, and aplite and pegmatite dikes. These rocks are commonly composed of potassic and sodic feldspars, quartz, biotite, hornblende, and accessory minerals. The only complex pegmatite known in the region, a dike three feet wide, is associated with the Birchdale Granite.

Diabase Dikes

The youngest rocks in the Emo and Birchdale-Indus areas are the quartz diabase dikes of Fletcher and Irvine. These correspond to the gabbro-diabase dikes of Ojakangas. The dikes have a common strike of about N.45°W. and range in width from 100-400 feet. These rocks often form the cores of low ridges that are conspicuous topographic features in the region. The dikes are generally fine-grained at the contacts and medium
to coarse-grained in the center. The mineralogy is labradorite, augite, interstitial quartz, magnetite, ilmenite, pyrite, and chalcopyrite. The usual texture is intergranular, where the augite is interstitial to the plagioclase laths.

**Structure**

The rocks in the Emo and Birchdale-Indus areas are not well enough exposed to permit a detailed structural analysis. Ojakangas and Fletcher and Irvine have utilized available data from drill cores, air photographs, geophysics, and outcrops to form an interpretation of the regional structure. They find that the major folds in the region generally trend east to northeast. Fletcher and Irvine (1955) indicate three major folds in the Emo area, two anticlines and a syncline. The limbs of the folds dip steeply and have variable plunge angles. Drag folds have also been found in several locations. Ojakangas (1972b) indicates the occurrence of a syncline and anticline in the Birchdale area. The limbs of these folds dip steeply. Some minor interpretive faults based on lineaments appear to offset diabase dikes and may indicate late movement among older faults; the total displacement along the faults is unknown. Most faults cannot be traced more than a mile. One major northeasterly trending lineament observed on air photographs can
be traced for about six miles.

**Metamorphism**

The regional metamorphic grade, as indicated by Ojakangas (1970) and Fletcher and Irvine (1955), is generally upper greenschist to lower amphibolite facies. Fletcher and Irvine report varying degrees of contact metamorphism, from low to high grade, around some intrusive bodies. They also observe that the regional metamorphic grade in the Mather sediments decreases away from the granitic intrusives. Their inference from this fact is that the regional stress was caused by the intrusion of the granites. Yardly and others (1959) have interpreted the border region granitic intrusives as being post kinematic.

**Mineralization**

The most prominent mineral deposits in the region are the iron formations in the Mather sediments of the Emo area and in the felsic-intermediate volcanics and sediments of the Birchdale-Indus area. There are several belts of magnetic iron-formation indicated in the Emo area. The longest has a length of seven miles (Fletcher and Irvine, 1955), and continues for 28 miles in a southwesterly direction in Minnesota. The iron-formation has been tested by drilling in both Ontario and Minnesota. Fletcher and Irvine (1955) report that
the iron-formation unit is about 40 feet thick and is interbedded with other steeply dipping sediments. "A representative sample ran 34.8 percent iron and 49.0 percent solubles (mostly silica). On grinding to 100 mesh, 89.1 percent of the iron content was recovered as a magnetic concentrate containing 65.6 percent iron." (Page 25, Fletcher and Irvine, 1955).

Sulfides are common throughout the region, but they are usually very low in base metal values. Two of the more encouraging occurrences are nickel sulfides occurring in the norite phase of a mafic intrusive in Dobie Township, Ontario, and the zinc sulfides in rock associated with the Birchdale anomaly.

Sulfides in the norite of the Dobie Township basic intrusive occur as disseminations and irregular patches without structural control (Fletcher and Irvine, 1955). The sulfide minerals are pyrrhotite, pyrite, pentlandite, and chalcopyrite with very minor violarite and sphalerite. Pyrrhotite is the principal sulfide and pentlandite the main nickel mineral. This deposit has been drilled and is fairly thoroughly explored. Fletcher and Irvine (1955) report that a grab sample from a massive sulfide zone from a test pit in the norite, assayed at 2.52% nickel with a trace of copper, but the more abundant disseminated zones contain about 0.3%
each of copper and nickel

The sulfide zones in the rocks associated with the Birchdale anomaly are low in base metal values. One two-foot thick zone in drill hole S-43-2 contained 4.06% zinc and 0.25 ounces of silver. This occurrence will be discussed in more detail later in this report.

Massive sulfide crops out about two and a half miles south of Indus. This outcrop is located on both sides of a northwest trending diabase dike. The sulfide occurs in the felsic-intermediate tuffs cut by the dike, and is mostly pyrite and pyrrhotite. A shaft and several test pits were dug in the outcrop many years ago. The results of this exploration work are not known. No assay information is available for this area, but an examination of polished sections shows that base metal values are low.
GEOLOGY OF THE BIRCHDALE ANOMALY AREA

Introduction

The Birchdale anomaly is located near the southern edge of the Birchdale Granite in an Early Precambrian greenstone belt. The rock-types here are mainly intermediate metatuffs and metasediments, which have been intruded by gabbroic rocks. These rocks dip steeply to the northwest and strike about N.45° E. The probable cause for the EM and magnetic anomalies is a graphitic zone which also contains variable amounts of sulfides. Almost all of the rocks in the area contain traces of sulfides. Because rock outcrops are scarce, this study of the rocks and sulfide mineralization in the Birchdale anomaly area is largely based on the study of core from seven drill holes. The rocks that crop out are all stratigraphically above the sulfide zones. Figure 4 shows the locations of outcrop areas and drill sites. The drill holes used in this study and the basic data for each are listed in Table 1.

TABLE 1: Drill Hole Data

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<tr>
<th>Hole #</th>
<th>Location</th>
<th>Direction</th>
<th>Angle</th>
<th>Length</th>
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<td>R-2-2</td>
<td>NW-NE, Sec. 21, T.159N., R.27W</td>
<td>S.60° E.</td>
<td>-45°</td>
<td>763'</td>
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<td>S.65° E.</td>
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<td>524'</td>
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<td>S-43-3</td>
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<td>450'</td>
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<tr>
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<td>R-2-1</td>
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<td>S.50° E.</td>
<td>-45°</td>
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Stratigraphy

Introduction

The rocks in all seven holes are similar, but correlative horizons have been identified in only the five northernmost holes. R-2-2 and R-2-3 are located in the southwestern part of the area and have not been correlated with the other five holes which are 1500' to 2000' to the northeast. The rocks intersected in R-2-2 and R-2-3 will be described briefly at the end of this section. The writer's logs and the company logs for these and the other holes can be found in appendices A and C, respectively. The stratigraphic column for the area in which correlations have been established is shown in Figure 5. It should be noted that this column represents a strike length of only about 1200'. Each unit is identified by letter in the column and text. The relationships of the rock units observed in the drill core are shown in the fence diagram (Figure 6).

Unit A

The metasediments of Unit A are very fine-grained, gray, and are intersected only in drill hole R-2-1. These rocks are cut by a few dioritic stringers, but are generally massive. The rock is composed of plagioclase, biotite, epidote, calcite, chlorite, amphiboles, ortho-
FIGURE 4: Outcrop Map of Birchdale Area
clase, quartz, and opaques, with trace amounts of pyrrhotite and chalcopyrite.

Unit B

The metasediments of Unit B are intersected in all five of the drill holes on the main part of the anomaly. The rocks are fine to medium-grained, hard, dense, gray to brown to green, biotite-rich, and usually massive. Some faint banding and possible graded beds were observed. The metasediments are recrystallized and have many healed fractures. The rock is composed of plagioclase, quartz, and biotite, with minor orthoclase, chlorite, muscovite, epidote, calcite, sphene, and opaques. Trace amounts of pyrrhotite, chalcopyrite, sphalerite, pentlandite, and pyrite are found disseminated throughout the unit. The unit becomes more mafic to the southwest, with increasing amounts of amphibole, chlorite and epidote, and a decrease in plagioclase, quartz, and biotite.

Unit C

Unit C, an agglomeratic metatuff, is found in all five drill cores. The unit is relatively thin with very indistinct contacts. The fragments are lapilli size and larger, and are usually slightly more mafic than the matrix material. The matrix material is compositionally about the same as unit D.
**FIGURE 5: BIRCHDALE AREA STRATIGRAPHIC COLUMN**

<table>
<thead>
<tr>
<th>LOWER PRECAMBRIAN</th>
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<tbody>
<tr>
<td></td>
<td>glacial till and lake sediments</td>
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<tr>
<td></td>
<td>L</td>
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<tr>
<td></td>
<td>granite pegmatite dikes *</td>
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<tr>
<td></td>
<td>K</td>
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<tr>
<td></td>
<td>trachy-andesite dikes *</td>
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<td></td>
<td>J</td>
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<tr>
<td></td>
<td>Birchdale granite *</td>
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<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>andesite and diorite intrusives *</td>
</tr>
<tr>
<td></td>
<td>H</td>
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<tr>
<td></td>
<td>metagabbro and metabase *</td>
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<tr>
<td></td>
<td>G</td>
</tr>
<tr>
<td></td>
<td>felsic-intermediate metatuffs</td>
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<tr>
<td></td>
<td>F</td>
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<td>interbedded metasediments and metatuff:</td>
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<td>tuffaceous metasediments</td>
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<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>metasediments</td>
</tr>
<tr>
<td></td>
<td>A</td>
</tr>
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</table>

*intrusive unit
FIGURE 6: Fence Diagram of Drill Holes
Unit D

The tuffaceous metasediments of Unit D are fine-grained, gray to green to brown, sheared, foliated, and sometimes graphitic. The rocks vary from massive to well banded. They are composed of varying amounts of plagioclase, quartz, amphibole, biotite, epidote, chlorite, carbonaceous material, sphene, and opaques. Several small massive to semi-massive pyrrhotite zones occur in the drill cores towards the northeastern end of the area. Commonly, small amounts of pyrrhotite, pyrite, chalcopyrite, pentlandite, and sphalerite are disseminated throughout. The rocks appear to become slightly more mafic towards the southwest.

Unit E

Unit E is comprised of interbedded graphitic metasediments and metatuffs. This is the main sulfide-bearing horizon in the column. The metasediments are usually very fine-grained gray to black, and frequently well fractured. The metatuffs are usually coarser grained than the metasediments. They are greenish and are strongly sheared. Compositionally, the metasediments are plagioclase and quartz, with minor amounts of biotite, epidote, chlorite, and varying amounts of graphite and opaques. The metatuffs are composed of amphibole, chlorite, plagioclase, quartz, biotite, epi-
dote, calcite, and opaques. Sulfides are irregularly distributed and vary from a few percent as disseminated grains, or interstitial fillings, to massive zones up to eight feet thick. The massive sulfides contain fragments of the metasediments and metatuffs. The main sulfide is pyrrhotite, with trace amounts of pyrite, chalcopyrite, sphalerite, and pentlandite. The amount of sulfide and graphitic material in this unit increases towards the northeast. The unit also appears to thicken somewhat in this direction.

**Unit F**

The metatuffs of Unit F are felsic to intermediate in composition. They are fine to very fine-grained, light gray to buff to light green, and are massive to thin banded. Lapilli-sized fragments are common throughout the unit but appear to increase in abundance to the southwest. An agglomeratic zone occurs from 112 feet to 165 feet in hole S-43-2. In general the fragments of andesite porphyry have about the same composition as the matrix material. Outcrops of Unit F are massive and do not show the banding commonly observed in the drill cores. Although the rock is recrystallized, ghosts of shards were observed in one thin section. The metatuff is usually composed of plagioclase, quartz, potassium feldspars, garnet, epi-
dote, calcite, sphene, amphibole, and opaques. Sul-
fides occur as fine disseminated grains and blebs com-
posed of pyrrhotite and pyrite, with minor chalcopy-
rite, sphalerite, and pentlandite. In this unit, there
appears to be an increase in mafic mineral content to
the southwest, which is similar to variations noted in
other units. An increase in potassium feldspar is noted
towards the top of the unit with up to 20-30% potassium
feldspar in some samples.

Unit G

Unit G, which is composed of the mafic igneous
rocks, was intersected by all five drill holes. It
includes the medium-grained metagabbro in the basal
section of R-2-1, metadiabase or metabasalt at the
base of S-43-2, and metadiabase-metagabbro in the
middle portions of S-43-2, S-43-3, S-43-1 and R-2-1.
These rocks are placed in the same unit because of
their similar compositions, and the lack, in some
cases, of definite evidence indicating an extrusive
or intrusive origin. In general, these rocks are
massive, dark green, and composed of plagioclase,
amphiboles, epidote, calcite, apatite, biotite, chlor-
ite, and opaques. Trace amounts of pyrrhotite, pyrite,
chalcopyrite and pentlandite occur.
**Unit H**

Unit H includes metadiorite and meta-andesite intrusives that are generally found as small irregular zones and stringers throughout the area. The metadiorites are usually medium-grained, black and white, and have a granitic texture. The meta-andesites are usually fine-grained, green, and porphyritic. These rocks do not appear to persist from one hole to the next and may occur as irregular dikes. They are composed of plagioclase, biotite, quartz, amphibole, calcite, epidote, and opaques. Traces of pyrrhotite and chalcopyrite are present. The relationships of these rocks to other intrusives are poorly known, but the intrusive relationship with rocks of Unit G, in the center part of R-2-1, suggests that the diorite is younger than Unit G.

**Unit I**

Unit I is the Birchdale Granite. Granite outcrops extensively northwest of the Birchdale anomaly and occurs as small veins and stringers throughout the drill cores and as a 97 foot thick unit at the top of hole S-43-2. It is massive, pink, medium-grained, and has a granitic texture. Near the contacts with Unit F the granite contains many xenoliths of metatuff and has slightly more mafic minerals. The Birchdale Granite is
composed of quartz, sodic plagioclase, potassium feldspars, and biotite with minor amphibole, epidote, calcite, and opaques.

Unit J

Unit J includes a series of trachyandesite dikes that were observed in outcrop. The dikes trend N. 75-80° E. and are usually 1 to 5 feet wide. The trachyandesite dikes are generally very fine-grained with phenocrysts of plagioclase and, rarely, potassium feldspar. The plagioclase phenocrysts are up to seven millimeters long. The plagioclase and mafic minerals have been somewhat altered, probably from contact metamorphism. These dike rocks are commonly composed of plagioclase, potassium, feldspars, quartz, biotite, amphibole, epidote, sphene, apatite, and opaques. Traces of pyrrhotite and chalcopyrite are also found in these rocks. One of these dikes may both intrude and be intruded by the Birchdale Granite. The inconsistent relationships with the Birchdale Granite is interpreted as an indication that the dikes were penecontemporaneous with the granite intrusion.

Unit K

Unit K, granitic pegmatite, cuts both the Birchdale Granite and the trachy-andesite dikes. Most of the pegmatite veins are composed only of quartz and
feldspars. One pegmatite also contained black tourmaline crystals up to six inches long, making it a complex pegmatite. The complex pegmatite is located in outcrop BD-9 (see Figure 4). The quartz and feldspar crystals in the complex pegmatite are up to a foot and a half across, but the crystal size in the simple pegmatites varies from about 2 to 8 inches.

Unit L

Unit L is composed of glacial till and outwash, glacial lake deposits, swamp deposits, and other surficial deposits that cover most of this area.

The Southwest Area

This area was not included in the stratigraphic descriptions above because no basis for correlation has been found. The rocks intersected in the two drill holes are very similar to units of the same type in the main area.

Drill hole R-2-2 is the southwesternmost hole examined in this study. The upper 113 feet of the hole are in glacial drift. The rocks intersected consist of metatuffs, metasediments, and metagabbro. Minor graphitic zones and some sulfide zones were intersected. Two of the more interesting sulfide zones are a massive pyrite zone from 118 to 131 feet that has very low base metal values and a 21 foot gabbro contact zone that
contains about 0.5% combined copper and nickel. These two zones will be discussed in more detail in a later section of this paper.

Drill hole R-2-3 went through 107 feet of glacial overburden before cutting bedrock. The main rock-type intersected was metagabbro, with minor metasediments. There were no graphitic or sulfide-rich zones intersected by this hole.

**Structure**

The structure of the Birchdale anomaly area is a steeply northwesterly dipping monocline that strikes approximately northeast. The anomaly area is located on the limb of a fold that plunges about 35° to the southwest (Ojakangas, 1972b). This writer was able to find only one place, location BD-8, where a strike and dip could be measured. Here the rock was a metatuff with some lapilli-sized fragments that had a N.45°E, strike and a 60° northwest dip. Because of the proximity of the outcrop to the massive Birchdale Granite intrusive, the measurement should be viewed with some skepticism, although the data presented below tends to confirm the reading. Measurements of bedding angles in the drill cores suggest dips in the area of drill holes S-43-2, R-2-3, and R-2-2 of about 65°. The dip appears to increase to nearly vertical in drill holes R-2-1
and R-2-1A. The structure between holes S-43-2 and R-2-3 is unknown, but the similar dips and lack of data to the contrary suggest that the major structure is continuous.

No evidence of major faulting was observed in the Birchdale anomaly area, although some brecciated and sheared zones were observed in the drill core. Some displacements of up to a foot were observed in outcrop. Many faults with a maximum displacement of one to two inches were observed in the drill core.

**Metamorphism**

Rocks in the Birchdale area have been metamorphosed at least twice. They were regionally metamorphosed to upper greenschist or lower amphibolite facies during the event that produced the major folds (Ojakangas, 1970). Some foliation, evidences of strong shearing, the stretched or lenticular shape of many fragments and sulfide masses, and the steep dips of the strata are remnants of this metamorphic event. Some of the massive sulfide bodies exhibit a swirly flow structure and contain fragments of the country rock, which could be a result of movement during this event. The granite cuts across the major structure which indicates that at some time after this regional event, the intrusion of the Birchdale Granite occurred. The characteristic mineral assemblage in the
rocks of this area is now; plagioclase, epidote, quartz, actinolitic amphiboles, and biotite, with small amounts of chlorite and other accessory minerals. This assemblage is characteristic of the albite-epidote hornfels facies. The main effects of this event were recrystallization and partial eradication of foliation in the country rocks, and some minor stress and recrystallization features in the sulfides. In general, the rocks are poorly foliated. Some hornfelsic or annealed textures are found in thin sections where plagioclase and quartz are the main constituents. The anomaly area is near the southern edge of the Birchdale Granite, and shows the results of thermal metamorphism. The probable temperatures of metamorphism, based on the size of the intrusive body and the distance from the contact, is believed to be between 450°-550°C. This prediction is based on an assumed initial temperature in the granitic body of 700°C, which could create albite-epidote hornfels facies metamorphism, based on temperature data given by Winkler (1967). The sulfides exhibit some metamorphic textures and structures.

Massive pyrrhotite shows a good polygonized or annealed texture, with many 120° triple points. Pyrrhotite also shows stress twinning and the development of kink bands and subgrains. Some of these features are
illustrated in Figures 7 and 8. Detailed descriptions of all photographed polished sections may be found in appendix B. Massive pyrrhotite also contains rock fragments and exhibits some swirly flow structures. Figure 9 shows some small rock fragments in pyrrhotite. Pyrite crystals have been observed broken, as shown in Figure 10. Where the sulfides are not massive, they tend to have a stretched or lenticular appearance.

The abundant pyrrhotite in the area and small amounts of pyrite may be the result of the metamorphic events that have affected these rocks. The regional metamorphism may have converted pyrite to pyrrhotite; but according to Stanton (1972), there is very little known about the chemistry of regional metamorphism of sulfide-bearing rocks. He states that sulfur loss and increasing sulfide-mineral assemblages may be effects. In the case of contact metamorphism, Stanton (1972, p. 621) states that, "In general, and in addition to thermally activated grain growth, contact metamorphism leads to sulfur loss from pyrite and its conversion to pyrrhotite or magnetite, conversion of pyrrhotite to its monoclinic modification or to magnetite...."

An effort to use sulfide phase relations to limit possible conditions of metamorphism has not produced significant results. The small amounts of Cu and Ni,
contained in the massive sulfides of the Birchdale area and the textures observed in polished section, appear to indicate that the minor phases containing copper and nickel exsolved from a pyrrhotite solid solution upon cooling. Craig and Kullerud (1969) indicate that when the copper and nickel contents are both below 2%, both will be accommodated in the pyrrhotite structure and would exsolve at a maximum temperature of $575^\circ C$. The exact temperature of exsolution in the Birchdale area would be dependent on the bulk composition and other minor factors.

**Sulfides of the Birchdale Area**

**Introduction**

The sulfides in the Birchdale anomaly area occur in both massive and disseminated forms. Small amounts of disseminated sulfide are found in almost all rock units. Most of the massive sulfide and the higher sulfide-content disseminated zones occur in Unit E, which consists of interbedded metatuffs and graphitic metasediments. The amount of sulfide in Unit E seems to vary directly with the amount of graphite.

**Mineralogy**

The sulfide minerals, in order of their relative abundance, are pyrrhotite, pyrite, chalcopyrite, sphalerite, pentlandite, marcasite, and cubanite. The identi-
FIGURE 7: Pyrrhotite from sample R-2-1A-337. Note 120° triple points and textural relationship between hexagonal (A) and monoclinic (B) pyrrhotites. This section tarnished in air. Reflected light 240X.

FIGURE 8: Pyrrhotite from sample S-43-1-153. Note triple points, annealed texture, hexagonal (A) and monoclinic (B) pyrrhotites, and the stress twins and kind bands in some grains (gray, banded). Reflected light, crossed nichols, intense light, 60X.
FIGURE 9: Pyrrhotite (A) with rock fragments (B) from sample R-2-1-286. Reflected light, 60X.

FIGURE 10: Broken pyrite (A) crystals in pyrrhotite (B) from sample S-43-1-307. Some chalcopyrite (C) (yellow) near center of picture. Some of the pyrrhotite on left side of picture is tarnished (brownish color). Reflected light, 60X.
ification of all minerals in some sections was difficult. In some sections an intermediate phase between pyrite and pyrrhotite is present; it is harder than pyrrhotite but softer than pyrite, isotropic or very nearly so, has a greenish-yellow color and polishes poorly (many small pits). Figure 11 shows the relationship of the three sulfide phases. This unknown phase is found where pyrite is replacing pyrrhotite. Ramdohr (1969) has observed similar relationships and also discusses the results of other work on this problem. The conclusion is that the intermediate phase is simply a transition phase in the replacement process that has X-ray patterns of either pyrite or marcasite. Ramdohr considers this transition phase to be an aggregate of very fine-grained particles.

The common sulfide assemblages are: pyrrhotite-
pyrite-chalcopyrite, pyrrhotite-chalcopyrite, pyrrhotite-
pyrite-chalcopyrite-sphalerite, and pyrrhotite-chalcopyrite-pentlandite.

Other combinations of sulfides were found but these four clearly dominate, with the first two assemblages accounting for nearly half of the total observations. The minerals in these assemblages are listed in order of decreasing abundance and clearly reflect the overall abundances of the minerals involved. It should be noted that marcasite was present in very few samples and then only in late veins. Cubanite was observed in only one sample.
FIGURE 11: Pyrite (A) replacing pyrrhotite (B) with intermediate phase (C) between, in sample R-2-1-110. Some concentric structures are found in the intermediate phase. Reflected light, 60X.

FIGURE 12: Hexagonal and monoclinic pyrrhotite with a more granular texture, in sample R-2-1-286. The brownish material is monoclinic pyrrhotite (A) and the yellowish is hexagonal (B). The gray material consists of rock fragments. Section has been etched in saturated chronic acid. Reflected light, 240X.
Pyrrhotite is the most abundant sulfide present and is found in both massive and disseminated sulfide zones. Macroscopically, it appears light yellowish-tan to light brown in color, with a very bright to dull metallic luster, and an uneven to irregular fracture. Microscopically, it appears a pinkish-buff or yellowish-tan color, depending on the adjacent minerals, is weakly birefringent, and moderately anisotropic. It occurs as aggregates of crystals in massive forms, and as isolated grains and blebs in disseminated zones. In massive zones, pyrrhotite has a polygonal or annealed texture and has minor pyrite and chalcopyrite along fractures and grain boundaries. An example of this texture is shown in Figure 7. In disseminated zones, pyrrhotite occurs as grains or blebs and may be associated with chalcopyrite, sphalerite, pentlandite, and pyrite.

Pyrrhotite has hexagonal and monoclinic forms. Using a method described by Arnold (1966), several sections were stained or etched with saturated chromic acid to determine the type of pyrrhotite present. Two textural relationships between the hexagonal and monoclinic pyrrhotite were found. Figure 12 shows the granular relationship. The tarnished pyrrhotite is the monoclinic type. The other textural relationship is illustrated in Figures 7, 8 and 13. These sections were not etched.
but show the same relationships observed in etched sections. Without etching, this relationship is visible under intense light with the nichols partially crossed. Ramdohr (1969) discusses and shows photographs of two types of pyrrhotite with similar textural relationships. The samples that Ramdohr shows are from the Matooster Nickel Mine, Transvaal; the North Mine, Broken-Hill, Australia; the Witwatersrand; and from Waterfall Gorge, Insizwa, South Africa. The cleavages shown in Figure 13 may be related to the hexagonal pyrrhotite. Note that the cleavage fractures bisect the angles shown by the lamellae of hexagonal pyrrhotite.

Pyrite is relatively abundant and is the only sulfide other than pyrrhotite found in massive form in the Birchdale area. It is, however, most commonly found as disseminated blebs and as cubic crystals. Pyrite is also commonly found as fracture fillings replacing pyrrhotite. In the metagabbros, pyrite may be altered to limonite or hematite. Macroscopically, pyrite appears a yellow or light yellowish-white color, with a metallic luster. Microscopically, pyrite is a light yellow to white color and is generally isotropic. Some pyrites have been observed to be slightly anisotropic.

Chalcopyrite, the third most abundant sulfide, occurs as small grains in some disseminated sulfide zones but
FIGURE 13: Pyrrhotite in sample R-2-1-178. In the large grain in the center, the patches of lighter colored material are hexagonal pyrrhotite (A) and the darker is monoclinic pyrrhotite (B). The monoclinic variety appears related to the cleavage fractures. The cleavage fractures may be related to the hexagonal pyrrhotite, note how they bisect the angles shown by the hexagonal lamellae. Gray grain of pyrrhotite in upper left shows kink banding. Reflected light, partially crossed nichols, intense light, 60X.

FIGURE 14: Chalcopyrite (A), sphalerite (B), and pyrrhotite (C) in sample R-2-1-351. The chalcopyrite is replacing the pyrrhotite and is being replaced by sphalerite. Dark gray is gangue (D). Reflected light, 60X.
most commonly is found in blebs along the edges of pyrrhotite grains, where it is commonly associated with sphalerite or pentlandite. In Figure 14, chalcopyrite is shown with pyrrhotite and sphalerite; note that some chalcopyrite is included in the sphalerite. Macroscopically, chalcopyrite appears as golden yellow grains or blebs. Microscopically, it appears golden yellow to light yellow to light greenish-yellow, and is weakly anisotropic to isotropic.

Sphalerite is rarely seen macroscopically because of its fine grain size and its generally disseminated occurrence. It usually occurs as minute grains or as part of an aggregate of sulfide grains. Macroscopically it is light brown or a reddish-brown color. Microscopically, in reflected light, it is medium to light gray and isotropic, with reddish internal reflections. In transmitted light, it appears as an orangey-reddish-brown colored isotropic mineral with extremely high relief.

Pentlandite was not identified macroscopically. It occurs within or along the edges of pyrrhotite grains as blebs and irregular flamey segregations. Microscopically, it appears as a white, isotropic mineral that is often visible only under magnifications of 120x or higher. Figure 15 shows pentlandite and chalcopyrite concentrated
along a pyrrhotite grain boundary. Pentlandite is also shown as small flame structures in the pyrrhotite. Ramdohr (1969) considers this type of occurrence to represent exsolution of pentlandite from pyrrhotite and migration towards grain boundaries.

Marcasite occurs in a few samples of late, sulfide-bearing veinlets. In these veinlets, pyrite is the main sulfide associated with traces of marcasite and chalcopyrite. Marcasite occurs as small grains in pyrite, visible only under the microscope. The grains are randomly oriented in the pyrite and have irregular boundaries. Marcasite is almost the same color as pyrite but has a slight greenish tinge and is slightly bireflective. It is slightly softer than the pyrite as indicated by the lower relief. It also is commonly twinned and often shows as interpenetrative relationship with the pyrite. Marcasite is strongly anisotropic and has a bright greenish-blue color in the brightest position and is brownish in the darkest position. It has been observed only in samples from drill core R-2-2 and has been determined to be post-deformation, as shown by the cross-cutting relationship of the veins to foliations. Ramdohr (1969) states that marcasite readily inverts to pyrite temperatures over 350°C.
FIGURE 15: Pyrrhotite (A) with chalcopyrite (B) and pentlandite (C) in sample R-2-2-518. The pentlandite and chalcopyrite are concentrated along the pyrrhotite grain boundaries. In center, some small flame structures of pentlandite can be seen in the pyrrhotite. Reflected light, 240X.
Cubanite may occur in one sample from drill core R-2-2. Identification is not positive because of the very fine grain size of the cubanite. It occurs as a small irregular bleb in a small pyrrhotite grain. It is similar in appearance to chalcopyrite but is more anisotropic. Reddish-brown and blue colors show upon rotation under crossed nichols.

**Massive Sulfides**

Several massive and semi-massive sulfide zones were intersected in the drilling of the Birchdale anomaly. In Unit E, (interbedded metasediments and metatuffs), the main sulfide-bearing horizon, several of these massive sulfide zones occur. The massive zones vary in thickness from about six inches to about ten feet. The contacts vary from sharp to gradational into disseminated or semi-massive zones. The amount of massive sulfides in Unit E increases towards the north-east. The massive sulfides are composed almost entirely of pyrrhotite with only traces of chalcopyrite and pyrite. No pentlandite or sphalerite were observed in the massive sulfide zones. The pyrrhotite occurs as polygonized grains with the traces of chalcopyrite and pyrite along the grain boundaries. The massive sulfides commonly show a swirly flow structure and often carry fragments of the host rocks.
A massive sulfide zone about ten feet thick occurs at the top of Unit D in holes S-43-1 and R-2-1. The sulfides are more massive and abundant in S-43-1 than in R-2-1. In both holes the massive sulfides grade downward into fine-grained disseminated sulfide. The upper contact in R-2-1 is gradational into disseminated sulfides while the upper contact in S-43-1 is sharp, against metagabbro. The textures and structures in this zone are similar to those in the massive sulfides in Unit E. The sulfides are mostly pyrrhotite with traces of chalcopyrite and pyrite. The pyrrhotite is polygonized and has traces of chalcopyrite along the grain boundaries. Pyrite occurs as blebs in pyrrhotite and as blebs and crystals along fractures. Figures 9, 10 and 12 show sulfides from this zone.

A massive and semi-massive pyrite zone with 10 to 50% pyrite occurs at the top of hole R-2-2 in metatuff. Massive pyrite occurs at the top of the metatuff and grades downward into disseminated sulfides. The massive and semi-massive pyrite is 18 feet thick. The grain size of the pyrite appears to decrease downward. The pyrite contains many small inclusions of irregularly shaped pyrrhotite. Some of the inclusions are lenticular and oriented parallel to each other. Traces of chalcopyrite occur as tiny blebs disseminated in the non-opaque
minerals between pyrite grains.

**Disseminated Sulfides**

The strongest zinc mineralization was intersected in drill hole S-43-2 between 184.5 and 187 feet. The ten foot section of core from 179 to 189 feet is missing and unavailable for study. The Ridge Mining Company drill log described the section from 184.5 to 187 feet as being an andesitic tuff with 5% pyrrhotite and pyrite and 5-10% sphalerite in possible slump structures. This zone is above the main sulfide horizon (Unit E) in Unit F. The rocks above and below the missing section showed none of this type mineralization.

The strongest copper-nickel mineralization intersected in the seven drill holes is in the upper contact zone of a metagabbro, from 510 to 531 feet in hole R-2-2. The sulfides occur as disseminated blebs and crystals. The sulfides present are pyrite, pyrrhotite, chalcopyrite, and pentlandite. All except pentlandite may occur as individual blebs. The pentlandite occurs as flamey segregations within pyrrhotite or as irregular blebs along pyrrhotite boundaries. Figures 15 and 16 show sulfides from this zone.

The disseminated sulfides of Unit E contain more sulfide phases than the massive zones. The sulfides are pyrrhotite, pyrite, chalcopyrite, sphalerite, and
pentlandite. All except pentlandite may occur as individual grains or blebs. Pentlandite occurs as flamey segregations in pyrrhotite. The texture varies from interstitial to blebby to granular. Figure 17 shows disseminated pyrrhotite with a blebby-interstitial type of texture. Figure 18 shows some grains or blebs of disseminated sphalerite.

Disseminated sulfides are found throughout the metasediments and metatuffs with the same mineralogy and textures as in Unit E. The total sulfide content of these rocks is generally less than 1% but with great local variation. Figure 19 shows interstitial pyrrhotite in Unit F.

**Base Metal Content**

The highest base metal mineralization intersected in drilling the Birchdale anomaly was the high zinc zone from 184.5 to 187 feet in S-43-2. A Ridge Mining Company assay indicates this 2.5 foot zone contained 4.06% zinc and 0.25 ounces of silver. The highest grade copper and nickel zone is in the metagabbro contact zone, from 510 to 531 feet in drill hole R-2-2. Exxon Company assays indicate a copper content of 4300 ppm over 1.8 feet with an average of 2870 ppm over six feet. Nickel ran as high as 3100 ppm over 2.3 feet with an average of 2300 ppm in that same six foot zone. Traces
FIGURE 16: Pyrrhotite (A) being replaced by chalcopyrite (B) in sample R-2-2-525. Reflected light, 240X.

FIGURE 17: Disseminated pyrrhotite in sample R-2-1-143. This blebby to interstitial texture is common in these rocks. The lightest material is the pyrrhotite (A). The light gray is iron oxides (B) and the dark gray is gangue (C). Reflected light, 60X.
FIGURE 18: Sphalerite (A) blebs in sample R-2-1-170. The darker gray minerals are nonopalescent. Sphalerite grains or blebs like this are strung in a band across this section. Reflected light, 240X.

FIGURE 19: Interstitial to semimassive texture of pyrrhotite (A) in tuffaceous metasediment (sample R-2-1A-117). Reflected light, 60X.
of gold also occur in this zone. The massive sulfide zones intersected in the drilling were all assayed and found to contain very low base metal values. Complete assay results can be found in appendix C with the company drill logs.

**Sequence of Mineralization**

A paragenetic sequence has been determined by compiling small bits of data from many polished sections.

<table>
<thead>
<tr>
<th>Time</th>
<th>Pyrite</th>
<th>Pyrrhotite</th>
<th>Chalcopyrite</th>
<th>Sphalerite</th>
<th>Pentlandite</th>
<th>Marcasite</th>
<th>Cubanite</th>
</tr>
</thead>
</table>

**Figure 20: Paragenetic Sequence**

The late pyrite, marcasite, and chalcopyrite are related to small, late fractures that occur throughout the area. They are shown to be the latest minerals by their relationships to the other sulfides and by the instability of marcasite at temperatures over 300° or 350°C. (Barton and Skinner, 1967, and Ramdohr, 1969). Hole R-2-2, where the marcasite occurs, is well within the contact aureole area in which the temperature should have been
over 350°C. The sequence, as it is shown by the present relationships, need not be similar to that before metamorphism. Most sulfide phases are readily susceptible to change caused by directed stress and pressure-temperature changes. The sulfides therefore often reflect the conditions during the last metamorphism. The mineralogy and/or the relationships between minerals may or may not be similar to the premetamorphic system.

Origin of Sulfides

The sulfides of the Birchdale anomaly area have been metamorphosed at least twice because of their easily altered nature. They exhibit the mineralogy, textures, and structures indicative of the conditions of the last metamorphism. This makes the determination of the primary origin of these sulfides difficult.

Most of the sulfides intersected in the Birchdale anomaly area are believed to be of syngenetic origin. This group includes the sulfides in Unit E, at the top of Unit D in S-43-1 and R-2-1, the high zinc zone in S-43-2, and most of the disseminated sulfides in meta-tuffs and metasediments. The sulfides of Unit E and Unit D have many of the same characteristics. The contacts between the massive and disseminated are sometimes gradational. The disseminated sulfides are the same grain size as the non-opaques in the host rocks. The sulfides
are associated with graphitic rocks, and as the graphite content increases northeastward, so does the sulfide content. The graphite, graphitic rocks and their association with the sulfides seems to indicate an environment which could have supplied biogenic sulfur for the syngenetic development of sulfides. The sulfides in nongraphitic metasediments and metatuffs, which includes the high zinc zone of Unit F in S-43-2, are also considered to be syngenetic. These sulfides are the same grain size as the nonopaque grains in the host rocks, and sphalerite often occurs in bands across sections. These metasediments and metatuffs may have small amounts of graphitic or carbonaceous material that can be seen in thin or polished sections. These small details, and the lack of evidence to the contrary, lead to the conclusion of a syngenetic origin for these sulfides.

The massive pyrite zone at the top of R-2-2 may also be syngenetic but is discussed separately because it is the only massive pyrite in the area. Polished section study shows that the pyrite contains many inclusions of pyrrhotite, including some that have parallel orientations. This may indicate a replacement with the pyrrhotite being unreplaced remnants. The process could have been similar to the small scale replacements of pyrrhotite by pyrite discussed earlier.
If this is the case then the original sulfides may have been syngenic but the pyrite would be of a replacement origin.

The sulfides in the metagabbro contact zone in drill hole R-2-2 are thought to have originated at the time of intrusion of the gabbro. If the sulfides were present in the magma as an original component, the concentration should be at the base, not at the top. Gravity should have caused the concentration to be at the base, because a sulfide liquid should have been more dense than the magma. It therefore appears that the metasediments at the upper contact of the gabbro supplied either the sulfur or the metals to form the sulfides. There is a slight increase in grain size of the sulfides towards the base of the contact zone which may indicate that the sulfides were beginning to settle but were stopped by crystallization of the gabbro.

The intrusive magmas in the Birchdale area could all have picked up sulfides from the country rocks, but some of the gabbros and diabases probably had small amounts of primary sulfides in the melt. Therefore, some of the sulfides may be classed as primary igneous in origin.

Trace Element Distribution

Trace element analyses on sixteen drill core
samples were made for copper, nickel, zinc, cobalt, and manganese by atomic absorption methods. Results of these analyses are shown in Table 2. The general rock types and estimated sulfide content are given with the sample numbers. Although analyses of many more samples would be required for a statistically valid evaluation, this work was done to see if there are trends in trace element content along strike or vertically in the section intersected in hole R-2-1. The samples from R-2-2, R-2-3, and S-43-2 are random samples of metasediments or metatuffs, as they are not from a correlative horizon. Samples S-43-3-165.5, S-43-1-165, R-2-1-178, and R-2-1A-327 are of massive sulfides from Unit E, listed in order from southwest to northeast. Figure 21 shows graphically the results for these samples. Nine samples from hole R-2-1 were analyzed to see if trends existed vertically in the section. Figure 22 graphically shows the results from these samples. The graphs (Figures 21 and 22) show that copper and zinc tend to vary in a parallel manner. The copper is always above the zinc in the massive sulfides and zinc above copper in all of the R-2-1 samples except for the massive sulfide samples at 108 and 178 feet and the metagabbro sample at 550 feet. It appears that the massive sulfides are either enriched in
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<td>S-43-1-307, massive sulfide</td>
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<td>R-2-1A-327, massive sulfide</td>
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<tr>
<td>R-2-1-108, massive sulfide</td>
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<tr>
<td>R-2-1-271, metadiorite</td>
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<td>R-2-1-586, metasediment</td>
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FIGURE 21: Graph of Trace Element Results in Massive Sulfides
copper, relative to zinc, as compared to the disseminated sulfide zones or depleted in zinc relative to copper. Cobalt and nickel also vary together but have absolute values more nearly the same. As shown in Figure 21, the absolute values for cobalt and nickel appear to be increasing, while in Figure 22 the values are almost consistent except for the massive sulfides and the metagabbro. In checking the metal values found in this study against the assay results of the companies, significant differences were found to occur. This is probably due to the fact that their sample intervals are generally over about two feet, while the interval used in this study was over about one inch.

Metal ratios are often used in trace element studies of ores and the enclosing rocks. Often absolute values may be inconsistent or erratic, but ratios will be constant and characteristic of ore in a district. Sixteen trace element ratios have been calculated using the data shown in Table 2. These ratios are shown in Table 3. Group 1 on the table is the low sulfide metasedimentary samples from R-2-1. Group 2 is the random metasedimentary samples and the average value from group 1. Group 3 is the massive sulfides of Unit E. Several of the ratios were relatively constant or showed increasing or decreasing trends. Cobalt:nickel increases upwards
### TABLE 3: TRACE ELEMENT RATIOS

Low Sulfide Metasediments from Hole R-2-1, Listed from Top to Bottom

| GROUP 1 | Ni/Zn | Co/Zn | Cu/Zn | Cu*Zn/Mn | Co/Zn | Cu/Zn | Cu/NI | Cu/Mn | Zn/NI | Zn/Mn | Co/Mn | Cu*Zn/Mn | Cu/Co | Cu/Zn*Co | Cu/Zn
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<td>R-2-1-170.5</td>
<td>0.07</td>
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<td>7.26</td>
<td>19.11</td>
<td>2.46</td>
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<td>9.33</td>
<td>0.93</td>
<td>0.10</td>
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<td>0.27</td>
<td>0.89</td>
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<td>0.08</td>
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<td>1.72</td>
<td>0.91</td>
<td>0.33</td>
<td>3.26</td>
<td>0.42</td>
<td>0.13</td>
<td>1.30</td>
<td>0.12</td>
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<td>0.28</td>
<td>0.51</td>
<td>0.06</td>
<td>0.11</td>
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<td>0.09</td>
<td>1.27</td>
<td>0.154</td>
<td>0.163</td>
</tr>
</tbody>
</table>

Random Low Sulfide Metasediments, Listed Southwest to Northeast

| GROUP 2 | Ni/Zn | Co/Zn | Cu/Zn | Cu*Zn/Mn | Co/Zn | Cu/Zn | Cu/NI | Cu/Mn | Zn/NI | Zn/Mn | Co/Mn | Cu*Zn/Mn | Cu/Co | Cu/Zn*Co | Cu/Zn
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<tbody>
<tr>
<td>R-2-2-153.5</td>
<td>0.17</td>
<td>0.09</td>
<td>0.93</td>
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<td>1.56</td>
<td>0.54</td>
<td>0.09</td>
<td>0.30</td>
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<td>0.25</td>
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<td>0.71</td>
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<td>0.36</td>
<td>2.88</td>
<td>0.30</td>
<td>0.10</td>
<td>0.69</td>
<td>0.10</td>
<td>1.43</td>
<td>0.215</td>
<td>0.220</td>
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</table>

Massive Sulfides, Listed Southwest to Northeast

| GROUP 3 | Ni/Zn | Co/Zn | Cu/Zn | Cu*Zn/Mn | Co/Zn | Cu/Zn | Cu/NI | Cu/Mn | Zn/NI | Zn/Mn | Co/Mn | Cu*Zn/Mn | Cu/Co | Cu/Zn*Co | Cu/Zn
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<tbody>
<tr>
<td>S-lj3-l-165.5</td>
<td>1.24</td>
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<td>1.25</td>
<td>2.39</td>
<td>0.13</td>
<td>0.71</td>
<td>1.09</td>
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<tr>
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<td>1.84</td>
<td>0.58</td>
<td>0.12</td>
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<td>0.16</td>
<td>0.103</td>
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in group 1, generally increases from southwest to northeast in group 2, and increases in the same direction but is more erratic in group 3. Copper:zinc increases upward in group 1, is erratic in group 2, and generally increases northeastward in group 3. Nickel:manganese is relatively constant in group 1, decreases northeastward in group 2, and is inconsistent in group 3. Cobalt:manganese is relatively constant in groups 1 and 2 but generally increases northeastward in group 3. Copper: copper + zinc increases upward in group 1, is inconsistent in group 2, and increases northeastward in group 3.

Table 4 shows metal ratios for all of the massive sulfide samples and the average value for each ratio. Table 5 shows the same ratios for all of the low sulfide metasedimentary samples, and the average value for each ratio.

The geological implications of these ratios are unknown. Other work on trace element distribution suggests that the results depend on the area studied because the ratios vary from district to district but are usually constant within a mining district. Trace element work done by Roscoe (1965) on known ore bodies in the Noranda and Matagami areas indicates that high cobalt:nickel ratios are common. He also found high absolute values for cobalt (600-1400 ppm) to be normal
in that area. Roscoe analyzed barren sulfides and found about 10 ppm cobalt. Fleisher (1955) working with trace element contents of individual minerals, found that cobalt is higher in pyrite than in pyrrhotite, but great variation is normal. Costantinou and Govett (1973) found that cobalt:nickel ratios in the Cyprus deposits were generally low but variable. Wilson and Anderson (1959) have used the ratio of copper : copper + Zinc to study copper-zinc ores of Canada and have concluded that each deposit or area may have a distinctive ratio.

Although the data obtained in this limited trace element study may be useful now, its value will increase when an ore body is discovered in the region and trace element studies completed across it. Until an ore body is discovered, the trends shown by this study should be checked out because trends of absolute values and metal ratios have been found to be useful in other areas for tracking down ore bodies. The increasing cobalt and nickel northeastward in the massive sulfides may indicate that an ore body lies in that direction. Copper appears to be enriched in the massive zones and may be increasing northeastward also. The trends are there and should be investigated.

Geologic History

The geologic history of the Birchdale anomaly area
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<th>Co/Zn</th>
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<th>Cu^2+Zn/Ni</th>
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<th>Cu/Ni</th>
<th>Cu/Zn</th>
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is poorly understood because of the sparse outcrop data available. One K-Ar age date of the Birchdale Granite indicates an age of 2.4 b.y., which is probably low but is still Early Precambrian. Goldich (1972) states that an age of around 2.7 b.y. is probably more correct for the greenstone belts in Minnesota. Rb-Sr and U-Pb methods appear to confirm the 2.7 b.y. age for these rocks. The granite intrudes the sediments, tuffs, agglomeratic tuffs, and volcanics of the greenstone belt and cuts regional structures, indicating that the granite is postkinematic. The greenstone belt rocks appear to have been deposited subaqueously. The sulfides in the metasediments and metatuffs may be contemporaneous with the deposition of those rocks. The source or sources of the sulfide components is open to question but may be, directly or indirectly, related to the volcanic activity. The graphite is considered to be of organic origin and may have aided in the deposition of the sulfides either directly or indirectly. The gabbros and related intrusives may have been penecontemporaneous with the volcanic activity. Regional metamorphism to upper greenschist or lower amphibolite facies accompanied the folding that developed the major northeast-trending folds. Mobilization and redeposition of the more massive sulfides may have occurred during this
event. Minor faulting and brecciation appear to have developed at this time. During or after folding, the Birchdale Granite was intruded into the greenstones. The contact metamorphic effects created assemblages and textures characteristic of the albite-epidote hornfels facies in the study area. Minor fracturing and faulting may have accompanied the intrusion and cooling of the granite body. Late in the Birchdale Granite intrusive event, pegmatites and trachy-andesite dikes were emplaced in and adjacent to the granite.

A long period of erosion occurred between Precambrian and Pleistocene time. The last recorded event was the pleistocene glaciation. Glacial deposits cover most of the area, with very little rock exposed. Evidence for at least two glacial episodes are found in the area. The earlier of the glaciers left a sandy-reddish-brown till and northeast trending striations. The ice probably came from the northeast. The other glacial event left a clay and limestone-rich till and an indicated southeasterly direction of movement.

Economic Potential

The potential for the occurrence of economic base metal sulfides in northeastern Minnesota is good. The Birchdale area has been explored, but not fully, and still has good potential. The rock-types are similar
to those in other producing greenstone belt areas, and the sulfides are there in sufficient quantity. The increasing amounts of sulfides northeastward, in the vicinity of the Birchdale anomaly, and trace element trends in that direction, indicate that further exploration may be justified. The occurrence of the high zinc zone in S-43-2 is encouraging. Further exploration to the west and southwest of S-43-2 should be undertaken to determine if the high zinc zone continues or expands in that direction. The unexplored area between S-43-2 and R-2-3 is large enough for an ore body to occur. The results of this study suggests that an environment suitable for commercial sulfide deposition may occur and that exploration should continue to the northeast and southwest of the areas drilled.

Conclusions and Summary

The metasediments and metatuffs of the Birchdale area were probably deposited in a basin and derived from nearby volcanism and volcanic rocks. The increase in volcanic rock fragments to the southwest and the increasing graphite northeastward suggests the location of the volcanic center to be to the west or southwest of drill hole S-43-2 (SE-SE sec. 16). The increasing graphite content suggests a deepening of the basin to the northeast because the closer to shore the more chance
of oxidation and complete destruction. The lack of
graded bedding, cross-bedding, and other common sedi-
mentary textures and structures in most of the rocks
indicated rapid deposition and little reworking. The
volcanogenic nature of the rocks also suggests a nearby
source within an active volcanic province.

Most of the sulfides in the Birchdale area appear
to have originated with the sediments and tuffs, syn-
genetically. The main sulfide horizon in Unit E con-
tains graphite. In general, the amount of graphite
varies directly with the amount of sulfides, suggesting
that the two may be related genetically. Base metal
content of the sulfides is low but some trends are
suggested by trace element studies. In the massive
sulfides the contents of cobalt and nickel appear to
be increasing northeastward. Relative enrichment of
copper over zinc also appears to increase northeast-
ward. These and other possible trends discussed in the
trace element section may be ore indicators but more
work needs to be done to determine their significance.
Bibliography


APPENDIX A: Drill Logs

by

William H. Listerud
R-2-3

107-192 Fine to medium-grained, uniform, massive, non-magnetic mafic flow or intrusive. Rock is mottled with small irregularly shaped whitish spots, and has a few small, somewhat sheared zones. Some inclusions or finer grained zones near base. Cut by a few granitic stringers. Traces of pyrite.

192-194 Fine-grained, sheared zone that could be a chill zone for the above unit. Possible metasediments.

194-300 Mixed zone. Rocks as in 107-192 and fine-grained to very fine-grained metasediments. Metasediments have large white porphyroblasts and are cut by granite stringers. This zone contains some pyrite and chalcopyrite as disseminated blebs. Zone of richer pyrite and chalcopyrite 224-227'. The darker gray and finer-grained metasediments seem richer in sulfides. All contacts and shearing is about 60° to the core.

300-400 Massive, uniform, fine to medium-grained, dark green flow or intrusive. Similar to 107-192'. Pyrite cubes throughout unit. Rock has many healed fractures. Some granite veins. Rock is more broken and sheared near base.

400-405 Chill zone to above unit. Fragmental, very fine-grained, greenish and somewhat fractured.

405-634 Fine to medium-grained, chloritic (?), green, massive, uniform, nonmagnetic flow or intrusive. Seems to have a zone at the top that could be a vesicular or amygduloidal zone. Rock often has dark green clots in it and is sheared at about 60° to the core axis. Some zones of pinkish feldspars (?). Pyrite cubes and disseminations throughout unit. Calcite and quartz along fractures. Some zones appear slightly finer-grained but no distinct breaks can be seen in this unit. There is an increase in the size and number of pyrite cubes right at the base.
634-666 Fine-grained, sheared, banded, broken and healed, green metasediments. Traces of pyrite.

666-701 Looks like a sheared flow or gabbro. Shearing 60° to core. Could be sheared metasediment.

701-706 Gray, very fine-grained, bedded metasediment. Some beds are finer-grained, darker colored and have more sulfides. Sulfides mostly pyrrhotite.

706-784 Gradational contact with above unit into mafic flow or gabbro. Rock is nonmagnetic, has some dark green clots, some finely-sheared zones, has many healed fractures and seems to be getting coarser-grained downwards.
Massive, granitic rock with occasional inclusion of greenish, fine-grained rock. Granitic rock is pink, medium-grained to coarse-grained, with quartz, feldspars, biotite, magnetite, and hornblende.

Zone of inclusion-rich granite. Contact zone. Inclusions of gray and greenish rocks. Probably metasediments or metatuffs and porphyry. Traces of sulfides in this zone.

Gray to brownish-gray, fine to medium-grained, agglomeratic, andesitic metatuff. Unit somewhat granitized, with a 6" granite pegmatite at 130'. Fragments vary in composition but trend to be more mafic towards base of unit. Traces of sulfides mostly pyrrhotite with some pyrite and chalcopyrite.

Dark green, fine-grained, sheared chloritic (?) rock with some dark porphyroblasts. Some brown spots and zones also. Some pyrrhotite and pyrite along fractures.

Somewhat granitized andesitic, agglomeratic metatuff. Fragments of very fine-grained, gray metatuffs. Sulfides mostly pyrrhotite and tend to be blotchy (up to 1").

Zone of coarser-grained, biotite-rich, fairly massive metasediment or metatuff. Some fragmental-looking zones. Disseminated pyrrhotite.

Zone of very fine-grained, greenish and brownish, blotchy-looking metatuff (?) or fine-grained flow. Some very fine-grained disseminated sulfides and some along fractures.

A sulfide-bearing, light gray, foliated, feldspar and biotite intrusive rock of intermediate to granitic composition. It is fine to medium-grained. Becomes inclusion-rich in bottom 2'.

Greenish-gray and brown, banded sometimes
mottled, fractured and healed, very fine-grained metatuff with some agglomeratic zones. Pyrrhotite lenses and disseminations.

234-238 Dark green, fragmental, fine-grained, metatuff. Some fragments have rinds and may have been small ejected fragments into water. Some zones of fine-grained disseminated pyrrhotite.

238-257 Zone of alternating coarse and fine-grained metasediments or metatuffs. Possible grading, banding and a medium-gray color. Some shearing perpendicular to core. Very fine-grained disseminated to semimassive pyrrhotite.

257-266 Zone of broken, highly sheared, light gray, fine-grained metasediment or metatuff. Some granitic stringers near bottom. This may be just a more sheared zone of the above unit. Sulfides along shear planes.

266-286 Biotite schist. Biotite-rich, strongly foliated, fine-grained, with disseminated to semimassive sulfides, mostly pyrrhotite. Has been intruded by granitic stringers near base (about 50% in last few feet).

286-295 Dark green, medium-grained, spotted, altered andesite porphyry. Massive, with only a few granitic stringers. Little to no sulfides.


306-311 Mostly granitic material with some bands of gray-green, fine-grained material (as below). Sparse sulfides.

311-322 Gray-green, fine-grained, banded and swirly, metasediment or metatuff. Irregular bands and blebs of sulfide, mostly pyrrhotite.

322-358 Brownish-gray to greenish-gray, very fine-grained, massive garnetiferous metatuff or metavolcanic. Many healed fractures. Traces of pyrrhotite. Becomes greener colored and looks fragmental near the base.

358-360 Granitic vein, pink and white.
360-374 Fine-grained, greenish-gray, sheared, possibly agglomeratic metatuff. A 1' granite vein at 372'. Rock becomes more sheared and foliated near base.

374-380 Light gray, irregularly banded and contorted, very fine-grained, partially granitized, siliceous metatuff or metasediment. Possibly a flow. Sulfides smeared out and irregular. Mostly pyrrhotite.

380-399 Fine-grained, biotite-rich, mostly massive, possibly graded metasediment. Granitized and somewhat banded at top of unit. Grain-size increases at base. Traces of sulfides.

399-419 Two boxes of core missing.

419-442 Fine-grained, biotite-rich metasediment. Rock is mostly massive with sheared base. Trace of sulfide.

442-447 Intrusive andesite porphyry.

447-466 Fine-grained, gray-brown, biotite-rich metasediments.

466-475 Core missing.

475-479 Very fine-grained, gray, massive metasediment.

479-498 Medium-grained, recrystallized mafic flow or possibly a metasediment.

498-504 Light gray, very fine-grained, dense, possibly fragmental rock. Metatuff is fairly silicic.

504-524 Possible mafic flow with many fragments of very fine-grained metatuff. Flow is fine-grained. Much core missing from this zone.
88-123 Very fine-grained, gray, green and brown, generally thin-bedded metasediments or metatuffs. Some zones of shearing and some broken zones. Pyrrhotite, pyrite, and chalcopyrite in stringers and small blebs. Some small zones of pink garnets. Rock is recrystallized very much in some places, has some dark green chloritic zones and is in some places carbonaceous.

123-129 Mixed zone of light green and pink granite with inclusions of metasediments.

129-136 Zone of dark gray, massive, fine-grained metasediments with only traces of sulfides.

136-145 Gray, green, brown disrupted metasediment. Can see displacements of 2" in fractures. Zone shows recrystallization and some granitization.

145-190 Zone of mixed dioritic or granitic intrusive and very fine-grained, massive metasediment.

190-194 Coarse-grained intrusive with brownish-colored feldspars.

194-245.5 Zone of mixed metasediments and granitic intrusive. Some zones with up to 25% pyrrhotite. Graphitic zone at bottom shows effects of shearing.

245.5-257 Light gray and light green, medium-grained dioritic intrusive. Rock is somewhat altered. Becomes darker and finer grained near base.

257-267 Very graphitic, sheared zone with some pyrrhotite, pyrite, and chalcopyrite in blebs.

267-303.5 Zone of busted and granitized metasediments. Irregular sulfide zones with pyrrhotite, pyrite, chalcopyrite. Some graphitic or carbonaceous zones. Pink and white granite 288-290', 296-299', and white granitic rock with smeared inclusions of metasediments from 299-303.5'.

303.5-365 Metasediments and/or metatuffs. Thin-bedded
metatuffs 303.5-322.5'. Dark gray carbonaceous to graphitic zone with stringers and disseminated sulfides. Thin-bedded, disrupted, fine-grained metasediments with semimassive pyrrhotite from 327-341.5'. Massive, dark green, garnetiferrous fine-grained metasediments, with pods of pyrrhotite and some granite stringers, from 341.5-365'.

365-377 Graphitic metasediments with some pyrrhotite, pyrite, and chalcopyrite in blebs and stringers. Rock is broken and bedding is very disrupted and contorted.

377-406 Gray, fine-grained, fairly massive metasediment with irregular blebs and blotches of pyrrhotite.

406-407.5 Dark green metasediment with small pink garnets.

407.5-408.5 Inclusion rich granite intrusive vein.

408.5-415 Massive, gray, fine-grained metasediment with only traces of sulfides.

415-416 Quartz and granite veinlets.

416-423 Broken metasediments in granite.

423-428 Dark green, garnet-rich, fine-grained metasediment.

428-445 Thin-bedded, disrupted, felsic metatuff with only traces of sulfides.

445-473 Broken, disrupted, fine-grained, biotite-rich metasediments with traces of sulfides.
18-40 Light gray to brownish, fine-grained, possibly somewhat bedded, agglomeratic (lapilli size) tuff. Can see small feldspar crystals and fragments in rock. Some sections are pinkish from granitization. Fairly massive but some sheared looking zones. No visible sulfides.

40-44 Granitic intrusive, some inclusions, medium-grained, usually greenish-gray colored. Can’t see striations on feldspars but some look like plag laths.

44-53 Very fine-grained, brownish-gray, slightly recrystallized with some granitization, fairly massive metatuff. Becomes agglomeratic near base (lapilli sized fragments). Some very fine-grained disseminated sulfides near base (po, py).

53-80 Very fine-grained, brownish-gray, busted-up metatuff. Contains very fine-grained disseminated po, some stringers and irregular blebs of po with some py. Sulfides appear to increase slightly towards base. Also more broken near base.

80-91 Mostly the same as the above unit but becomes more agglomeratic. Fragments are andesite porphyry, with squarish pink feldspars and plagioclase laths. Almost looks like a good porphyry near base.

91-157 Series of thin tuffs, all fine-grained, with some granitization and brecciation. Some lapilli-sized fragments. Sulfides (po, py, cp) in fine-grained disseminations, and in lenses and blebs.

157-174 Zone of graphitic and chloritic, very sheared and broken, sulfide-rich metatuffs. Sulfides (po, py, cp, sl) massive and semimassive or in bands parallel to bedding or banding (l to core). Sulfides semimassive 158-163, massive 163-164, mixed massive and semimassive 165-167, and massive 169-174. Rock is highly altered and chloritized with calcite veining 167-169. Some zones of about a foot thick, scattered through zone, that are more massive and silicic.
174-182 Zone of light brown, fine-grained metatuffs that become more biotitic near base. Some granitic stringers (with small inclusions) and some brecciated zones in rock.

182-190 Dark Green, fine-grained, chloritic, sheared and granitized metasediment. Some development of red garnets. Some small disseminated-semimassive sulfide zones (po,py, some cp).

190-228 Zone of busted up metasediments with some granitization. Some development of red garnets. The rock varies downward from silicic to biotitic to chloritic to silicic to chloritic. Sulfides usually in scattered blebs and lenses (po,py,cp). Small semimassive zone (po,py) from 215-216'. Towards base of unit rock becomes very broken and sheared. Garnet-rich zone from 226-228'.

228-234 This unit is finer-grained at the top and gets slightly coarser downward. It is slightly porphyritic with white feldspar phenocrysts. Some blebs of chlorite also occur. Rock appears massive and could be a flow.

234-450 Rock is fine-grained, slightly granitized, and discolored metasediments. There are some zones with vague bedding, some agglomeratic zones, and some massive zones. Some think black carbonaceous zones are scattered in the unit. From 283-309' the rocks are more massive, biotite-rich metasediments. They are generally equigranular, with a few larger feldspar grains and unbedded. The zones from 368-378 and 408-420' are broken and sheared. From 369-372' are semimassive pyrrhotite and pyrite. Disseminated blebby and streaky pyrrhotite and pyrite occur throughout the unit. Traces of chalcopyrite also occur.
63-65 Dark brown, fine-grained, partially granitized metasediment with fine-grained disseminated pyrrhotite and pyrite.

65-67 Breccia zone with angular, felsic, leached fragments. Some shearing in this zone also.

67-88 Light gray and brown fragmental rock that is a lapilli tuff with possible agglomeratic zones. The fragments are very fine-grained and have sulfides and other fine-grained material in the interstices. The sulfides are pyrrhotite, pyrite and chalcopyrite. Green copper stains occur on fractures. From 82-87' is a broken vuggy zone. Some small scattered semimassive pyrite zones occur.

88-106 Brown, biotite-rich fragments or inclusions in granitic material. May be only granitization. Irregular blebs and stringers of pyrrhotite and pyrite occur in zones of fine-grained disseminated sulfides.

106-114 Massive pyrrhotite with inclusions of metasediments. Swirly texture suggests movement of sulfide mass.


116-134 Metasediments. Fine-grained, light colored, with some graphitic and semimassive sulfide zones. Usually 10-20% pyrrhotite. Rock is sheared at about 80° to the core.

134-148 Metasediments as above but with some granitic stringers and blotches.

148-187 Metasediments. Darker colored than above, with some graphitic zones. Rock is more massive and generally has only traces of sulfides. Some granitic stringers. Semimassive pyrrhotite from 151-154'. Granitized and graphitic zones with some pyrite and traces of chalcopyrite. From 178-187' is a brownish, fractured and healed (with calcite) metasediment. Contains
fine disseminated pyrrhotite with rare larger clots.

187-258 Mafic flow or intrusive. Brownish-gray to green, fine-grained, massive. Rock is bleached along fractures and has some darker green chloritic (?) zones. Some dark green sieve-textured porphyroblasts have developed and bluish quartz is present in pods and veins. The rock generally becomes coarser-grained near base. Some small granitic veins and stringers near the base of unit.

258-272.5 Diorite. Black and white, medium to coarse-grained, and looks altered with cloudy white feldspars and red garnet. Traces of sulfides. Inclusions of metasediments and much biotite near top of unit.

272.5-344 Metasediment. Gray to brown to green mottled, fine-grained, sheared and foliated, sometimes graphitic. Disseminated pyrrhotite, pyrite and chalcopyrite along with some stringers and lenses in unit. Up to 30% sulfides 283-288'. From 288-344' the rock is granitized, more greenish and almost looks fragmental. Unit is more granitized and coarser-grained near the bottom. Rock is also more sheared near base. Zone of disseminated chalcopyrite about 335'.

344-352 Metasediments or metatuffs. Light gray or buff colored, thin-bedded, sheared and very fine-grained. More siliceous than the rocks above and below. Traces of disseminated sulfides.

352-368 Mixed mafic porphyry and metasediments. Porphyry is fine to medium-grained and biotite-rich. Metasediments as above. There is chalcopyrite along fractures, also white feldspar and quartz veins. Pyrrhotite is the main sulfide and varies from occasional blebs to fine disseminated to massive in nature.

368-409 Metasediments or metatuffs. The rocks are granitized, sheared, massive to thin-bedded, fine-grained, and green to gray to buff colored. Traces of sulfides.
409-490 Metasediment. Rock is fine-grained, massive, recrystallized, and biotite-rich. Many dioritic veinlets. In some places looks fragmental but it may be only granitization.

490-573 Mafic intrusive. Rock is medium-grained, sheared and altered. Becomes porphyritic near the base. Contains disseminated pyrrhotite, pyrite, and chalcopyrite.

113-153 Metatuffs. Broken and weathered at top. Some thin-bedded siliceous zones near top, becoming more massive and fragmental towards base. Massive to semimassive pyrite at top, grading downward into disseminated pyrite. Unit has some healed fractures and small sheared zones. Rock is light gray and fine to very fine-grained.

153-158 Thin-bedded, sheared, dark gray, very fine-grained, carbonaceous or graphitic mudstone. Pyrite is stretched blebs or lenses. Some pyrrhotite also.

158-282 Similar to 113-153'. Small pyrite-rich zone at top, grading to very fine-grained disseminated pyrite. Alteration along fractures has caused some discoloration and a blotchy appearance. Traces of pyrrhotite and chalcopyrite scattered in unit. Small massive pyrrhotite zone at 203'. Zone 201-205' has some dark green chloritic (?) bands. Rock is somewhat sheared below 273'.

282-297 Zone of fine-grained, thin-bedded, gray and brownish metasediments. Some of the darker gray beds are carbonaceous or graphitic. Small amounts of pyrite and pyrrhotite occur as lenticular blebs.

297-360 Gradational contact into rocks similar to 158-282'. They are gray and brown, sheared, broken, discolored along fractures, and contains some larger fragments. A few dark green chloritic (?) zones also occur. Rock is phyllitic along fractures and contains a few disseminated sulfides. Rock has a sheared-cataclastic look near the base of the unit.

360-365 Rock is a forcefully intruded andesite porphyry. Sheared at both contacts. Phenocrysts are plagioclase. Foliation of plagioclase is about 70° to core axis.

365-527 Zone of mixed very fine-grained, fractured, gray to brown to green metatuffs, as those above, and biotitic, coarser-grained, cataclastic-looking, metasediment. Foliation of the biotites per-
perpendicular to the core. Becomes coarser-grained and more cataclastic looking towards the base with increasingly larger blebs of pyrrhotite, pyrite, and chalcopyrite.

527-723 Metagabbro. Medium to coarse-grained, greenish to brownish near top but becomes more greenish downward. Upper zone contains inclusions of the overlying metasediments (some up to a foot across). Blebs of chalcopyrite, pyrrhotite, and pyrite occur from 527-531', and the rest of the unit contains only traces of pyrite and chalcopyrite. Rock contains poikilitic biotites except in zone 673-679'.

723-763 Mixed zone of gabbro and fine-grained metasediments. Some porphyroblasts developed in metasediments. Gabbro in this zone is sheared. Metasediments 728-733' and 735-739' contain minor pyrite, pyrrhotite, and chalcopyrite. The gabbros in this zone contain only traces of pyrite.
7-30.5 Very hard, very fine-grained to aphanitic, brown to gray, slightly banded, siliceous metatuff. Has some fragmental zones and has many subhedral feldspars up to 2 mm. Also contains many chloritic fragments. Some small granite stringers with pink feldspars. Black dendrites on fracture surfaces. Prominent shear or fracture planes at high angle to core. Only traces of very fine-grained disseminated sulfides.

30.5-36 Very fine-grained to aphanitic, buff colored, banded, agglomeratic-looking metatuff. Banding at about 70° to core. Contains some lenticular stretched chloritic blebs and some darker-brown, speckled, smeared-out fragments (?) -- looks like pumice. Only traces of sulfides.

36-43 Alternating 2' bands of buff and gray-brown colored rocks, as above. Buff colored has fine banding of darker colored micaceous minerals. Only trace of sulfides.

43-91 Brownish-gray, very fine-grained, weakly banded, very hard, agglomeratic tuff or felsic volcanic. Contains subhedral white feldspars, in places, and stretched chloritic, dark green fragments (up to 1'). Rock is bleached along fractures. Whitish feldspars concentrated in some zones. Only traces of sulfide.

91-165 Mixture of very fine-grained andesitic tuff and granitic intrusive. Intrusive is composed of white, lathy feldspar, pink feldspar, quartz and hornblende. Can see rounded fragments of tuff in intrusive. There are some very mafic (dark green) zones in the tuff. From 91' begin to develop pyrrhotite and chalcopyrite as disseminated blebs or grains. Pyrrhotite increases to about ½" blebs at 130' then begin to get large blotches (about 1") of pyrrhotite. 140-165' has big blotches of pyrrhotite and also along fractures. Pyrrhotite increases towards the base, to about 20%. There are some siliceous bands near the bottom also. There are also some fractures filled with pyrite in this zone.
165-200 Finely laminated or sheared, sometimes con- 
torted, coarse-grained, probably dacitic tuff 
which has been intruded by many small stringers 
of quartz-feldspar. Rock appears to become 
more mafic downward. Sulfides follow banding 
and occur as stringers, or as blebs in the 
quartz-feldspar veinlets. Some 1" massive pyrrhotite zones. Sulfides are mainly pyrrho- 
tite with small amounts of pyrite and chalco-
pyrite.

200-300 Mafic intrusive with some fragments of tuff 
included. Rock looks blotchy, mafics not 
evenly distributed. Has pyrite-healed frac-
tures, some of which are still vuggy. A 
brownish mineral, possibly sphalerite, also 
occurs as small crystals in these fractures. 
Rock seems to have a finer-grained zone at 
the bottom but not at the top. Generally 
medium to coarse-grained, and green colored. 
Rock is cut by granitic and dioritic stringers. 
Sulfides scattered through unit, mostly pyrro-
tite with traces of chalcopyrite.

300-328 Very fine-grained, brownish-gray metasediment 
or metatuff. Semimassive pyrrhotite from 300-
311', blotchy pyrrhotite from there to 328' 
with some smaller massive zones.

328-432 Fine-grained, gray to brownish-gray meta-
sediment. No structures visible. Extensive 
fracturing (healed) and veining with calcite 
and mica (micas on the edges of veins). In 
the zone 372-420', the rock has many dark-green 
and black porphyroblasts. Sulfides spotty 
but most often as very fine-grained disseminated 
pyrrhotite with some chalcopyrite. Small patches 
of pyrrhotite (1/4"-1/2") not uncommon. Some pyrrho-
tite and pyrite along fractures. Rock looks 
granular with handlens and is phyllitic lo-
cally. From 420-432' rock is more massive, 
seems slightly coarser grained, and is mottled-
looking. At about 430' there is a 6" sheared chloritic zone.

432-436 Shear zone. Top 6" is sheared chloritic zone 
with smeared pyrrhotite. Then a 1' zone with 
pink stringers and small white spots that could
be feldspars, very silicic. Looks like metasediment. The lower 2½' are a highly sheared (perpendicular to core axis) crumbly, green chloritic rock with calcite and traces of pyrrhotite, pyrite, chalcopyrite and sphalerite.

436-443 Very light gray, dense, hard, very fine-grained, but with some larger crystals, banded, very siliceous, slightly granitized metasediment or metatuff.

443-498 Gray, fine-grained, somewhat biotitic, banded, possibly bedded and graded, blotchy, partially granitized, sheared metasediment. Cut by calcite and dioritic veinlets and contains some patches of granite. Some parts are fragmental with augen-like draped fragments. In some zones the rocks are blotchy and tan colored.
APPENDIX B: Polished Section Descriptions
APPENDIX B

R-2-1A-337 (Figure 7)

Contains about 40% total sulfides, mostly pyrrhotite, with some of chalcopyrite.

Pyrrhotite occurs as semimassive, irregular patches and stringers. Both hexagonal and monoclinic pyrrhotites are present. Deformation textures such as stress twinning, kink banding, and annealing are shown magnificently in this section. The pyrrhotite contains some very tiny blebs of chalcopyrite that may be inclusions.

Chalcopyrite occurs mainly as stringers and veinlets through pyrrhotite but is also found within pyrrhotite.

The texture suggests a fairly complete recrystallization of the pyrrhotite, with subsequent stress developing the stress twins and kink bands. The chalcopyrite may have come in along fractures developed during this stress.

Paragenesis: pyrrhotite, chalcopyrite.

S-43-1-153 (Figure 8)

Contains about 80% total sulfides, mostly pyrrhotite with traces of chalcopyrite and pyrite.

Pyrrhotite occurs in massive zones and as disseminated grains in volcanic fragments. Both hexagonal and monoclinic. A polygonal texture with 120° triple...
points is observed. Stress twins, kind bands, and subgrain development are also exhibited.

Chalcopyrite occurs as irregular blebs and along grain boundaries of and fractures in pyrrhotite. Twinning is observed in the chalcopyrite.

Pyrite occurs as two small blebs with pyrrhotite and nonophaques. The relationship to the pyrrhotite is uncertain and the pyrite could be either early or late.

Texture suggests a fairly thorough recrystallization with late stress. Fractures filled with nonopaque minerals cut sulfides and rock fragments.

Paragenesis: pyrrhotite, chalcopyrite, pyrite (?).

R-2-1-286 (Figures 9 and 12)

Two sections made from this sample, the one photographed with the B sample.

Section A contains 70% total sulfides, mainly pyrite, with inclusions of pyrrhotite and the intermediate phase mentioned in the text.

Pyrite occurs in massive form and contains many irregularly shaped pyrrhotite inclusions and rare inclusions of the intermediate phase. Rock and mineral fragments are also included in the pyrite.

Pyrrhotite occurs as inclusions in pyrite and has ragged irregular boundaries. It is also present in
some silicate (?) zones, that cut across the section, as disseminated grains or blebs.

The intermediate phase present occurs as at least one small rounded inclusion in pyrite. It polishes and has less relief than the pyrite. It cannot be scratched with a needle. The color is greenish-yellow.

Texture suggests a replacement of pyrrhotite by pyrite, with replacement of some rock fragments also beginning. Section exhibits apparent flow structure.

Paragenesis: pyrrhotite, intermediate phase, pyrite.

Section B contains about 90% sulfides, mostly pyrrhotite with traces of pyrite.

Pyrrhotite occurs in massive form but has a small grain size and a cataclastic-annealed texture. Etching has shown a granular texture between monoclinic and hexagonal pyrrhotite. Variations in grain size may be due to "pressure shadows" effects in conjunction with the rock fragments. Many of the rock fragments have been shattered and invaded by stringers of pyrrhotite.

Pyrite occurs as small rounded to irregular blebs and stringers, mainly along the larger rock fragments.

Texture indicates movement or shearing of the rock with some annealing in pyrrhotite. Pyrite appears to
be replacing pyrrhotite. Fragments include mineral grains of variable size and larger rock fragments that appear to be metavolcanics.

Paragenesis: pyrrhotite, pyrite.

S-43-1-307(Figure 10)

Contains 70-80% total sulfide, mostly pyrrhotite with some chalcopyrite and pyrite.

Pyrrhotite occurs in massive form as aggregates of polygonized grains, as disseminated grains in the rock fragments, and as small inclusions in some pyrite grains. Both hexagonal and monoclinic forms are present. Deformation features such as twinning and kink banding are well developed in the pyrrhotites of this section.

Chalcopyrite occurs as irregularly shaped masses along shear or fracture planes with the [busted] pyrite crystals. It also occurs as a grain by itself in one rock fragment.

Pyrite occurs as broken crystals and rounded blebs concentrated along shear or fracture zones. Some replacement of pyrite by pyrrhotite and nonopaque minerals has occurred. Inclusions of pyrrhotite and gangue are found in pyrite.

Texture suggests recrystallization, and shearing along planes where pyrite is observed.
Paragenesis: pyrrhotite, pyrite, pyrrhotite, chalcopyrite.

R-2-1-110 (Figure 11)

Contains 90% total sulfides, mainly pyrrhotite with minor pyrite, intermediate phase, and chalcopyrite.

Pyrrhotite occurs in massive form as large grains that have been recrystallized and strained. The grains are polygonized with frequent 120° triple points. Individual grains show stress twinning, kink bands, sub-grain development, and both monoclinic and hexagonal forms. Pyrrhotite is being replaced by the intermediate phase (which is being replaced by pyrite) along fracture zones.

Pyrite occurs in irregular shaped blebs and tiny stringers. It often shows some concentric structures and has the intermediate phase between the pyrite and pyrrhotite. The pyrite contains many small inclusions of non-opaque materials and some inclusions of pyrrhotite. Also a few inclusions of intermediate phase.

The intermediate phase occurs between pyrite and pyrrhotite, and along edges of pyrite. The concentric structures are shown better in this phase than in the pyrite.

Chalcopyrite occurs with pyrrhotite, along the fractures and grain boundaries in pyrrhotite and as
blebs on the edges of pyrrhotite grains. Chalcopyrite is concentrated in areas where pyrrhotite is not massive. This area could be a volcanic rock fragment which is being replaced by the pyrrhotite.

Textures of sulfides and nonopakes suggest alignment and some replacement of rock fragments. Polygonal texture suggests thermal metamorphism while stress features in pyrrhotite suggest post-polygonization stress.

Paragenesis: pyrrhotite, chalcopyrite, intermediate phase pyrite.

R-2-1-178 (Figure 13)

Contains about 60% total sulfides, mostly pyrrhotite with traces of chalcopyrite.

Pyrrhotite occurs in massive and disseminated forms. It is disseminated in the black carbonaceous metasediment that is the host rock for the massive pyrrhotite. The pyrrhotite has polygonized but is elongated in a direction generally perpendicular to the stress twinning and kink bands. The foliation varies within the section as it has a swirly flow-type structure. The pyrrhotite occurs in both monoclinic and hexagonal forms in the section, with the hexagonal forming the interior portions of grains. Cleavage fractures with 90° angles occur in most
grains, with the fractures apparently related to the hexagonal pyrrhotite, as they bisect the angles shown by the hexagonal pyrrhotite.

Chalcopyrite occurs as small blebs along fractures in isolated grains of pyrrhotite. It is rare in this section.

Texture indicates directional stress causing elongation of pyrrhotite grains and deformation features in some. Small flakes of graphite define the foliation in the host rock. Some graphite flakes occur within the pyrrhotite.

Paragenesis: pyrrhotite, chalcopyrite.

R-2-1-351 (Figure 14)

Contains about 5% total sulfides, mainly pyrrhotite, with minor pyrite, chalcopyrite, sphalerite and traces of pentlandite.

Pyrrhotite occurs throughout the rock as blebs or grains, and is concentrated along small fractures or shears. Some pyrrhotite is included in chalcopyrite.

Pyrite occurs as rare small blebs with the disseminated pyrrhotite but is concentrated along the fractures or shears as coarser grained, partially broken crystals.
Chalcopyrite occurs as small blebs on the edges of disseminated pyrrhotite grains with the boundaries being concave into pyrrhotite. Chalcopyrite also occurs in greater concentrations, along the fractures or shears, with pyrrhotite and sphalerite. Small pieces of chalcopyrite are included in the sphalerite in some places.

Sphalerite occurs as small blebs along the edges of disseminated pyrrhotite grains and as small blebs or grains by itself. Sphalerite is also concentrated along the fractures or shears and has inclusions of chalcopyrite. Most of the boundaries between sphalerite and chalcopyrite are concave into the chalcopyrite.

Pentlandite was observed as one small flamey segregation in one pyrrhotite grain.

Deformation features, stress twinning in pyrrhotite, elongated pyrrhotite grains, and broken pyrrhotite crystals are found in this section. Chalcopyrite is also twinned.

Paragenesis: pyrite, pyrrhotite, pentlandite, chalcopyrite, sphalerite, and pyrite.

R-2-2-518 (Figure 15)

Contains about 5% total sulfides. Pyrrhotite is the main sulfide with minor chalcopyrite and pentlan-
dite, and traces of pyrite.

Pyrrhotite occurs as irregular blebs between the larger nonopaque grains. It contains pentlandite as "flamey" segregations and commonly has pentlandite and chalcopyrite along its edges. Pyrrhotite is being replaced by some chalcopyrite. Some stress twins and kink bands are observed in these pyrrhotites. Hexagonal and monoclinic forms are both present and easily visible in some grains.

Chalcopyrite occurs as irregularly shaped blebs and along grain boundaries, with pentlandite, of pyrrhotite. Chalcopyrite, pyrrhotite, and pentlandite occur as clusters or concentrations of very tiny blebs in the centers of some nonopaque grains. Chalcopyrite replaces pyrrhotite.

Pentlandite occurs in and along the grain boundaries of pyrrhotite. It is sometimes associated with chalcopyrite.

Pyrite occurs as rare, slightly rounded blebs in gangue.

Paragenesis: pyrite, pyrrhotite, pentlandite, chalcopyrite.

R-2-2-525 (Figure 16)

Contains about 5% total sulfide. Pyrite and
are the more abundant phases, with minor chalcopyrite and pentlandite.

Pyrite occurs as large crystals, grains, or blebs. Some have inclusions of pyrrhotite and chalcopyrite. They appear to be about the same grain size as the nonopaceous.

Pyrrhotite occurs as irregular blebs of variable size in the gangue, and as inclusions in pyrite and chalcopyrite. Almost all of the pyrrhotite contains "flamey" pentlandite segregations. Pyrrhotite is commonly associated with chalcopyrite, which it is being replaced by. Many of the large "grains" of gangue have very tiny blebs of pyrrhotite and chalcopyrite concentrated at their centers. About 20% of the sulfide in these zones is chalcopyrite. The rest is pyrrhotite with a little pentlandite. Deformational features in the pyrrhotite are rare.

Chalcopyrite occurs as irregularly shaped blebs associated with larger pyrite and pyrrhotite blebs as inclusions in pyrite and with pyrrhotite as tiny blebs concentrated in the centers of grains of gangue. The larger blebs of chalcopyrite are twinned. Chalcopyrite is replacing pyrrhotite.

Pentlandite occurs as small "flamey" segregations in pyrrhotite and as blebs along pyrrhotite grain
boundaries. Pentlandite appears to have exsolved from the pyrrhotite.

Paragenesis: pyrrhotite, chalcopyrite, pyrite, pyrrhotite, pentlandite, chalcopyrite.

R-2-1-143 (Figure 17)

Contains about 10-15% total sulfides, mostly pyrrhotite with traces of chalcopyrite, sphalerite and pyrite, irregularly distributed.

Pyrrhotite occurs as irregularly shaped blebs disseminated throughout the rock. Some pyrrhotite occurs in tiny fractures. Both hexagonal and monoclinic forms are present, but not in all grains. The pyrrhotite grains show stress twinning, kink banding, some subgrain development and polygonization. Banding of pyrrhotite zones and elongation of individual blebs are also observed. Pyrrhotite contains tiny pyrite blebs as inclusions. Sphalerite and chalcopyrite are associated with some grains or blebs.

Chalcopyrite occurs as blebs along the edges of pyrrhotite grains and along fractures in these grains. It also occurs as very tiny blebs by itself. Twinning is evident in some of the larger blebs.

Sphalerite occurs as small blebs by itself and along the edges of pyrrhotite grains.
Pyrite occurs as small blebs or remnant grains in pyrrhotite.

Textures of sulfides is interstitial to blebby with a banded appearance. Stress evident from textures of sulfides and from fine lamellar stress twinning.

Paragenesis: pyrite, pyrrhotite, chalcopyrite, sphalerite.

R-2-1-170 (Figure 18)

Contains less than 1% total sulfides, mostly pyrrhotite with traces of sphalerite, chalcopyrite and pyrite.

Pyrrhotite occurs as small blebs by itself and in blebs associated with chalcopyrite and sphalerite. The grains show very fine, lamellar stress twinning upon close examination. Often associated with biotites (?).

Sphalerite occurs as blebs by itself and in blebs associated with pyrrhotite. It appears to be strung out in certain beds or zones.

Chalcopyrite occurs in and around grains of pyrrhotite. It occurs also as tiny blebs by itself.

Pyrite occurs as at least one very small grain by itself. It is slightly anisotropic with bluish and brownish colors.
The texture of the sulfides is interstitial to granular. Some grains of pyrrhotite are observed to shapes roughly like that of a hexagonal dipyramid.

Paragenesis: pyrite (?), pyrrhotite, chalcopyrite, sphalerite.

R-2-1A-117 (Figure 19)

Contains about 30% total sulfides, but not equally distributed in the section. The sulfide is mostly pyrrhotite, with traces of pyrite and chalcopyrite.

Pyrrhotite occurs generally as interstitial material between nonopales and sometimes as rounded grains or blebs. Pyrrhotite exhibits some polygonization, stress twins, kink bands and some subgrain development. Both monoclinic and hexagonal forms are present.

Pyrite occurs as rare small blebs in pyrrhotite. Three are rounded and two appear to be bounded by crystal faces. All are anisotropic with some bluish and brownish colors. They appear to lie in one band across the section. It is possible they could be marcasite or another mineral of similar color and hardness but their small size precludes positive identification. They occur along and with
pyrrhotite but show no conclusive evidence establishing a paragenetic sequence. The crystal forms may indicate that the pyrite is the later of the two.

Chalcopyrite occurs with pyrrhotite along the grain boundaries and fractures.

Textures indicate that the sulfide may be replacing some matrix material in a coarse, recrystallized sediment or tuff. Sulfides may have been emplaced in parts of the section after metamorphic recrystallization of the nonopaque minerals.

Paragenesis: pyrrhotite, chalcopyrite, pyrite.