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THE PYRITE ZONE OF THE TEMAGAMI MINE
OF COPPERFIELDS MINING COMPANY,
TIMAGAMI, ONTARIO

by
James McWillie Franklin, B.Sc.

A thesis submitted to the Faculty of
Graduate Studies in partial fulfillment
of the requirements for the degree of
Master of Science.

Carleton University
Ottawa, Ontario
May, 1967.

The undersigned hereby recommend to the Faculty of
Graduate Studies acceptance of this thesis, submitted by
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ABSTRACT

The pyritic copper-nickel zone at the Timagami mine of Copperfields Mining Company lies in the base of a mafic sill, and is in contact with footwall rhyolite. All rocks are of Archean age, and were metamorphosed during the Kenoran orogeny.

The sulphide zone and wallrocks were studied petrographically and chemically.

Sulphide-silicate distribution and textural relationships, and copper-nickel distributions indicate that the sulphide and silicate phases coexisted after emplacement in a liquid state, and were possibly segregated because of immiscibility.

Sulphide textures and geochemical relations suggest a primary pyrrhotite-pentlandite-chalcopyrite sulphide assemblage.

Petrographic study of the wallrocks indicates that regional metamorphism in the greenschist facies completely altered the silicate assemblage, and the primary sulphides were metamorphosed to the assemblage pyrite-nickeliferous pyrite-millerite-siegenite-chalcopyrite.

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Mr. Walter Yzerdraat of Carleton University prepared excellent polished and thin sections. Mrs. D. Mah aided in the analytical work. Mrs. F. Thomas typed the manuscript.

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INTRODUCTION

The Timagami pyritic nickel-copper zone is a major strata-bound concentration of sulphide minerals. It has an uncommon mineral assemblage, and is spatially associated with an unusual concentration of chalcopyrite. The pyritic zone is adjacent to a mafic sill; the chalcopyrite bodies are in a thick footwall sequence of salic volcanic rocks.

The object of this study is to investigate the genetic relationship between the pyrite body and its wall rocks, and to establish some factors which prevailed in the environment of formation of the sulphide mineral assemblage.

Location and Access

The Timagami area is located approximately 60 miles north of North Bay, Ontario. It may be reached by road (Highway 11) and the Ontario Northland Railroad.

Copperfields Mine is located on Island 234 (Timagami Island) in Lake Timagami, and is in Phyllis Township, District of Nipissing. It may be reached by a road which leaves Highway 11 at a point 3 miles south of Timagami Village, and extends 11.9 miles westward to the shore of the lake. From there it is necessary to travel by boat to the island. It may also be reached by boat via the North-east Arm of Lake Timagami from Timagami Village.

Fig. 1. Regional Index Map showing location of
fig. 2 Northeastern Ontario (ODM, 1964).

Previous Investigations

The Timagami area has been mapped by W.W. Moorhouse (1947) and P.S. Simony (1964), both field officers of the Ontario Department of Mines. E.R. Rose (1965, 1966) of the Geological Survey of Canada has published two papers describing certain aspects of the chalcopyrite bodies and their genesis. Various company geologists, notably T.O.H. Patrick and F. Sharpley have carried out detailed mapping and some petrographic study of the Copperfields area. E.W. Nuffield and M.H. Frohberg (1960) have described millerite in the Copperfields sulphide bodies.

Several consulting geologists have studied the chalcopyrite bodies; early work at Copperfields involved a cursory study of the pyrite zone (Smith, 1957).

REGIONAL GEOLOGY

The Timagami copper deposit is located in a belt of Keewatin volcanic and sedimentary rocks which have been intruded by Algoman salic and mafic rocks. These Archean rocks form a window which has been exposed along the Northeast Arm of Timagami Lake by erosion of the overlying Huronian sedimentary rocks and Keweenaw sills and dikes (Fig.2 in pocket). The Archean has been mapped by W.W. Moorhouse (1942), the Huronian by P.S. Simony (1964). The following description is based primarily on their observations.

Keewatin

Keewatin rocks in the Lake Timagami area consist of salic, intermediate and mafic volcanic rocks with a small amount of intercalated sedimentary rocks including iron formation.

Salic volcanic rocks are well exposed along the south shore of the Northeast Arm of Lake Timagami, and are spatially related to the deposit (Simony, 1964). Generally these rhyolites are pale yellow, massive, fragmental, tuffaceous, or spherulitic rocks. Rhyolitic agglomerate is composed of lapilli and bombs ranging in diameter up to six inches, in a rhyolite matrix. It is only slightly altered and deformed. Some of the fragments were rounded by water action and have formed volcanic conglomerate. Other fragments are large bombs which form an agglomerate and are composed of alternating light and dark layers; the smaller agglomerate fragments are composed of black mafic material.

Table 1

Table of Formations

CENOZOIC

Recent: Swamp, lake and stream deposits
 Pleistocene: Glacial and glaciofluvial deposits
 _____ Unconformity _____

PRECAMBRIAN

Keweenawan: Olivine diabase dikes
 Intrusive Contact
 "Nipissing" quartz diabase sill, granophyre
 _____ Intrusive Contact _____

Huronian:

Cobalt group: Lorraine Formation: feldspathic
 quartzite, arkose
 Gowganda Formation: argillite, slate,
 greywacke, breccia, conglomerate,
 quartzite.
 _____ Unconformity _____

Algoman: Lamprophyre, amphibolite, carbonate, diorite
 and greenstone dikes.

_____ Intrusive Contact _____

Quartz porphyry, feldspar porphyry, felsite dikes.
 Granite, granodiorite, albite granite, granite
 and aplite dikes.

_____ Intrusive Contact _____

Diorite, quartz diorite.

Pre-Algoman (?): Diorite, quartz diorite, peridotite,
 metadiabase.

Keewatin: Mafic and intermediate flows, pillow lavas,
 amygdaloidal lavas, pyroclastics, tuffs, and
 metamorphosed equivalents.
 Banded iron formation
 Rhyolite, quartz and feldspar porphyry, salic
 tuff, agglomerate, and metamorphosed
 equivalents.

Salic tuffs (in addition to the agglomerates), are abundant along the Northeast Arm of Lake Timagami. These have been metamorphosed to chlorite-sericite schists.

In the mine area, massive, undeformed rhyolite and rhyolitic fragmental rocks prevail. These will be described in more detail later.

The intermediate and mafic lavas vary considerably in texture and composition. To the north and northeast of the mine the andesites are pillowed, vesicular, amygdaloidal and spherulitic. Fine to medium grained purple andesites, with small yellow grains of leucoxene crop out in Strathy and Strathcona townships. Along the north shore of the Northeast Arm of the lake volcanic rocks are intermixed with tuffs, slatey tuffs and agglomerates.

The mafic volcanic rocks have been extensively recrystallized around the granite intrusions in Chambers and Strathy townships. They are generally dioritic or amphibolitic, composed of saussuritized feldspar, uralite and quartz, and have a diabasic texture.

Keewatin iron formation forms a continuous stratigraphic marker in Strathy, Strathcona, Chambers and Cynthia townships. The Ko-ko-ko-Lake and Vermillion Lake-Iron Lake bands form the north limb of a syncline. The Timagami band forms the south limb. The iron formation varies in width from less than five to over five hundred feet, and consists of alternating beds of "almost massive magnetite, sugary white quartzite, jasper, grey (cherty) quartz, and chlorite

to tremolitic tuff" (Moorhouse, 1942, p.9). Bedded units are strongly folded and range from less than one-tenth of an inch to several inches in width. Cross faults with displacements of a few inches are common. There are variations in thickness due to folds in parts of the Timagami band. Variations in mineralogy result from facies changes along strike, and metamorphism.

Pre-Algoman

The "Pre-Algoman" diorite, peridotite and metadiabase are not contemporaneous, but are grouped together by Moorhouse for convenience. The diorites are highly altered and deformed, and thus classed as Pre-Algoman. They are located in Phyllis, Briggs and Strathcona townships, and are locally important to the Copperfields pyritic zone. A sill of diorite occurs along the Northeast Arm of Lake Timagami. It may be differentiated, with a dioritic phase on the north, and a gabbroic phase to the south. This diorite will be described later.

Peridotite and metadiabase occur in Strathy township. Inclusions of diabase have been found in Algoman granite on the east shore of Net Lake, thus fixing their age relationship. These inclusions are amphibolitic and highly altered.

Algoman

Four intrusive rock types are classified in the Algoman group; quartz diorite, granite, quartz and feldspar porphyry dikes, and mafic dikes.

Quartz diorite is exposed south of the Northeast Arm of Lake Timagami. It is composed of altered plagioclase with interstitial quartz, hornblende, and biotite or chlorite. Certain sections (e.g. in Briggs township) are sheared, cut by quartz veins, and contain disseminated pyrite.

There are three major granitic masses to the north and east of Timagami Island. The northern stock in Chambers, Strathy and Cynthia townships, is a coarse, equigranular, pink granite composed of euhedral plagioclase, anhedral microcline, perthite and quartz with a small proportion of biotite. Surrounding this stock is an alteration halo of recrystallized volcanic rocks, varying in width up to several hundred feet.

The central stock in Briggs, Chambers, and Joan townships is a massive porphyritic granite, containing large phenocrysts of oligoclase up to $1\frac{1}{2}$ inches in length. The matrix is similar to that of the northern granite body.

The southern stock (Phyllis, Yates, Briggs, and Strathcona townships) of white or greenish to pink granite is more albitic than the other masses and is characterized by chloritized ferromagnesian minerals. Grain size is variable and gneissosity is locally developed. This mass has many satellite bodies along its north boundary.

Quartz and feldspar porphyry dikes which may be related to the granite are distributed throughout the area. Numerous lamprophyre, greenstone and carbonate dikes are grouped by Moorhouse (1946, p. 19) as 'basic' dikes of Algomian or Pre-Cobalt age.

Huronian

Huronian sedimentary rocks surround the Archean window of which Timagami Island forms the southwest corner. The Cobalt Group consists of two slightly deformed formations of low metamorphic grade. The older Gowganda Formation consists of greywacke, conglomerate, argillite, breccia and quartzite as its basal member, followed conformably by argillite, then an upper conglomerate and greywacke, and finally an upper argillite. It varies in thickness to over 2000 feet, and lies unconformably on an Archean basement which has a relief of at least 1000 feet.

The Lorraine Formation, consisting of over 2000 feet of feldspathic quartzite and arkose, lies conformably on top of the Gowganda. The contact between the two formations is transitional.

Keweenawan

There are two intrusive post-Huronian rock types in the Timagami area. The major type is represented by a sill-like mass of Nipissing diabase. It is generally concordant with the Cobalt stratification, but in places the contacts are discordant. It is medium to coarse grained, moderately to highly altered, and ophitic in texture. It is composed of two varieties of plagioclase, a calcic type ranging from andesine to labradorite in composition, and a sodic type, usually untwinned albite. Pyroxene is altered to uraltic hornblende and chlorite. Pyrite, magnetite, leucoxene and apatite are common accessory minerals.

The minor Keweenaw rock type, olivine diabase, intrudes all consolidated formations present in the Timagami area. This rock is fresh, and consists of labradorite, olivine, and augite.

Pleistocene and Recent

The area has an extensive cover of Pleistocene glacial drift (Simony, 1964). Eskers were deposited by south moving glaciers. Much of this material has been reworked by recent water action to form beach and gravel deposits.

Structure

Folding

The Keewatin rocks are folded into a major syncline whose axis extends through Link and Tetapaga Lakes, approximately parallel to the Northeast Arm of Lake Timagami. The syncline is truncated by the Spawning Lake granite stock to the southwest. Moorhouse (1942, p.21) gives the following points of proof for the existence and location of the axis:

- (1) grain gradations indicate a north facing of the tuffaceous beds in the Timagami iron formation
- (2) minor drag folds and a northerly dip of the Timagami iron formation corroborate a north facing
- (3) overlying formations contain fragments of the iron formation
- (4) determinations on pillows in Strathy township north of Link Lake suggest that the andesites face south
- (5) drag folds and fracture cleavage in the Iron Lake iron formation suggest a south-facing top.

If this syncline exists, the rhyolites mapped by Moorhouse are on the bottom of the exposed Archean sequence, and are overlain by andesitic and basaltic volcanic rocks which include minor sedimentary horizons and the siliceous iron formation.

Archean rocks are not otherwise folded. Variations in strike and schistosity appear to be related to the granitic intrusions.

Cobalt rocks are folded into a series of open anticlines and synclines which plunge northward at about 5° . The flanks of the folds dip at approximately 20° (Simony, 1964).

Faulting and Shearing

Two major shear or fault zones occur in the Archean rocks. The most prominent zone follows the Northeast Arm of Lake Timagami. The volcanic rocks near Timagami Village and along the entire south shore of the Arm are deformed into highly sheared and carbonated schists. Complimentary to this shearing are tension fractures striking $N60^{\circ}-70^{\circ}W$ (Moorhouse, 1942). This major shear zone extends as far southwest as Sulphide Point opposite Timagami Island, but is not evident on the island.

A few miles east of the Copperfields deposit, but beyond the map area, the Grenville front separates the Grenville and Superior provinces. The 'front' is marked by a major fault or shear zone which trends northeast, and parallels the Northeast Arm fault zone (Johnston, 1958).

A smaller fault or shear zone of schistose volcanic rocks, parallel to the Northeast Arm, is found to the north of the Northeast Arm zone, near Link Lake.

GEOLOGY OF THE COPPERFIELDS MINE AREA

A thick sequence of salic volcanic rocks forms most of the southern portion of Timagami Island. They are intruded by a metadiorite or metagabbro sill, accompanied to the north by gabbroic or andesitic rocks (Figs. 3, 4, 5). The pyrite occurs in the southeast edge of the metadiorite. The north and south extremities of the island are covered by flat-lying Gowganda conglomerate. Several dikes transect these units.

Thin and polished section examinations, augmented by selected chemical analyses were used to study in detail the petrography of the rocks in the vicinity of the pyrite zone.

The rocks are conformable with the regional stratigraphy and structure.

Table 2 lists the formations in the vicinity of Copperfields mine.

Structure

The rocks strike N50°E. The average dip of the rhyolite-metadiorite contact is 67° to the northwest. The dip has been locally observed to flatten with depth (Fig. 5). Close examination of contacts between rhyolite and rhyolite breccia, and between rhyolite breccia and rhyolite fragmental shows that their average dip is approximately 72° to the northwest. This minor discordancy, as well as strike and dip discordancies of a few degrees along the Northeast Arm of Lake Timagami, suggests the metadiorite may be a dike rather than a sill (Patrick, personal communication, 1965).

FIGURE 4 Section 2+00E showing pyrite zone and chalcopryite bodies
Copperfields Mining Company, Temagami Mine
(After Copperfields Mining Company section 2+00 E)

FIGURE 5 Section 12+00E showing faulting and the relationship of the pyrite and chalcopyrite bodies
Copperfields Mining Company, Temagami Mine
(After Copperfields Mining Company section 12+00 E)

Table 2

Table of Formations

CENOZOIC

Pleistocene: Stratified sands and gravel;
 fluvioglacial outwash containing
 calcareous coral fragments:
 thickness 15'

 Unconformity

PRECAMBRIAN

Huronian: Gowganda Conglomerate

 Unconformity

Algoman: Diorite dikes

Minor faults

 Intrusive contact

Pre-Algoman: Metadiorite, metagabbro, thickness
 up to 1000'

Northeast Arm fault

Keewatin: Massive rhyolite, thickness 150'
 Rhyolite breccia, thickness 250'
 Fragmental rhyolite, thickness 400'
 Rhyolite breccia, thickness 500'

There exists a possibility that the body is a volcanic rock. However, much of the previously presented data do not support this suggestion. Grain size does not change across the body; pillow structures, flow structures and vesicles are absent. The large thickness would be unusual for a flow. The metadiorite has altered the underlying rhyolite by addition of mafic constituents, but shows no development of chilled margin at its bottom contact. It would probably be finer grained, show diminishing grain size gradation towards the outer surfaces, and have a chilled margin if it were a volcanic rock. Thus petrographic and structural relationships indicate that the metadiorite is probably an intrusive (hypabyssal) rock, and not a coarse flow. Moorhouse (1946) reached the same conclusion.

There is no local folding. Changes in the thickness of major units are due to varying accumulation of ejecta and variations of flow thickness. Some units appear to be truncated by the overlying unit as is evident on the rhyolite-rhyolite breccia contact immediately to the north of the Phillips Bay thrust fault. Combined with the regional synclinal structure, these truncations are evidence for a northwest facing of the volcanic rocks in the vicinity of the sulphide deposits.

The rocks are strongly faulted but not sheared in the mine area. Two major groups of faults exist, as well as the previously mentioned Northeast Arm shear zone or fault.

The most prominent faults are three parallel thrusts exhibiting right hand displacement. These strike 95° to 115° and dip south at 55° to 60° . They are exposed in the mine workings, and maintain a constant dip.

Numerous normal and reverse faults with steeper dips cause considerable local offset of the volcanic and intrusive units. Some of these are filled by later lamprophyre and diorite dikes. The normal and reverse faults strike north and dip steeply west. Resultant horizontal offset on these faults varies to 200 feet. All movement along these faults is post-metadiorite and prior to the emplacement of diorite and lamprophyre dikes.

Jointing is moderately well developed; joints are normal and parallel to the strike of the metadiorite.

Salic Volcanic Rocks

All of the rhyolitic rocks have been regionally metamorphosed to the quartz-albite-muscovite-chlorite subfacies of the greenschist facies. This metamorphism is quite uniform; no original mineralogy is detectable, although some original texture may remain.

Chalcopyrite and pyrite are disseminated through most of the volcanic rocks near and along the contact between massive rhyolite and rhyolite breccia, both near the deposit and south of the Northeast Arm of Lake Timagami.

Rhyolite Breccia

Rhyolite breccia forms the basal and third units of the volcanic formation on Timagami Island. Samples from the basal unit were not examined in this study, but the two units are considered to be lithologically similar (Sharples, 1962; Patrick, 1962).

The upper unit is a pyroclastic breccia, with local flow breccia horizons. Massive rhyolitic flows are intercalated throughout. In some areas rhyolite breccia is tuffaceous, but most sections have a brecciated texture (Plate 1). The unit is 250 feet thick.

The bottom unit is also a silic pyroclastic breccia, composed of ejecta. This breccia may be similar to the explosive breccias of Sudbury. Minor andesitic horizons occur near the base, and some massive rhyolite members are intercalated throughout.

The rhyolite breccia has a light grey, hard matrix, with medium green, soft fragments dispersed throughout. The matrix is aphanitic. The fragments are mottled, with a dark reaction rim surrounding them, and are composed of quartz with up to 60 percent chlorite. They are angular, range in size from 1 mm to 15 mm, and form up to 60 percent of the rock (Plate 2).

The matrix minerals are quartz, sericite and carbonate, with accessory chlorite, tourmaline and opaque minerals. Quartz occurs in two distinct grain sizes; approximately 40 percent of the matrix quartz has an average diameter of 0.01 mm, while the remainder has an average diameter of 0.1 mm.

Plate 1: Rhyolite breccia fragments surrounded by sericite-chlorite matrix; $\times \frac{1}{2}$.

Plate 2: Rhyolite breccia fragments composed of granular quartz, surrounded by sericite matrix; qtz = quartz, ser = sericite (x-nicols) $\times 75$.

Plate 1: Rhyolite breccia fragments surrounded by sericite-chlorite matrix; $\times \frac{1}{2}$.

Plate 2: Rhyolite breccia fragments composed of granular quartz, surrounded by sericite matrix; qtz = quartz, ser = sericite (x-nicols) $\times 75$.

Plate 1: Rhyolite breccia fragments surrounded by sericite-chlorite matrix; $\times \frac{1}{2}$.

Plate 2: Rhyolite breccia fragments composed of granular quartz, surrounded by sericite matrix; qtz = quartz, ser = sericite (x-nicols) $\times 75$.

Sericite in the fine-grained portion is aligned in one direction, with a pattern suggestive of metamorphic foliation. The coarse portion is heterogeneous and structureless. Fine grained, untwinned feldspar may be present with quartz in the rhyolite rocks.

The breccia fragments are composed of chlorite, carbonate, and quartz, with accessory opaque minerals. Chlorite forms a reaction rim around all breccia fragments. This rim is in some fragments outlined by a fine coating of hematite. The central portion of the fragments has varying amounts of chlorite, calcite, quartz and epidote with accessory opaque minerals. In some cases the entire center has been replaced by calcite, whereas others are composed of up to 50 percent chlorite, 40 percent calcite, and 50 percent epidote, with accessory leucoxene and magnetite.

The fragments exhibit considerable primary texture. Pseudomorphic structures, similar in habit to pyroxene crystals, are outlined by secondary magnetite. These show a euhedral to subhedral crystal form, with well developed basal parting, and have an average length of 0.2 mm. In addition, a few relict crystals of saussuritized plagioclase are evident.

Fragmental Rhyolite

Basal rhyolite breccia is overlain by fragmental rhyolite. This is an autoclastic silic volcanic rock. It is hard, competent and white to blue grey. Fragments are ellipsoidal in shape, and stand out on a weathered surface due to oxidation of

the more ferruginous matrix. The fragment size varies from 0.2 to 1.2 inches.

The minerals present are mainly quartz, sericite and calcite with accessory tourmaline and pyrite. Quartz grains have an average diameter of 0.2 mm. Grain boundaries are highly serrate, irregular, and surrounded by sericite. Quartz is confined mainly to the volcanic fragments, and composes up to 75 percent of them.

The matrix is composed of up to 80 percent sericite with micro-crystalline quartz. Sericite forms anhedral, platy grains, and has formed around the volcanic fragments. It appears to emphasize flow features, as the orientation around an ellipsoidal fragment is parallel to the long axis of the fragment.

Opaque minerals are scattered throughout the unit. They are mainly pyrite and chalcopyrite. Hematite surrounds the breccia fragments in some areas.

The average mode for this unit is 70 percent quartz, 25 percent sericite and 5 percent carbonate.

Massive Rhyolite

Massive rhyolite is the youngest unit in the volcanic sequence on Timagami Island. It is structureless and almost homogeneous in appearance both on outcrops and in underground workings and drill core. It has an average thickness of 150 feet. Up to three feet of the rhyolite has been thermally altered by the adjacent metadiorite.

In hand specimen the rhyolite is grey to grey green, has medium hardness, and is fine grained to aphanitic. Minerals present are quartz, sericite, chlorite, calcite, and accessory pyrite, magnetite, and leucoxene (Plate 3). The original rhyolite was probably very fine grained or micro-crystalline, and thus amenable to recrystallization.

Secondary quartz is ubiquitous, and varies in size from 0.05 to 2.5 mm, with an average of 0.15 mm. It has highly irregular, serrate grain boundaries. The grains are inclusion-free, and show sharp extinction except in shear zones or near faults, where extinction is undulatory, due to strain.

Sericite is found through the bottom 80 percent of this unit. Sericite grains have an average length of 0.01 mm and width of 0.001 mm, but range to a length and width of 0.1 mm and 0.01 mm, respectively. Orientation is random, except near fault and shear zones, where it is parallel or sub-parallel to the direction of movement.

Chlorite is fine grained (av. dia. 0.01 mm), equant, and distributed through the upper 70 percent of the massive rhyolite unit. It has anomalous Berlin blue interference colors, and shows parallel extinction.

Calcite is abundant in some areas of the rhyolite, and completely absent in others. It occurs in small (0.05 mm av. dia.) irregular patches, which are mostly disseminated evenly through localized areas. Calcite is concentrated in shear and fault zones, which are often entirely filled by

calcite and quartz. Post-depositional strain has caused elongation of the calcite and quartz grains; strain has also caused partial recrystallization of calcite.

Opaque minerals are distributed through the rhyolite, and have an average diameter of 0.01 mm. Pyrite typically has a cubic habit, and is concentrated within 25 feet of the pyrite zone. Leucoxene is anhedral, contains little or no magnetite, and forms small medium brown flakes. It is evenly distributed. Magnetite and hematite are the least common opaque minerals. Disseminated chalcopyrite surrounds the copper-rich sulphide bodies located along the contact between rhyolite and rhyolite breccia.

Tourmaline, a minor accessory, occurs as short stubby crystals, with marked blue-yellow pleochroism.

The rock is fine grained and homogeneous. There is no mineral orientation, except due to the local effects of shearing. Generally the rhyolite has a granoblastic texture. In a few places near the top of the rhyolite there is a relict lath-like texture suggestive of primary feldspar phenocrysts.

The minerals are distributed in a consistent pattern within the massive rhyolite unit. Quartz and sericite contents decrease, and the chlorite content increases upwards from the bottom. There is an abrupt change in the variation

Plate 3: Massive rhyolite; quartz grains evenly distributed in a sericite matrix; qtz = quartz, ser = sericite (x-nicols) x 75.

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Figure 6. Relative changes in quartz and chlorite content, and in quartz grain size in rhyolite.

patterns at a distance of 30 to 50 feet from the metadiorite contact (Fig. 6). The carbonate content is irregular; the opaque minerals, although variable in mineralogy, are constant in mode. The modal ranges are presented in Table 3. This change is further reflected in grain size. Quartz in the upper 30 feet has an average diameter of 0.1 mm. Below this it is much finer, with an average diameter of 0.01 mm.

Table 3

Mode of major minerals in massive rhyolite

	range
Quartz	10 - 75%
Chlorite	5 - 90%
Sericite	5 - 40%
Carbonate	0 - 5%
Tourmaline	0.1%
Opaque	0.1 - 2%

The systematic modal variation through the massive rhyolite is probably due to the inclusion of two or more rhyolite flows within the stratigraphic unit.

Mafic Intrusive Rocks

Two groups of mafic intrusive rocks occur on Timagami Island. The largest and most important has been termed 'metadiorite' by the Copperfields geologists. It will be seen that, on the basis of petrographic and chemical work, the rock is correctly termed a metadiabase.

The second group consists of several types of dike rocks which generally occupy post-metadiorite fault zones.

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The second group consists of several types of dike rocks which generally occupy post-metadiorite fault zones.

Metadiorite

The 'metadiorite' is a massive, metamorphosed sill approximately 1000 feet thick. The sulphide-rich "pyrite zone" occurs within it, along the bottom, and is in contact with underlying rhyolite (Figs. 4, 5). No primary minerals remain in the metadiorite, but primary structure is present.

The weathered surface of the metadiorite is dark green to black, smooth, and soft. The fresh surface is mottled medium green, exhibits relict ophitic texture, and is massive (Plate 4).

Mineralogy

The minerals present are (a) chlorite, (b) albite, (c) epidote, (d) quartz and calcite, (e) leucoxene, and (f) accessory magnetite, hematite, pyrite, and possibly serpentine.

(a) Prochlorite is the predominant chlorite mineral present. It is colorless to green in plane light, and shows distinct pleochroism, with the formula:

α = green

β = green

γ = pale yellow to brown

Near the pyrite zone pleochroism is more pronounced, and the colours are deeper. The average refractive index is 1.650. It is length-slow, and has first order grey to yellow interference colours. In some areas birefringence increases to anomalous first order blue or purple. The grains form a felt-like mass.

Plate 4: Hand specimen of metadiorite showing relict feldspar laths (white) in a chlorite groundmass (green) x $\frac{1}{2}$.

Plate 5: Albite outlining relict plagioclase lath; Groundmass (dark green) is chlorite; smaller relict plagioclase crystal (1) exhibits remnant twinning. Cream-white granular aggregate (2) in bottom area of picture composed of carbonate and epidote; ab = albite, chl = chlorite, cb = carbonate and epidote (x-nicols) x 40.

The deep colour and high refractive index indicate a high magnesium and iron content in the prochlorite (Deer, Howie and Zussman, Vol.3, 1962); an increase in absorption and birefringence towards the pyrite zone indicates a corresponding increase in iron content. The grains are generally subhedral, elongate, multiply twinned on (001), and vary in size from 0.02 to 0.1 mm.

The chlorite mass is interstitial to relict plagioclase laths and opaque minerals. Texturally it reflects the anhedral habit of the original mafic minerals. A few euhedral mafic forms remain near the pyrite zone. These show relict cleavage parallel to the long axis of the primary mineral, and are possibly pseudomorphous after an amphibole.

(b) Albite is present throughout the metadiorite, and exhibits three forms. In its most common form, it is transparent, colorless, and occurs as euhedral, round, equant grains, with an average diameter of 0.04 mm, and range from 0.01 to 0.4 mm. Grain boundaries are sutured and ill-defined. The refractive index is less than 1.536; the grain relief is low. The grains are filled with minute inclusions (av.dia. 0.004 mm) of chlorite and epidote. They frequently show undulatory extinction. Albite twinning is present in about one percent of the grains.

Albite in the granoblastic aggregate, or 'sugary' form, is associated primarily with altered feldspar laths, and is disseminated throughout the rock. The most heavily saussuritized areas are composed of up to 30 percent albite, the remainder being epidote.

Saussuritized plagioclase is rimmed and has fractures filled by albite (Plate 5). This albite is finer grained than the granular variety (av.dia. 0.008 mm). It forms anhedral to subhedral, generally elongate crystals, which clearly outline the primary feldspar texture. The grains are generally inclusion free. Albite twinning is present in 5 percent of the grains of this habit.

Albite also occurs in the less highly altered portions of the metadiorite, where it is completely pseudomorphous after a more calcic plagioclase. The original form and twin structures are retained, but the composition is altered to albite with inclusions. The grains consist of 20 percent to 50 percent epidote, with up to 10 percent carbonate and chlorite. This form of albite is most common 100 to 150 feet from the north contact of the metadiorite, and within 10 to 30 feet of the pyrite zone, but is formed to a lesser extent throughout.

(c) Epidote commonly occurs as a fine replacement aggregate, after calcic feldspar. In some portions of the metadiorite, however, it is medium grained (av.dia. 0.2 mm), and randomly distributed. The fine grained 'saussurite' variety is, however, always associated with these laths (Plate 5).

Coarse epidote is anhedral, moderately to strongly pleochroic, has high relief and high birefringence. The most extreme pleochroic effect shows a red - violet - yellow scheme. Less pleochroic varieties show a colorless -

yellow - pale green scheme. An increase in the degree of pleochroism is usually related directly to the manganese content (Deer, Howie and Zussman, Vol.1, 1962). Thus the most highly pleochroic varieties are probably manganiferous epidote, possibly piedmontite. This form of epidote exhibits second and third order interference colours.

The microcrystalline to very fine grained aggregates which replace plagioclase laths have a light brown, 'cloudy' appearance in plane polarized light, and are black under crossed nicols. Where both forms of epidote coexist, the coarser variety discontinuously surrounds the finer. It is difficult to accurately estimate the proportions of albite and saussurite, as they are extremely fine grained and intermixed.

(d) Quartz and calcite are secondary minerals, probably generated through metamorphism. Quartz is clear and usually colorless. It is anhedral and inclusion free; the average grain diameter is 0.2 mm. It shows no preferred association with other minerals. Extinction is sharp, indicating the absence of post-metamorphic strain.

Calcite is ubiquitous in the metadiorite. It is anhedral, patchy, and randomly distributed.

In addition to the quartz described above, fine discontinuous quartz-carbonate veins are scattered randomly through the metadiorite. The average grain diameter is 0.2 mm for both minerals. They are anhedral, with sutured grain boundaries, and are inclusion-free. The proportion of constituents varies from total calcite to total quartz.

(e) Leucoxene occurs as anhedral patches, 0.02 to 30 mm in diameter, and is the most common oxide mineral. In hand specimen it forms medium brown plates; some plates are homogeneous, but usually they exhibit thin black lamellae. In other plates only the lamellae are evident, with a small amount of the brown material aligned parallel to them.

Microscopically, leucoxene is composed of a partially opaque, medium brown groundmass of microcrystalline grains. Some of the particles (rutile) have high birefringence, others (hematite) are opaque. Most of the leucoxene grains exhibit thin magnetite lamellae (Plate 6), varying in width from 0.002 to 0.010 mm and length up to 1 cm. Due to the oblique section at which they are usually cut, tend to form triangular patterns.

The proportion of hematite and rutile to magnetite is variable. In most grains, approximately 85 percent of the exposed area is composed of the former two minerals. However, many grains contain equal amounts of both, and a few have a very high proportion of magnetite. In the latter case, the morphologic relationship is reversed, as magnetite forms the groundmass and pseudobrookite-rutile the lamellae.

(f) Accessory Minerals: Hematite is the most abundant accessory mineral. It is pseudomorphous after magnetite, and occurs in subhedral to euhedral grains, with an average diameter of 0.2 mm. It probably was formed by the oxidation of primary magnetite during regional metamorphism (Plate 7).

Magnetite has formed from the alteration of iron-bearing minerals, as well as the breakdown and alteration of ilmenite, as previously described. In some sections magnetite outlines

Plate 6: Leucoxene (white) with magnetite lamellae (black) in an albite-epidote-chlorite groundmass (right side of picture); (x-nicols) x 75.

Plate 7: Hematite pseudomorphs (white) after magnetite in chlorite groundmass; (x-nicols) x 25.

Plate 6: Leucoxene (white) with magnetite lamellae (black) in an albite-epidote-chlorite groundmass (right side of picture); (x-nicols) x 75.

Plate 7: Hematite pseudomorphs (white) after magnetite in chlorite groundmass; (x-nicols) x 25.

cleavage planes and grain boundaries of primary mafic minerals; in others it forms a net-like structure.

Pyrite, chalcopyrite and other sulphide minerals are associated with the pyrite zone, and will be described in another section.

Fibrous serpentine occurs as a few large pseudomorphic aggregates, probably after olivine near the pyrite zone.

Texture

Gross textural relationships in the metadiorite are essentially those of an igneous rock. Primary minerals were plagioclase (probably labradorite or andesine) and mafic minerals (pyroxene and/or amphibole, accessory olivine), ilmenite, and accessory sulphide minerals.

Plagioclase formed euhedral, lath-shaped crystals, varying in length from 0.05 to 10 mm. The mafic minerals were mainly anhedral, and crystallized interstitially to the plagioclase laths. The texture was thus intergranular.

Plagioclase laths are mostly randomly oriented, and in places show a vague layering suggestive of a cumulate texture.

Thus, the texture is blastophitic, in part cumulate, and suggests that the parent of the metadiorite was formed from a silicate melt.

Metamorphic Grade

The entire Archean sequence in the Timagami Island area has undergone metamorphism in the greenschist facies, which

in the metadiorite has produced a chlorite-albite-epidote-(quartz-calcite-leucoxene) assemblage. Although the overall grade is constant, there are local variations as shown by the change in alteration of feldspar and grain size of epidote.

In general, the observed assemblage fits the Barrovian Bl.1 (Quartz-albite-muscovite-chlorite) subfacies of the greenschist facies (Winkler, 1965).

Modal Analysis

A series of thin sections from specimens taken from the bottom (southeast) 150 feet of the metadiorite were modally analyzed (Table 4; sample numbers increase towards the pyrite zone, which is not included).

Table 4

Variation in the modal analysis of metadiorite (based on point counts of 8 thin sections) with proximity to the pyrite zone.

DDH footage	11	31	45	60	95	109	119	124
Chlorite	32.2	33.7	41.97	24.32	37.86	42.35	17.0	24.43
Albite	15.7	16.7	10.68	25.29	18.14	37.18	39.42	26.28
Epidote	18.0	9.4	1.56	.15	-	-	-	-
Saussurite ¹	20.5	26.7	28.96	38.13	42.51	3.73	26.48	20.12
Carbonate	3.7	4.7	.68	10.4	.12	1.05	9.03	1.08
Quartz	6.0	2.3	.36	.02	-	-	-	-
Opaque	3.3	5.8	6.5	10.4	12.6	6.0	8.0	28.13

¹Saussurite is composed primarily of epidote, but is a mixture including calcite and albite as well.

Quartz decreases and opaque minerals increase as the pyrite zone is approached (Fig. 7). The opaque minerals are leucoxene and sulphides. The proportion of both increases towards the pyrite zone, but the sulphide content increases more rapidly than the oxide content.

The distribution of quartz, mafic mineral and sulphides is suggestive of some differentiation during crystallization. Further discussion of this possibility will follow a description of the chemistry of the sill.

There is an overall increase in albite as the pyrite zone is approached, but no appreciable systematic variation in chlorite.

Epidote and saussurite are differentiated on the basis of grain size. Coarse, highly birefringent material is classified as epidote, while microcrystalline, apparently anisotropic, material is classified as saussurite. It is impossible to draw any conclusions from the saussurite distribution; it is intergrown with albite, and accurate differentiation is impossible.

In most areas the pyrite zone appears as a single unit. However, there is, in some areas, a break in the distribution of the opaque minerals in the pyrite zone. In places along the sill, the pyrite zone is not a single unit but consists of two layers separated by sulphide-poor metadiorite.

Gabbro

The northwest contact of the metadiorite is against gabbro, very similar in most respects to the metadiorite. This rock, however, is darker in hand specimen, and has a hypidiomorphic-granular texture. It is composed of saussuritized plagioclase and chlorite, and contains up to ten percent magnetite near the metadiorite contact. Its structural relations with the metadiorite are unclear; it may be a variety of the metadiorite, or it may be separated from it by an intrusive contact.

Dike Rocks

Three types of dikes intrude the rhyolite and metadiorite sequences. These are (1) lamprophyre, with locally altered hornblende phenocrysts (Simony, 1964), (2) fresh massive medium to fine grained diorite, and (3) chloritized and amphibolitized fine to coarse grained mafic dikes.

In addition, at the southern edge of the mine area a diabase dike of the Nipissing type has been observed.

Gowganda Conglomerate

Over one-half of the northern section of Timagami Island, and the southern tip of the island, are covered by flat-lying Gowganda conglomerate. This unit is a massive polymictic boulder conglomerate with a greywacke matrix (Simony, 1964). Red granite is the most common boulder in the conglomerate, but other forms of granite, metamorphic, and sedimentary rocks are common.

The Gowganda conglomerate forms the lowermost formation of the Cobalt Series and is of Huronian (Early Archean) age.

Summary

(1) The rhyolite breccia is probably a flow breccia; the fragments probably were completely solid prior to final deposition.

(2) The massive rhyolite may be a composite flow.

(3) All salic volcanic rocks have been completely metamorphosed; the present mineral assemblage and texture is a result of this metamorphism; little or no primary texture or structure remains.

(4) The metadiorite is a mafic igneous body that has been completely metamorphosed to the greenschist facies. Primary texture has been partially retained.

(5) There is no petrographic or structural evidence to support a volcanic origin for the metadiorite.

CHEMISTRY OF THE ROCKS

All rocks were analyzed for silica, iron, sodium and potassium. A few samples of the salic rocks were quantitatively analyzed for several additional trace elements. Silica was determined by X-ray fluorescence, iron colorimetrically with orthophenanthroline, sodium and potassium by flame photometry. Trace elements were determined by emission spectroscopy.

Chemistry of Salic Rocks

Samples of rhyolite breccia and rhyolite were analyzed for silica, iron, sodium, potassium, and several trace elements, in order to determine distribution patterns and geochemical irregularities (Appendix tables 1 and 4; Figs. 8 and 9).

Rhyolite Breccia

Average composition of three samples was 59 percent SiO_2 , 4 percent total iron as Fe_2O_3 , 1.75 percent Na_2O , and 1.8 percent K_2O . These data suggest that the rock is actually a trachyte or dacite (Nockolds, 1948).

Rhyolite

Silica in ten samples of rhyolite ranges from 46.5 percent to over 72 percent (Figs. 8 and 9). Silica increases away from the pyrite zone and reaches a maximum near the contact with the rhyolite breccia. Silica content ranges from that of a basalt to that of a true rhyolite. The distance from

FIG. 9

the zone of lowest silica near the contact to the area containing the highest silica varies from 40 to 60 feet.

The sodium content of 10 samples ranges from 0.5 percent to 2 percent. The content increases slightly away from the rhyolite-metadiorite contact.

Iron and silica have reciprocal distribution patterns in the rhyolite. Iron ranges from 2.5 percent to 11.2 percent total iron (as Fe_2O_3).

Discussion

Silica Content of Rhyolite Breccia

The deviation from the silica content of a true rhyolite (Nockolds, 1954) results from the silica deficient nature of the breccia matrix. As the rhyolite breccia is composed primarily of sericite, it has a lower SiO_2 content than the breccia fragments. However, petrographic examination reveals that the fragments approach a true rhyolite in composition; the name rhyolite breccia is thus correct.

Content and Distribution of Silica in Rhyolite

Three explanations of the increase in silica away from the metadiorite-rhyolite contact may be given.

1. A variation in original composition of the salic flow rocks is possible, with upper units more mafic, and thus less siliceous, than lower. The fact that upper units contain more chlorite may, in part, validate this idea.

2. The silica content has been modified by contact metasomatism during intrusion of the sill. Later regional

metamorphism may have masked macroscopic evidence, but chemical variations have remained. As the Timagami metadiorite is at least 1000 feet thick, and was intruded at a high temperature, it is possible that a 60 foot contact reaction zone would develop. Given a large compositional gradient, ions may migrate up the temperature gradient. Thus silica would migrate from rhyolite to metadiorite, while iron, aluminum and magnesium would move in the opposite direction.

3. The third possible mechanism, that of migration during metamorphism, would invoke similar processes in an attempt to attain the same equilibrium. Iron could in part be derived from the pyrrhotite-pyrite reaction to be mentioned in the discussion of sulphide chemistry below (p.91).

Proof of either of the last two hypotheses is difficult due to incomplete studies of the stoichiometric requirements of all of the reactions involved, as well as of ionic mobilities.

Trace Elements in Rhyolite and Rhyolite Breccia

Two samples of rhyolite and one of rhyolite breccia from widely separated localities were analyzed qualitatively by emission spectrography for trace element content (Appendix table 4).

The two rhyolite samples compare closely; the sample closest to the pyrite zone is high in iron, as was shown by other analyses.

Chemistry of the Metadiorite

Samples representing the exposed width of the 'metadiorite' sill were analyzed for silica, iron, sodium and potassium.

The mean silica content in 32 samples is 46.4 percent SiO_2 (Appendix table 1). A weighted average is difficult to assign as sampling from drill core was concentrated in the bottom (southeast) two hundred feet of the sill, with surface samples representing the remaining width. However, a weighted average, assuming each value to be representative of one half the distance to the sample on either side of it, is approximately 48 percent SiO_2 .

A profile across the metadiorite sill (Fig. 10) shows an abrupt downward increase from 38.2 percent silica to 48.7 percent silica. From the latter point, silica gradually decreases to between 45 and 48 percent silica near the bottom. Detailed analyses of the 100 feet of metadiorite immediately adjacent to the pyrite zone shows an erratic pattern (Figs. 11, 12).

Iron

The iron content in the metadiorite is almost constant, increasing slightly towards the pyrite zone (Fig. 11). The average value is 11.0 percent iron as Fe_2O_3 , and the standard deviation is 0.4 percent (Appendix table 1).

Sodium

The sodium content of the metadiorite is extremely variable. Twenty samples from drill core were analyzed; sodium

K-E
10 X 10 TO 1/2 INCH 46 1320
7 X 10 INCHES
MADE IN U.S.A.
KEUFFEL & ESSER CO.

content varies from 0.1 percent to 2.9 percent Na_2O . In one of the two drill-cores analyzed the average value is 1.92 percent Na_2O , in the other 0.47 percent Na_2O .

The average value of all sodium analyses in the metadiorite is 1.43 percent.

Potassium

The metadiorite contains an average of 0.25 percent K_2O , with values ranging from 0 to 0.6 percent K_2O . Potassium shows a general decrease towards the pyrite zone, although distribution is irregular.

Major Element Distribution in Metadiorite

The silica trend, although based on unequal sample spacing, indicates that some differentiation may have taken place during cooling of the original igneous melt. The low silica content (Md 1) at the top (northwest) edge of the sill edge may be anomalously low, as in thin section there is 10 percent quartz. Irregularities at the bottom (southeast) edge of the sill are similar to those in many other intrusive sills, such as the Palisades sill in New York State and Mount Wellington sill in Tasmania (Turner and Verhoogen, 1962). Alternatively, the increase in silica may be due to silica assimilation during initial intrusion and cooling, or to equilibrium readjustment during metamorphism. The former process would be caused by partial melting of the underlying rhyolite, the latter by silica migration from the rhyolite

towards the silica poor metadiorite, with possible corresponding iron migration into the rhyolite, during metamorphism, in an attempt to establish chemical equilibrium between the two units.

The average silica content, when compared to a series of analyses for all types of rocks (Nockolds, 1954), falls near that of basalt or gabbro. The highest value obtained was 50.6 percent SiO_2 , the lowest 38.1 percent SiO_2 . Rocks with this silica composition range are gabbro, norite, troctolite, anorthosite, tholeiite, alkali and olivine basalt, and gabbroic diorite. Troctolite and anorthosite may be excluded on the basis of petrography. The name 'metadiorite' is obviously inaccurate, and the body is more properly termed metagabbro. As the texture is ophitic (see 'metadiorite') the most accurate name, pending further whole rock analyses, is metadiabase.¹

The average total iron content of the Timagami metadiorite is similar to that of the Palisade sill and other such gabbroic bodies.

The sodium distribution in drill hole 671 is more regular than in drill hole 681. Sodium decreases slightly towards the pyrite zone (Figs. 11 and 12). As sodium occurred originally in plagioclase of the primary metadiorite, the composition and mode of this mineral are

¹ To be consistent with local usage the name 'metadiorite' will be retained in the text to follow.

reflected by the total sodium content. Furthermore, as sodium is relatively immobile, it probably has not moved far during metamorphism. The data suggest a decrease in the amount of feldspar, or in the albite content of the plagioclase towards the pyrite zone.

Postmagmatic sodium enrichment is not evident. Tholeiites have a low (2 percent) average sodium content, as opposed to alkali-olivine basalts, which have 3 to 4 percent sodium (Turner and Verhoogen, 1960). Thus, the Timagami metadiorite is possibly a tholeiitic sill.

The potassium values (Appendix table 1) are similar to those in plutonic gabbros or olivine gabbro (Nockolds, 1954) and similar to tholeiites such as the Palisade sill (Turner and Verhoogen, 1960).

Potassium probably occurred in potash feldspar, or as solid solution in plagioclase, but during metamorphism was converted to sericite. The latter mineral was not positively identified during petrographic examinations.

Summary

From the foregoing chemical data, the following suggestions are preferred:

(1) The "metadiorite" magma was similar in composition to a tholeiitic basalt. In view of previously discussed textural data, the correct name for this rock is metadiabase.

(2) Differentiation within the metadiorite is slight or non-existent.

GEOLOGY OF THE MASSIVE CHALCOPYRITE AND PYRITE ZONES

History

The occurrence of copper mineralization on Timagami Island was first noted by W.G. Miller (1901) and G.C. Hoffman. Although the economic possibilities were mentioned by Moorhouse (Moorhouse, 1946), it was not until 1951 that Dewey Derosier applied for a licence of occupation. Derosier and associates undertook a modest drilling program, before optioning the property to a subsidiary of Anaconda American Brass Co. in 1952. Anaconda carried out an extensive drilling and geophysical program, but after intersecting only the non-economic pyrite zone, dropped the option (Savage, 1952).

In 1954 Temagami Mining Company, under the direction of Dr. N.B. Keevil Sr. and his associates, optioned the property and conducted more extensive geophysical work. Self-potential surveys indicated small conductors to the southeast of the main pyrite zone. The first drill hole intersected massive chalcopryrite, and subsequent drilling outlined "the largest body of massive chalcopryrite ever found in Canada" (Copperfields, 1965).

Two chalcopryrite lenses, one of 21,000 tons grading 14 percent copper, and the other of 18,000 tons grading 10 percent copper, were mined by open pit methods in 1956 (Savage, 1956). In 1957, no ore was mined, but exploration continued. By 1958 a third chalcopryrite lens had been located

under Lake Timagami, and underground work began. Production resumed in 1958, and early in 1959 a mill and concentrator began processing about 150 tons of ore per day.

Since the initial discovery, 23 high grade chalcopyrite zones have been discovered within the area of the mine workings. In addition, several lower grade discoveries have been made to the southwest. In 1965 the shaft was deepened to 1575 feet, and alterations to surface equipment were made in order to allow mining to an ultimate depth of 3000 feet. Two million feet of diamond drilling had been completed to this time.

To November 4, 1965, 72,000 tons of dry copper concentrate with an average grade of 29.24 percent copper, 0.085 ounces gold and 1.75 ounces silver had been shipped to the Noranda smelter. Average mill feed grade is 6.67 percent copper. Proven ore reserves total 95,348 tons at 6.9 percent copper, inferred reserves are an additional 16,700 tons grading 5 percent. (Copperfields, 1965).

Massive Chalcopyrite Bodies

General Description

There are two types of massive chalcopyrite deposits, (a) 'vein' type, and (b) 'pod' type.

Vein deposits occupy fractures in the rhyolite breccia (or rhyolite tuff breccia) - massive rhyolite contact zone. The length of each zone varies from 50 to 400 feet, the width up to 25 feet, and the depth from 100 to 600 feet. The plane

of these zones is parallel to the rhyolite-rhyolite breccia contact, and approximately parallel to the dip of the metadiorite (Fig. 4). The chalcopyrite is localized in large fractures and along the contact. Nowhere does it penetrate deeply into either wall rock. Angular rhyolite breccia fragments are commonly found in the chalcopyrite of the Number Six zone (Fig. 5). All of the known 'vein' deposits are found west of the Phillips Bay fault.

East of the Phillips Bay fault, the high grade zones are structurally different, although mineralogically similar to the vein type bodies. The eastern bodies are pod shaped, varying in length from 50 to 100 feet, in width to 40 feet, and in depth to 60 feet. The chalcopyrite is concentrated in massive bodies, irregular in detail but generally of disk or pod form, aligned parallel to and within the rhyolite-rhyolite breccia contact. The boundaries of the bodies are sharp, with only a narrow disseminated chalcopyrite halo surrounding them. The rhyolite-rhyolite breccia contact is generally marked by a few chalcopyrite grains.

The wall rocks are only slightly altered. The regional metamorphism has produced a chlorite-quartz-sericite assemblage in the rhyolites, but evidence of further metamorphism is slight. Tourmalinization is reported to be associated with the chalcopyrite, but this association is not ubiquitous (Sharpley, 1962). A small increase in chlorite was noted as the high grade zones are approached; this may be a reflection

of the wall rock composition rather than a metamorphic grade change.

Mineralogy

The mineralogy of the chalcopyrite bodies was determined by examining six polished specimens of the sulphide material. X-ray powder photographs confirmed the identification of several of the minor constituents.

The veins and pods consist of chalcopyrite, pyrite, millerite, sphalerite, gersdorffite, and magnetite. In addition galena has been identified (Rose, 1966) and silver, sperrylite and gold reported (Patrick and Sharpley, personal communication, 1965).

Chalcopyrite forms equant tightly interlocking, anhedral grains, ranging in size from 0.1 to 2 mm (average 0.4 mm). Individual grains are distinguishable only after staining. The chalcopyrite is slightly twinned, and shows no cleavage. It forms 65 percent to 85 percent of the chalcopyrite zones. Chalcopyrite contains small amounts of the other sulphide and oxide minerals, as well as gangue, scattered randomly throughout.

Pyrite forms equant euhedral crystals, in some places scattered randomly throughout the chalcopyrite, in others aligned in trains (Plate 8). The average grain size is 0.1 mm. The crystals show well developed cubic cleavage. Most are extremely pure, but a few have small blebs of chalcopyrite and gangue. The amount of pyrite present is variable, and varies

from 1 percent to 25 percent of the total volume of sulphides. The alignment of pyrite in chains is controlled to a small extent by the grain boundaries of the chalcopyrite, but the complete explanation of this phenomenon is lacking. A few pyrite cubes are partially replaced by chalcopyrite. The replacement is evident as eroded cube edges, and has had only a minor effect.

Sphalerite is anhedral, light grey, soft, and present as an accessory. Grain size varies from 0.01 to 1.0 mm. Most sphalerite grains contain minute (0.0005 mm average diameter) rounded specks of chalcopyrite, distributed in a pattern which may represent exsolution along sphalerite crystal boundaries or twin planes. These grains are larger and more abundant in the centre of the sphalerite grains; the outer quarter of the individual grains is usually devoid of them. Every sphalerite grain has a selvage of chalcopyrite around it; this is most evident where sphalerite is in contact with gangue minerals.

Magnetite is present throughout the sulphide zones, and locally forms narrow fine-grained bands, penetrated by chalcopyrite. The magnetite grains are dark grey, anhedral, almost inclusion free, and have an average diameter of 0.15 mm.

Small grains of gersdorffite are present as an accessory mineral throughout the sulphide zone. Gersdorffite is commonly located near gangue-chalcopyrite boundaries. It shows cubic cleavage on fracturing. The average diameter of gersdorffite crystals is 0.01 mm.

Plate 8: Pyrite cubes in massive chalcopyrite;
(plane light) x 20.

Plate 9: Contact between rhyolite and the pyrite zone;
note sharpness of contact, massive character
of pyrite at contact.
py = pyrite zone, rhy = rhyolite. x $\frac{1}{25}$

Millerite occurs as large bladed aggregates, in crystals up to $\frac{1}{2}$ inch in length. It is euhedral, twinned, and has good cleavage. Millerite is usually accompanied by abnormally high concentrations of gersdorffite when in the bladed form. Occurrences such as this are restricted to the eastern 'pod' type of sulphide body. It has been reported (Rose, 1966) in quartz blowouts, formed as acicular crystals.

The gangue consists of quartz and dolomite. It forms less than 20 percent of the chalcopyrite zones, and occurs as ovoid blebs or irregular stringers. The average grain size is 0.5 mm.

Pyrite nodules are found in many of the chalcopyrite pods (Rose, 1965). These are "roughly ovoid shaped lumps, composed mainly of cellular pyrite, that occupy relatively smooth walled cavities in massive crystalline chalcopyrite." They range in size from $\frac{1}{4}$ to 8 inches in diameter, and are porous, vuggy masses of fine grained pyrite. The pyrite forms platey ribs which criss-cross each other. The voids formed by these ribs are usually empty, but in places are filled by quartz and carbonate. The pyrite ribs ramify into the massive chalcopyrite.

Pyrite Zone

Structure

The pyrite zone is the major concentration of sulphide minerals in the Timagami area. It is continuously traceable for five miles, and may extend as far as fifteen miles. It varies from a few inches to almost 100 feet in thickness.

The zone is located in the metadiorite, adjacent to the rhyolite (Figs. 3, 4 and 5). An exact thickness is difficult to determine; although the lower (southeast) contact between the pyrite zone and rhyolite is sharp, the upper (northwest) is gradational over a distance of up to 25 feet (Plate 9). In this discussion, the upper contact has been arbitrarily set as the point at which pyrite constitutes less than 5 percent of the total volume of the rock.

The dip of the contact between the pyrite zone and the rhyolite is somewhat irregular, in places slightly discordant to the regional dip of the volcanic horizons. There are variations in thickness with depth; the zone generally thins and at a depth of 800 to 1000 feet below surface it is represented by only a few inches of disseminated pyrite.

The structure is complicated by numerous faults, as described earlier. The predominant, throughgoing faults are three 'thrust' faults (Fig. 3). These have an average dip of 58° south and are thus by definition reverse faults. In addition, there are many steeper reverse faults, and a few normal faults. The major reverse faults have a horizontal displacement of 150 to 800 feet. All faults intersect the pyrite zone at a high angle.

The pyrite zone in places flattens slightly with depth (Fig. 4). This may represent a trough or sag in the underlying volcanic units.

Within the pyrite zone there are a few large angular blocks of rhyolite. A rhyolite block was found within the metadiorite at one locality beyond the pyrite zone.

Mineralogy

The pyrite zone is at the base of the metadiorite and represents a major concentration of sulphide minerals containing iron, copper, nickel, cobalt and arsenic. The opaque minerals present are pyrite, chalcopyrite, hematite, millerite, siegenite, gersdorffite and magnetite.

Pyrite is the most abundant sulphide mineral in the zone. It is creamy-white, and under high intensity (xenon arc) light it is slightly but distinctly anisotropic. Pyrite grains are anhedral, show no cleavage and are equant, with an average grain size of 0.5 mm.

Pyrite occurs as large granular aggregates; it forms up to 80 percent of the total volume of the pyrite zone, and up to 98 percent of the total sulphides present. Sulphide-silicate grain boundaries are, on a minor scale, angular and irregular.

The pyrite aggregates are fractured. The patterns are irregular and do not follow cleavage surfaces. They are usually filled with gangue, but many fractures are filled with chalcopyrite. In some areas, pyrite surrounds gangue minerals, and in many places is interstitial to them.

Two distinct types of pyrite are present. One has high relief, and is white to very light cream-white; the other is less hard, and thus has lower relief. It is cream to very slightly pinkish cream (Plate 10). The two forms are always intergrown; the latter variety is usually more abundant than

Plate 10: Pure (white) and nickeloan (cream, lower relief) pyrite with interstitial chalcopyrite.
 p = pure pyrite, np = nickeloan pyrite,
 c = chalcopyrite; (plane light) x 20.

Plate 11: Lamellar texture shown by pure and nickeloan pyrite; np = nickeloan pyrite, p = pure pyrite,
 cpy = chalcopyrite (plane light) x 25.

the former, but often they are present in equal amounts. Contact between the two varieties is sharp. Grain boundaries are best shown by HNO_3 staining. The softer variety will occasionally stain with HgCl_2 .

Although many pyrite aggregates show no regular inter-growth pattern, an irregular lamellar distribution is most common. (Plate 11). This may have been derived from a pre-existing texture, and is, in general similar to an exsolution pattern.

The relief difference is due to compositional variations. Although quantitative analyses were impractical, electrochromatographic contact prints of several pyrite samples proved that the low relief grains had an appreciable nickel content, and as such should be termed nickeloan pyrite. This phenomenon has been recorded by Hawley (1962) at Sudbury. In the latter case nickel content of up to 6 percent has been recorded in such grains.

Where the differential relief in the pyrite was greatest, few or no nickel minerals were observed, and where this effect was absent or less pronounced, a higher proportion of distinct nickel minerals (millerite and siegenite) were generally observed. The nickeloan pyrite probably has a considerable cobalt content, as mine assays show cobalt to be present even where no cobalt sulphide minerals were observed.

Chalcopyrite (CuFeS_2) is distributed throughout the pyrite zone. It has two habits, one associated with pyrite, the other with gangue minerals.

Chalcopyrite is light brass-yellow and is lighter colored than that from other deposits such as Sudbury; this may be due to a higher iron content. It is untwinned, very weakly anisotropic, and usually occurs in monocrystalline form. When it forms granular aggregates, individual grains are equant and have rounded grain boundaries.

Chalcopyrite commonly occurs as an interstitial filling to aggregate masses of pyrite and is difficult to distinguish in hand specimen. As pyrite has an anhedral rounded habit, chalcopyrite forms highly curved irregular boundaries with it. The shape and size of the interstitial fillings are irregular; in some areas the shape is equant, in others it forms veins and embayments (Plate 10). Chalcopyrite in this habit is massive and inclusion free. It ranges in grain size from 0.01 to 1 mm, with an average diameter of 0.2 mm.

In addition to its interstitial form, chalcopyrite occurs as a vein filling in fractures through massive pyrite. This form is a result of redistribution after pyrite formation.

Chalcopyrite associated with silicate minerals is equant, usually monocrystalline, and in anhedral masses. It is usually massive, but in some areas has a boxwork texture. It has been formed interstitially to silicates, and is randomly distributed. There is a wider distribution of chalcopyrite than pyrite along the metadiorite-rhyolite contact. Recent drilling at a depth of 1200 feet indicates that up to 5 percent chalcopyrite is present, even where there is little or no

pyrite. These grains range up to 2 mm in diameter, with an average size of 0.3 mm.

Chalcopyrite also occurs as minute inclusions in pyrite. These are randomly arranged, and in some grains have a dendritic pattern. It appears to partially replace, and thus to have formed, later than pyrite.

Millerite (NiS) is the most common nickel mineral in the pyrite zone. It has two distinct forms, both being interstitial to pyrite aggregates.

It is a pale cream-yellow mineral, with very pronounced blue-golden yellow anisotropism. It forms massive anhedral grains, and is always monocrystalline.

In its most prevalent form it is interstitial to pyrite aggregates, identical in habit to chalcopyrite.

The crystallographic continuity of millerite is easily studied as it is anisotropic. Several separate interstitial millerite grains in one small area appear to have parallel optic orientation. It is probable that they crystallized contemporaneously, and form a single interstitial grain.

Millerite and chalcopyrite coexist and share well defined rounded contacts. They do not embay each other, but share a similar habit, and appear to have crystallized simultaneously.

In its less common habit, millerite and siegenite coexist. Millerite forms an equant monocrystalline mass within siegenite. Grain boundaries are difficult to distinguish, due to similarities in hardness and color, but are generally round

and unsutured. Millerite constitutes less than one-third of the volume of the siegenite grain. The relationship of millerite and chalcopyrite to siegenite will be discussed later.

Siegenite $(\text{Ni}, \text{Co})_3\text{S}_4$ is present in most of the pyrite zone. Its composition lies within the polydymite (Ni_3S_4) -linnaeite (Co_3S_4) solid solution series. It was not feasible to determine its exact composition, as it is not present in sufficient quantities for accurate analytical work.

Siegenite is creamy white and isotropic. It is highly fractured, with well developed cubic cleavage. Grain size, range, and form are identical to that of chalcopyrite.

Siegenite is formed interstitially to both pyrite and silicate minerals. It is usually associated with chalcopyrite, and commonly with millerite. Chalcopyrite occurs as exsolution lamellae and fracture fillings in siegenite, and also coexists with it in equant anhedral grain aggregates. Millerite coexists with siegenite and has an identical habit; they form granular aggregates, and have curved irregular grain boundaries.

The textural relations of chalcopyrite, millerite and siegenite suggest that they formed contemporaneously; chalcopyrite in solid solution with millerite and siegenite exsolved into lamellae during cooling. Where siegenite occurs as a minor phase within chalcopyrite, it forms thin laths, and probably exsolved along chalcopyrite cleavage planes after initial crystallization in a solid solution.

The siegenite-millerite-chalcopyrite association is only found interstitial to pyrite grains. Where siegenite is interstitial to silicate minerals, the other sulphides are generally absent, and in such cases, siegenite has a boxwork texture.

Siegenite also occurs only where the pyrite zone has a high content of oxide minerals (generally hematite after magnetite). Millerite as the major nickel mineral is most prevalent where no oxide minerals are present.

Millerite and siegenite are similar in that both occur interstitially to both pyrite and silicate minerals.

Gersdorffite (NiAsS) is a minor sulphide mineral, and occurs locally in the pyrite zone. It is light grey, anisotropic, massive, occurs interstitially to pyrite, and has a form similar to chalcopyrite. It is present only near the rhyolite-pyrite zone contact and in the disseminated portion of the pyrite zone.

Oxide Minerals: Hematite is present through much of the pyrite zone. It is pseudomorphous after magnetite. The grains have a corroded boxwork texture. Hematite morphology is the same in both the pyrite zone and the metadiorite.

Leucoxene, with characteristic exsolved magnetite lamellae, is abundant throughout the pyrite zone. It is coarser grained than similar material in the metadiorite, with grain diameters ranging up to 2 cm. It coexists with all sulphide minerals, but is most abundant in the gangue.

Gangue: The gangue mineralogy is identical to that of the metadiorite. The degree of alteration is variable, but primary textures are generally better preserved than in the sulphide deficient portions of the metadiorite. Albitized feldspars exhibit relict twin planes and sharp cleavage traces. Chloritized mafic minerals usually have relict cleavages, and are outlined by secondary magnetite or hematite. Both feldspar and mafic minerals are euhedral to subhedral.

The sulphides do not appear to have had any structural or chemical effect on the silicate minerals. The existing silicate assemblage is that formed in the greenschist facies of regional metamorphism, and is identical to that elsewhere in the Timagami area. Idiomorphic feldspar crystals abut sulphide minerals and have sharp, regular boundaries. No discernible chemical reaction zone exists between adjacent sulphide and silicate grains, and there is no evidence of large-scale replacement of silicates by sulphides. An 'alteration halo' attributable to sulphide emplacement is not discernible.

Sulphide Distribution

It is difficult to obtain an accurate estimate of sulphide distribution in underground workings. Drill core, however, can be more easily and closely examined. Estimating sulphide tenor in this manner is more accurate than determining sulphide content from polished sections, as the latter were chosen for maximum sulphide content. The modal distribution

of sulphides (pyrite) as estimated from drill core shows an abrupt increase at the top of the pyrite zone approximately fifty feet above the base of the sill (Fig. 13). The sulphide content of the rhyolite within a few inches of the contact was less than one percent.

Copperfields Mining Company diamond drill logs also show this pattern to be consistent throughout the area.

Figure 13. Sulphide distribution in metadiorite

Gross Sulphide-Silicate Textural Relationships

The pyrite zone and associated wall rocks are well exposed on the 525 level of the mine. Several short cross-cuts allow adequate examination of the textural relationships

between sulphide and silicate rocks, as well as the nature of the contact between rock types. The relationships exposed in underground workings are also evident in drill core.

The rhyolite is texturally undisturbed at the contact between rhyolite and metadiorite, although it is softer and darker in colour due to compositional changes, as previously discussed. It is massive, unbrecciated and unsheared.

The contact of the pyrite zone with rhyolite is sharp (Plate 9). Variations of a few degrees in strike and dip occur due to rolls and local stoping of the rhyolite. In all cases examined, rhyolite is in contact with massive pyrite. Within the rhyolite, a few inches from the pyrite-rhyolite contact and parallel to it, there are fine grained disseminated 'waves' or lines of pyrite. These rarely exist two feet beyond the contact.

The pyrite at the contact is almost devoid of silicates. Within a few inches to a foot of the contact, silicates begin to appear as ovoid to perfectly round 'blebs' disseminated throughout the pyrite (Plate 12). They are 2 to 5 mm in diameter, and have uniform shape and size. The bleb content in the massive sulphide zone varies from 5 percent to 25 percent; the number of blebs increases away from the rhyolite-pyrite contact. At a distance of approximately 10 feet from the contact, silicate blebs begin to lose their sphericity, and increase in size.

Plate 12: Blebs of silicate gangue (black) in massive sulphide; (plane light) x 5.

The massive sulphide-silicate bleb relationship reverses within 18 to 20 feet of the base of the sill zone contact, in the metadiorite. Pyrite in this area forms interstitially to silicates. At 20 to 25 feet, it forms round blebs. These blebs are identical in shape to the silicate blebs, but are generally larger (5 to 10 mm in diameter). They make up less than 40 percent of the rock, but appear throughout all the metadiorite examined in underground workings and drill core. At a distance of 125 feet from the rhyolite contact the metadiorite still contains 2 percent to 5 percent pyrite. Small blebs of pyrite were found in many of the surface samples; it is thus assumed that pyrite is disseminated throughout the metadiorite.

Chemistry of the Pyrite Zone

Distribution of Metals in the Sulphide Zone

A series of samples from diamond drill and underground samples were analyzed, and assays of 20 drill hole cross sections of the pyrite zone were examined (Fig. 14).

No distinct distribution of copper or nickel was evident from this examination. There was, however, general parallelism of distribution of copper and nickel within any localized area.

A weak but discernible increase in copper occurs near the rhyolite-pyrite contact within the area studied. Copper also increases towards the center of the pyrite zone.

Copper and Nickel Distribution in the Wallrocks

Copper distribution adjacent to the pyrite zone is strongly asymmetrical (Figs. 15 and 16). The background copper value in the metadiorite is approximately 100 ppm. Copper increases regularly and rapidly towards the pyrite zone. It diminishes to less than 10 ppm in the rhyolite within a few feet of the contact.

Nickel

Thirty-five samples from two diamond drill holes were analyzed semiquantitatively for nickel (Appendix table 3). The background value for nickel was established by examining the distribution plot of nickel for each rock type and averaging the analyses which occurred before the slope significantly changed (Figs. 15 and 16).

The background nickel content in the metadiorite is 325 ± 50 ppm, and 80 ± 50 ppm in the rhyolite. Nickel increases regularly through the metadiorite towards the pyrite zone. At contact of the pyrite zone with rhyolite the nickel content falls away to less than 100 ppm and remains fairly constant throughout the rhyolite and rhyolite breccia.

The average nickel content in the metadiorite is higher than that in rhyolites. Nickel is distributed asymmetrically, with a gradual increase towards the pyrite zone and a sharp decrease in the rhyolite.

FIG. 15 Distribution of Copper and Nickel in DDH 671

FIG 16 Distribution of Copper and Nickel DDH 681

FIG 16 Distribution of Copper and Nickel DDH 681

Discussion

Chalcopyrite Bodies

All of the minerals except pyrite formed contemporaneously. The general absence of cleavage, small amount of replacement phenomena, and the inclusion of chalcopyrite in sphalerite indicate that only minor metamorphism took place after initial crystallization. The sphalerite-chalcopyrite relationship may represent increasing immiscibility of the two phases on crystallization. After the sphalerite formed, chalcopyrite exsolved.

The chalcopyrite bodies could have originated as either an igneous melt or a hydrous emanation from an igneous source. If the chalcopyrite bodies originated as an igneous melt high in copper and sulphur, and from the same source as the pyrite zone, the gangue minerals should probably be similar to those of the pyrite zone. Also, a high temperature alteration halo should be evident. Since these are not present, this hypothesis may be incorrect. The stratiform nature of the chalcopyrite bodies, and their association with explosive volcanism might lend support to a volcanic exhalative origin, with the metal content originating from the metadiorite source. The similarity of mineralogy between the pyrite and chalcopyrite bodies may be a post-emplacement feature, i.e. the same effects could result through metamorphism of minerals formed by different processes originally. The vein-type chalcopyrite may represent the aerated subsurface or feeder portion of an exhalative body, the pod type, the surface deposits. More detailed studies of

the chalcopyrite bodies and their host rocks is needed before a complete theory on the origin can be postulated. However, it must be remembered that in a rock as amenable to fracture as the rhyolite, it is not impossible for atmospheric conditions to affect hot waters or volcanic exhalative solutions for a short distance below the surface, thus allowing for precipitation of sulphide minerals below the surface of aeration.

The pyrite nodules probably originated as partially assimilated xenoliths or as vesicle fillings. The ramification of pyrite plates into chalcopyrite suggests the pyrite crystallized earlier than the remaining sulphide minerals (chalcopyrite, sphalerite) and was incorporated and possibly recrystallized in the chalcopyrite. Carbonate or silicate gangue which may have filled the vugs in the nodules has been leached away.

Rose (1965) envisages incorporation of earlier formed pyrite in a chalcopyrite magma. This magma removed most of the nodule gangue material, and partially replaced the gangue with chalcopyrite. It is also possible that the chalcopyrite was transported hydrothermally, and the replacement phenomenon was effected by the action of hot water on the gangue.

The absence of an obvious alteration halo around the chalcopyrite bodies has little genetic significance. Upper greenschist facies metamorphism would remove or obscure alteration caused by either hydrothermal or low grade thermal metamorphism. As will be further demonstrated in the discussion to follow, the pyrite zone and chalcopyrite

bodies have chalcopyrite, pyrite, millerite and gersdorffite, as common sulphide minerals. The chemical and mineralogical similarity between the chalcopyrite bodies and pyrite zone suggests they have a common source although further geochemical studies are necessary to confirm this.

Pyrite Zone

Most of the information from the petrographic study of the pyrite zone will be discussed in a later section. However, a few points should be mentioned here.

(1) Rhyolite Blocks in the Pyrite Zone:

These blocks were probably broken off the rhyolite surface and incorporated in sulphide and silicate melts at the time of their emplacement. There is chloritic contact alteration surrounding the blocks. The existence of blocks of rhyolite in both the pyrite zone and metadiorite may indicate to a simultaneous emplacement of both of these rocks.

(2) Metal Distribution in the Pyrite Zone:

The parallelism of nickel and copper distribution is controlled by the distribution of major copper and nickel minerals. As these minerals are interstitial to pyrite and silicate minerals, and have probably been remobilized during metamorphism, their present distribution has been established in metamorphism. The degree of mobilization of these minerals is not known.

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The variations in copper distribution could thus be related either to division of sulphides by immiscibility during cooling of the sulphide section of the primary igneous melt, or to migration of the copper and nickel minerals during metamorphism.

It is possible that detailed examination of metal distribution within the entire pyrite zone might aid in correlation between fault blocks.

DISCUSSION OF PYRITE ZONE-WALLROCK RELATIONSHIPS

Thus far the petrology and geochemistry of the pyrite zone and its wallrocks have been investigated. It is now necessary to draw these data together and to examine the applicable phase relations which aid in an understanding of the genesis of the pyrite zone.

Copper-Nickel Distribution in the Wallrocks

Nickel and copper are distinctly more abundant in the metadiorite, and both have similar distribution patterns. Thus it is probable that the nickel and copper mineralization within the pyrite zone was derived from the metadiorite magma, rather than from a post-magmatic hydrothermal source. Nickel distribution suggests that division between silicate rich and sulphide rich portions of the metadiorite is sharp and differentiation due to liquid immiscibility is complete. The time of differentiation is difficult to establish; it may have occurred in a primary magma chamber, or it could have taken place 'in situ'. If it occurred in the primary magma chamber, it is possible that sulphides were emplaced as a separate magma injection, although petrographic evidence of this is lacking. If differentiation took place 'in situ', it was fairly complete. If cooling were slow enough, it is probable that sulphide and silicate melts could separate almost completely.

The nickel in the metadiorite is contained mainly in silicate minerals, principally chlorite. Mine assays of chlorite mill tailings show a high nickel content (Sharples and Amos, personal communication, 1965). Nickel can substitute for magnesium and iron in ferromagnesian minerals to a considerable extent.

The degree of partitioning of nickel between silicate and sulphide fractions during immiscibility separation is related to the sulphur fugacity (Chamberlain, personal communication, 1966). Copper, nickel, and iron have a higher affinity for sulphide formation than silicate formation. With decreasing sulphur pressure, nickel will begin to enter the structure of many ferromagnesian silicate minerals; at a later stage, iron will also do this. However, copper will not enter into the silicate lattice with such ease. The substitution effect is related to charge and ionic radius effects. Nickel, magnesium and iron have similar ionic radii, with nickel = $.69\text{\AA}$, magnesium = $.66\text{\AA}$, iron = $.74\text{\AA}$, all for the 2^+ ionic charge state, in sixfold coordination, (Mason, 1952), which favours complex formation (Heslop and Robinson, 1963). Copper forms the 1^+ and 2^+ cationic state, with the most common Cu^{1+} state having an ionic radius of $.96\text{\AA}$, and the Cu^{2+} state with a radius of $.72\text{\AA}$ (both in the sixfold coordination state). It thus is much less available to substitutions as its charge is different and its ionic radius unfavorable, in the monovalent state.

As previously mentioned, the amount of nickel which enters the silicate lattice is dependent on the sulphur fugacity in the primary magma. As copper will use up sulphur in preference to nickel, the copper to nickel ratio of the sulphide body will be to a considerable extent dependent on the primary sulphur availability. If sulphur availability is high, then the copper-nickel ratio will be low, as nickel will have plenty of available sulphur, and thus form sulphide rather than silicate bonds. However, if sulphur is limited copper will use it preferentially, and the copper to nickel ratio in the sulphide body will be high, as will be the nickel content of the silicate minerals in the metadiorite.

The average copper to nickel ratio in the Timagami pyrite zone is 2.35 to 1. In Sudbury ores it varies from 1 to 1 to 0.5 to 1 (Hawley, 1962).

Sudbury norite contains an average of 150 ppm nickel. (Stonehouse, 1954). Timagami 'metadiorite' has over 300 ppm nickel. However, Sudbury sulphides average 1.4 percent nickel, and 0.8 percent copper (Canadian Mines Handbook, 1965), while those of Timagami average only 0.43 percent nickel, and 0.92 percent copper. Thus a much larger proportion of nickel must have entered silicate minerals in the Timagami magma than in that of Sudbury, and an initially low sulphur fugacity must thus have been present.

Textural Relationships between Sulphide and Silicate Phases

The sulphide-silicate textural relationships discussed previously suggest a primary sulphide-silicate segregation during cooling of the gabbroic melt as the primary origin for the pyrite zone. The mechanism which best explains this phenomenon is sulphide-silicate immiscibility (Fig. 17).

Figure 17. Diagrammatic section illustrating cooling, separation of immiscible silicate-rich and sulphide-rich liquids and crystallization, treated as a binary system. Point e lies close to left ordinate. Crystallization starting at e or g would extend over a range of temperatures. Point d represents approximate composition of "immiscible-silicate-sulphide" ore from Frood. (In part after Wager, Vincent and Smales, 1957).

(Hawley, 1963).

There is a striking resemblance in macro-textures between Sudbury ores (Hawley, 1962) and the pyrite zone of the Timagami region. The sulphide-silicate bleb relationships are identical with those of the Frood ores. Hawley (1962, p.163) stated that "differentiation of sulphide-silicate liquids by liquation, as shown more precisely by modern experiments, but long recognized from smelting practice, thus seems quite adequate to account for the segregation of great volumes of sulphide liquid towards the base of an intrusion as the Sudbury eruptive or its offset dikes."

Immiscibility relations have been examined by Wager, Vincent and Smales (1957) and also by Kullerud (1962).

The size of the miscibility gap between sulphide and silicate-oxide liquids is variable. Smith (1961) noted that this gap is reduced by oxides of iron, alkalies and hydrogen, and increased by CaO , Al_2O_3 and CuS . Regardless of the size of the gap, the phenomenon occurs in the same mode. When the solubility of sulphide in a silicate liquid is exceeded, two liquids will form, such as a and b of Figure 17, and the liquids will begin to separate due to gravity, with the more dense sulphide liquid settling to the lowermost areas. With continued decrease of temperature, the solubility of one phase in another decreases even more. Depending on its composition, a silicate magma will begin crystallization at some compositional-dependent temperature, along path a c e (Fig. 17) and some sulphide liquid which previously has been dissolved in the silicate rich fraction will exsolve and will form

disseminated sulphide 'blebs' in the silicate portion. Similarly, on the other side of the diagram, cooling of the sulphide melt will continue along the path b d f. Silicate liquid will exsolve with decreasing temperature, and will form silicate 'blebs' such as those seen in the massive sulphide portions of the Timagami pyrite zone. It is also possible that direct crystallization of silicates from a sulphide melt could occur; this would not cause the formation of silicate 'blebs' in the massive sulphides, but rather euhedral feldspar laths and mafic minerals. Conclusive evidence for this effect is not present, and the former mechanism is thus the more likely.

Kullerud (1962) states that "metal rich sulphide drops not only separate by gravity settling from a silicate magmatic solution but may, even before this event, have formed through liquid immiscibility among sulphide phases." He found that a two-liquid + vapor field extends across the sulphur-rich part of the ternary Fe-Ni-S system at temperatures above 991°C for the NiS side and 1083°C for the FeS side. Thus it is possible to have iron- and nickel-rich sulphide assemblages separate because of immiscibility within the sulphide-rich fraction, and to have two sulphide phases initially forming. Although no direct evidence of this is present, it may be used to explain the separation of nickel-rich and nickel-poor assemblages, which on recrystallization formed Ni-rich and Ni-poor pyrites.

Crystallization of the Sill

Significance of Leucoxene

Some information regarding the original water content of the "metadiorite" magma may be derived from the study of the composition of the leucoxene.

Leucoxene is a metamorphic alteration product of ilmenite (FeTiO_3), and is composed of one or more of pseudobrookite (Fe_2TiO_5), rutile (TiO_2) and magnetite (Fe_3O_4). (Karkhanavala and Momin, 1959). It is a semi-opaque amorphous, chemically variable mineral.

The bulk Fe-Ti ratio of the leucoxene is probably the same as that of the primary ilmenite from which it was derived. Oxidation takes place along the $\text{FeO} \cdot \text{TiO}_2 - \text{O}$ tie line of the system represented in Figure 18.

Figure 18. Ternary system Fe-Ti-O showing progressive oxidation of ilmenite along the $\text{FeO} \cdot \text{TiO}_2 - \text{O}$ tie line.

(after Karkhanavala and Momin, 1959)

Once the stage of oxidation has reached the tie line $\text{Fe}_2\text{O}_3 - \text{TiO}_2$, the ilmenite portion of the magnetite-ilmenite grains is partially converted to pseudobrookite and rutile, according to the equation: $2\text{FeTiO}_3 + \frac{1}{2}\text{O}_2 \rightarrow \text{Fe}_2\text{TiO}_5 + \text{TiO}_2$, at temperatures in the order of 850°C . However, below this, only rutile and hematite are formed ($2\text{FeTiO}_3 + \frac{1}{2}\text{O}_2 \rightarrow \text{Fe}_2\text{O}_3 + 2\text{TiO}_2$). The magnetite portion remains unaltered (Moorhouse, 1959).

From the proportion of brown leucoxene to magnetite, the original oxide composition may be derived. The average leucoxene-magnetite intergrowth composition throughout the metadiorite is 75 percent leucoxene to 25 percent magnetite. This gives an $\frac{\text{Fe}}{\text{Fe}+\text{Ti}}$ ratio of approximately 0.65.¹ This ratio may be related by the isothermal phase diagram (Figure 19) to oxygen pressure. It is obvious that, in order for magnetite (spinel) plus α -oxide (ilmenite) to coexist, the oxygen partial pressure of the magma must have been moderate to low ($\log P_{\text{O}_2} = -4$ to -12 bars) (Webster and Bright, 1961). As oxygen partial pressure is directly related to water

¹ Assuming a crystallization temperature for the oxide phases near 1200°C .

partial pressure,¹ this suggests that the original igneous melt was of moderate to low water content.

Figure 19. System Fe-Ti-O; phases present at 1200°C. The lines separating the (α oxide + ortho) field from the (ortho + rutile) field and from the (spinel + α oxide) field represent solid solutions of small, but finite width. (Ortho = orthorhombic).

(Webster and Bright, 1961)

Yoder and Tilley (1962) have examined the relation of basalt compositions to crystallization temperatures (Fig. 20).

¹ P_{O_2} is related to P_{H_2O} by the following equation (Buddington and Lindsley, 1964, p. 320):

$$K_T = \frac{(f_{H_2})(f_{O_2})^{\frac{1}{2}}}{P_{H_2O} \cdot V_{P_3T}}$$

and $f_{O_2} = P_{O_2}$

where K_T is the dissociation constant of water at temperature T .

f_{H_2} , f_{O_2} are the fugacities of hydrogen and oxygen, respectively

P_{H_2O} is partial pressure of water

V is activity coefficient of water at T and pressure P .

Figure 20. Projection of the natural olivine tholeiite-water system using data on 1921 lava, Kilauea caldera, Hawaii (Cambridge No. 57364). Mineral stable on side of curve along which name is printed. Chemical analysis, Table 2, No. 14. (Hydrothermal data from Table 28 and 1 atm data from Table 14, No. 14)

(Yoder and Tilley, 1963)

If the Timagami metadiorite is a sill, as previously suggested, it was emplaced at a shallow to intermediate depth in the crust. In that the volcanic suite has been metamorphosed

to only greenschist facies, it is probable that the sill was introduced at a depth of 10 kilometers or less.

If water pressure in the melt equalled total pressure, then the maximum water pressure would be approximately 2500 bars. In that the melt probably had a moderate to low water content, it is more probable that the water partial pressure was approximately 1000 bars or less. At this pressure the melt was completely crystallized at 900°C (Fig. 20).

From the above discussion it is obvious that any sulphide phase which settles within a magma either in crystalline form or as a high density liquid must do so before complete crystallization, and quite probably above 900°C.

Thermometry of the Sulphide-Silicate Assemblage

Holland (1963) studied the stability fields of the Fe-S-O system at selected temperatures for varying sulphur and oxygen fugacities. The accompanying isothermal diagrams (Fig. 21) show these fields for any f_{S_2} - f_{O_2} conditions.

At temperatures in excess of 727°C it is virtually impossible to form pyrite as a stable mineral unless the sulphur fugacity is extremely high. At such a sulphur fugacity it is impossible to form any oxide minerals. Pyrrhotite forms the major stable field (together with magnetite) at normal sulphur and oxygen fugacities.

At lower temperatures, for the same sulphur and oxygen fugacities, pyrite, along with hematite, occupy large stability fields.

From these data it is evident that if the sulphide melt segregated from the silicate melt as a result of liquid immiscibility, as the textural and metal distribution data suggest, and if crystallization of the sulphides took place soon after emplacement of the magma, contemporaneous with silicate crystallization, that at the prevailing temperatures and probable oxygen and sulphur fugacities, only pyrrhotite and magnetite can form an equilibrium assemblage. It is possible that other components such as nickel and copper may have an effect on crystallization temperatures but, in that they are relatively minor components, their effect would be minimal.

Figure 21. Isothermal stability fields of iron oxide and iron sulphide minerals with variable Oxygen-Sulphur fugacities.

(after Holland, 1963).

Figure 22. The upper stability curve of pyrite shown in relation to the beginning-of-melting curve of natural tholeiitic basalt and the minimum-melting curve of granite.

(Kullerud, 1957)

Thus the observed sulphide assemblage probably formed in a different thermal environment than that of the silicate assemblage, which could not exist as a melt below 900°C.

Kullerud and Yoder (1956) have established the upper stability curve of pyrite. They found that pyrite breaks down to a solid solution of pyrrhotite plus sulphur above a 746°C at 1 atmosphere pressure. The composition of the pyrrhotite solid solution at the breakdown is given by the intersection of the pyrrhotite solvus curve with the liquidus in the system FeS-S. Comparing the upper stability curve of pyrite with the lowest crystallization (or initiation of melting) curve of a natural tholeiite (Yoder and Tilley, 1962)

it is further shown that pyrite cannot be formed in such a melt except at a prohibitively high sulphur fugacity (Fig. 22).

The conversion of pyrite to pyrrhotite plus sulphur is reversible, and would explain the conversion of pyrrhotite, which must have formed initially, to pyrite. This conversion may have taken place during metamorphism (see below).

The gradational distribution of sulphide blebs indicates that silicate and sulphide liquids existed contemporaneously. The sulphides were possibly introduced at a separate stage from the main metadiorite magma, but this second introduction was separated from that of the metadiorite by a very short time. As a result the silicate liquid had not cooled below its crystallization temperature, and local mixing of the sulphide rich melt into the silicate melt took place. This mixing was not extensive, due to the density differences of the liquids, but was sufficient to cause some mixing and consequent resettling. Crystallization of both sulphide and silicate phases continued after the second injection.

The sulphide and silicate melts probably originated from the same magma chamber. Primary splitting from immiscibility occurred here, and allowed two phases to be emplaced at separate times. The existence in the sulphides of silicate blebs of the same composition as the metadiorite excludes the possibility of primary pyrite formation, regardless of melt origin, as these would have crystallized

long before the pyrite, and would have been carried in solid form to their present position. Instead of forming immiscibility blebs, they would have a lath-like habit.

It is also possible that the sulphide and silicate liquids, having been introduced in a single melt, and after separating by immiscibility, were further separated by filter pressing. If the sulphide melt remained in liquid form after silicate crystallization began, the silicate crystals would float on the more dense liquid, and thus cause the sulphide liquid to migrate to the bottom of the sill. This would happen before complete crystallization of the silicate melt; the silicate crystals would be somewhat mobile, in a crystal 'mush' form. Such a phenomenon would require a slow cooling rate.

Interpretation of Sulphide Texture

Two distinctly different processes may have contributed to the textures present in the Timagami pyrite zone.

In the discussion of sulphide-silicate relationships, it was stated that the sulphide concentration possibly originated through immiscibility of sulphide and silicate liquids, with segregation due to gravity settling. It was also pointed out that the observed pyrite-siegenite-millerite-chalcocopyrite-hematite assemblage cannot be formed by the immiscibility process, and must be due to some other process, possibly secondary alteration. It is probable that some features of the sulphide textures are primary, but most of these features are due to secondary processes.

The lamellar textural relationship of the nickeloan pyrite with nickel-free pyrite suggests that two pyrrhotite phases (or possibly pyrrhotite-pentlandite) were initially present, and were separated due to exsolution. It is also probable that some of the nickeloan sections were originally pentlandite, with nickel partially released during alteration. Irregularities in the contact between the two varieties of pyrite may be due to volume readjustment, for in the change from pyrrhotite to pyrite there is a slight increase in volume. Pyrrhotite has recrystallized 'in situ' to pyrite, and little distortion of original form has taken place. Thus the overall pyrite texture is primary. Fracturing of the pyrite may be due to readjustment during metamorphism as the silicate minerals underwent some volume expansion during hydration, and the pyrrhotite-pyrite conversion, if stoichiometric, would also involve some expansion. The removal of nickel and cobalt from primary pyrrhotite and pentlandite would allow some expansion, and cause departure from stoichiometry. It is possible that some replacement of pyrite by chalcopyrite has taken place, as chalcopyrite in many instances is disseminated throughout pyrite aggregates. Chalcopyrite, a primary mineral, probably has undergone redistribution during metamorphism, and moved out into the silicate areas of the metadiorite adjacent to the pyrite zone (possibly due to lack of room for it due to pyrite volume expansion).

The gangue texture is primary, as is discussed in the metadiorite description. This texture was formed during the crystallization of a tholeiitic basalt. Only slight redistribution, due to carbonate introduction and volume expansion, has taken place during metamorphism.

Chemistry of the Sulphide Assemblage

From textural data, chemical analyses, and an investigation of crystallization of an igneous melt, it has been established that the sulphide assemblage has a secondary origin, but that the metallic components were introduced due to primary igneous crystallization.

It remains to examine the possible mode of recrystallization in relation to the observed assemblage and associated secondary silicate assemblage.

Millerite (Ni_{1-x}S) and polydymite (Ni_3S_4) can coexist only below 280°C (Fig. 23). The β NiS polymorph (millerite) is unstable above 374°C at low pressures and 400°C at high pressures (Eugster and Kullerud, 1956).

Although the exact composition of siegenite in the pyrite zone could not be determined, it is probably close to the nickel-rich member of the polydymite (Ni_3S_4) - linnaeite (Co_3S_4) solid solution series. Thus siegenite would act in the nickel-sulphur system in a manner similar to polydymite.

Pyrite (FeS_2) and vaesite (NiS_2) are isostructural (Clark and Kullerud, 1958). Clark determined experimentally the solubility of FeS_2 in NiS_2 . However, on the pyrite

Figure 23. Subsolidus phase relationships in the NiS-NiS₂ binary join. (Clark and Kullerud, 1958)

Figure 24. Bravoite is stable below $137^{\circ} \pm 6^{\circ}\text{C}$ as determined in experiments involving mixing of liquid at elevated temperatures. Below 137°C bravoite is stable with FeS₂ (pyrite or marcasite) or with vaesite, depending on the bulk composition. Above this temperature pyrite and vaesite form a stable mineral assemblage.

(Clark and Kullerud, 1958)

side of the FeS_2 - NiS_2 system, equilibrium has not been reached at any temperature. Up to 8 mole percent NiS_2 enters into metastable solid solution with pyrite, and this is not exsolved unless prolonged heating at high temperature is applied.

The Timagami pyrite and nickeloan pyrite probably represent a mixture of pure pyrite and vaesitic pyrite. The pyrite-vaesite assemblage breaks down to pyrite and bravoite at 137°C . (Fig. 24). As no bravoite was found, it is assumed that the lowermost temperature limit of secondary processes was above this.

With this assumption the temperature range in which the present sulphide assemblage formed is between 137°C and approximately 280°C at atmospheric pressures; temperatures would increase by 50 to 150°C for a one to two kilobar increase in pressure. Such an increase would make these temperatures compatible with those believed to hold during metamorphism to greenschist facies. This suggests that the sulphide assemblage present in the Timagami pyrite zone could have formed through regional metamorphism.

In summary, after introduction and formation of the sulphide-rich liquid, pyrrhotite-pentlandite-chalcopyrite crystallized with or soon after the primary silicate minerals (mafic plagioclase).

Original pyrrhotite was converted to pyrite; pentlandite was converted to nickeloan (vaesitic) pyrite; excess nickel and cobalt were redistributed interstitially as siegenite-millerite. In addition, chalcopyrite was redistributed by the same process. At the same time, magnetite was converted to hematite. The conditions of metamorphism were those associated with the greenschist facies, i.e. temperatures of 250-450°C. Thus the metamorphic event which altered the entire Timagami region was responsible for forming the observed sulphide assemblage.

The physico-chemical details of such a transition have received little experimental work. It would appear from chemical considerations that the pyrrhotite-pyrite conversion would involve a volume expansion if such a reaction were stoichiometric. Furthermore, such a reaction would involve addition of sulphur or removal of iron.

There is no necessity to assume absolute stoichiometry; the system is open to H_2O , and nickel, cobalt and copper components are free to move both within the pyrrhotite lattice and externally, for some volume expansion. It is possible to add some sulphur as dissolved SO_2 in H_2O during metamorphism. However, such a reaction did not occur on a large scale, as

primary oxide minerals (magnetite) in the presence of high sulphur fugacities, should convert to pyrite (Kullerud, 1957).

It is also possible that some excess iron was removed. The anomalously high iron content in the adjacent rhyolite may in part be due to redistribution of iron.

CONCLUSIONS

1. Textural, mineralogical and geochemical relationships indicate that the Timagami metadiorite has formed from a tholeiitic melt. Regional metamorphism has converted the primary silicate assemblage to the chlorite-albite epidote-muscovite subfacies of the greenschist facies.
2. Sulphide-silicate textural relations suggest that the sulphide concentration which formed the pyrite zone originated through liquid immiscibility with a silicate phase.
3. As a result of metamorphism the sulphide as well as silicate assemblages have been completely altered. The sulphide assemblage was altered to pyrite-nickeloan (vaesitic) pyrite-millerite-siegenite. This alteration is complete.
4. There is, on the basis of this study, no evident genetic relation between the pyrite and chalcopyrite zones. However, it is probable that these zones were metamorphosed simultaneously.

APPENDIX A

Sampling

Samples were obtained from 5 diamond drill holes, representing four cross sections, all starting in metadiorite and terminating in either rhyolite breccia or rhyolite. (see accompanying sample location map.) Four holes were collared on the surface, two were collared underground. Samples for thin and polished section, as well as chemical analyses were taken from drill core at regular intervals. Sample numbers delineate drill hole number and footage. Attempts were made to take material representative of surrounding rock, with as little anomalous alteration as possible.

In addition, samples from the 525 level, 551 west drift, 570 crosscut were examined in detail, both in place and in the laboratory.

Surface samples to represent the entire width of the metadiorite were taken along the shoreline of Adanac Bay. Sample locations and their straight line projection are shown on the accompanying map.

Samples of dike rocks, millerite, and pyrite nodules, were provided by mine personnel. Dr. E.R. Rose of the Geological Survey of Canada provided several polished sections of the chalcopyrite and pyrite zones.

Polished and Thin Section Preparations

All polished and thin sections were prepared by Mr. Walter Yzerdraat of the Geology Department of Carleton University. Standard thin section preparation methods were used, and need not be reviewed. Polishing was done on a series of diamond impregnated cloth laps prepared to fit custom designed polishing machines. It was found that chalcopyrite tarnished very rapidly after polishing. This tarnish was very easily removed on a cloth lap impregnated with a .1 u alundum and 10 percent chromic acid mixture. This method, if applied for a short time to sections with a low carbonate mineral content, produces a highly satisfactory super-polish. It may also be applied to polished thin sections.

Petrographic Techniques

Polished and thin sections were examined on a binocular Leitz polarizing microscope equipped with transmitted and reflected light sources which could be operated simultaneously. Some polished section examination was done at the Geological Survey of Canada with a similar microscope equipped with a high intensity, xenon-arc light. Anisotropic features are more easily discernible with this equipment.

Point counting was carried out on a Swift Automatic Point Counter, using a .66 mm interval. At least 1200 points per section were counted.

APPENDIX B

Chemical Analysis (b) Sample Preparation,
Grinding, Weighing and Dissolution.

Samples were prepared for colorimetric and x-ray fluorescence analysis by several stages of grinding. A Bico 'Chipmunk' Crusher, with hardened steel jaws, was used for coarse grinding. A Bico pulverizer equipped with ceramic plates was used for finer grinding. A Pica Blender Mill with ceramic capsule and grinding ball was used as a final stage. Cleaning after each sample was carried out with a brush, forced air, and a very dilute HNO_3 washing. Sieving with a Spex-400 nylon screen was used to determine appropriate time for complete pulverization. Samples were not all sieved, in order to reduce preferential grinding effects. The grinding stages were as follows:

All samples were weighed by differential methods to $\pm .0005$ grams. Care was taken to avoid intersample contamination, and samples were weighed directly into the containers in which they were to be dissolved.

Samples for copper and nickel analysis were dissolved as follows: to each sample, 0.5 gm of potassium pyrosulphate was added. Samples were roasted in pyrex test tubes over a bunsen flame until fusion was complete (approximately 10 minutes). After cooling, 10 ml of 2 molar HCl was added to each, and the samples warmed on a sand bath for one hour. Samples were then filtered and diluted to an appropriate volume.

For iron, sodium and potassium analyses, Solution B according to Shapiro and Brannock (1956), using Hydrofluoric acid dissolution, was used.

For silica analyses, pellets with a one-inch, flat, exposed-surface diameter were prepared by pressing 1 to 2 grams of sample with a boric acid backing in a 40 ton hydraulic press. Care was taken in order to assure a homogenous, shiny, uncontaminated surface.

Chemical Methods

(a) Electrochromatographic contact prints

Contact print analyses for nickel was carried out under the supervision of Dr. W. Petruk of the Mines Branch, Department of Mines and Technical Surveys. The method followed was close to that of Williams and Nakhla (1950).

Polished sections to be studied were drilled with a 1/16" metal drill, and an electrode attached either by means of a wood screw or a soldered wire. Care was taken to insure electrical continuity between electrode and polished section surface.

Paper was prepared by fixing ordinary Kodak positive film for 20 minutes, then soaking it thoroughly in the reagents. It was cut to appropriate size and allowed to drip until excess solution was removed.

The reagents used were as follows:

- (a) Dimethyl glyoxime (1 percent) in alcohol
- (b) Rochelle salts (10 percent) in water
- (c) Ammonium hydroxide (NH_4OH) (10 percent).

These were mixed in the proportions 1:1:1.

The prepared paper was placed face down on the polished section. An electrode made by wrapping a flat piece of plasticene with aluminium foil was placed on top of the paper, and the entire apparatus clamped tight in a vertical press. The lower electrode was connected to the positive pole of a 25 volt (direct current) source. The upper (plasticene-aluminium foil) electrode was connected to the negative pole. A 10 milliamperes current was allowed to pass for from 6 to 20 seconds; the paper was then carefully removed and allowed to dry prior to examination. The nickeliferous areas of the sections caused a pink print.

X-Ray Fluorescence Method

All X-ray fluorescence analyses were performed on a Seimens X-ray spectrograph equipped with a chromium tube and digital counters. A gypsum analysing crystal, with an evacuated X-ray path, flow proportional counter and pulse height analyser were used. Argon gas with a low methane content was passed continuously over the plates of the flow proportional counter.

The $K\alpha$ peak for Silicon, with a 2θ of 55.89 degrees was measured. A Background 2θ of 57 degrees was used. The X-ray tube was energized with 50,000 volts at 40 milliamperes. The counter voltage was set at 2046; analyzer base line was set at 18.6, and a window width of 0.8 was used. Counting continued for one minute; each sample was analyzed at least four times. Reproducibility was checked by preparation of two pellets for all standard and 10 of the unknown samples.

A calibration curve was prepared from a series of previously analyzed rocks covering the range of from 42 percent to 90 percent SiO_2 . Standards included U.S.G.S. standard sample W1, several U.S.B.M. standards, and some previously analyzed rocks provided by M. Shafiqullah, obtained from the University of Alberta. In order to avoid matrix effect complications, samples of approximately the same rock type were chosen.

Precision or reproducibility can easily be evaluated; accuracy is dependent on the standards used. No wet chemical analyses of the standards were carried out. The maximum variation of reproducibility was 1.5 percent of the value represented, or ± 0.7 percent. Error in the curve determination was ± 0.4 percent. Thus total error in silica determinations is ± 1.1 percent.

The values obtained are presented in Appendix tables 1 and 2. Sample numbers refer to the drill hole number and footage; those prefixed by the letters Md are surface samples.

Total Iron

Total iron as Fe_2O_3 was determined by orthophenanthroline colorimetric methods (Appendix table 1) according to Shapiro and Brannock (1956), Fortune and Mellon (1938). The absorbence of the orange ferrous - orthophenanthroline complex at 555 μ in a solution of pH 4.5 (sodium citrate buffer). Ferric iron was reduced by addition of hydroxylamine hydrochloride. A Bausch and Lomb Spectronic 20 spectrophotometer was used.

Sodium and Potassium

Sodium and potassium were determined on a diluted aliquot of solution B as prepared for iron analyses, using an Eel flame photometer and with appropriate filter and propane-air flame (Appendix table 1). Synthetic sodium and potassium standards were prepared by A.W. Hounslow, a graduate student at Carleton University.

Accuracy and Precision of Iron, Sodium and Potassium Results

As determination curves were prepared using synthetic standards, it was necessary to analyze standard rocks in order to establish accuracy. Precision or reproducibility was determined by weighing out two or more aliquots of a single sample. U.S.G.S. samples W1 and G1 were used for accuracy control. The accuracy of colorimetric iron determinations is ± 0.2 percent. The precision, as determined from the standard deviation, is 0.48 percent.

The accuracy of sodium and potassium value is 0.15 percent and 0.10 percent respectively. The precision is less than 0.1 percent for both.

Nickel

Nickel in both sulphide and silicate rocks was analyzed semiquantitatively by the colorimetric α -furildioxime organic extraction method (Appendix table 1). The intensity of the yellow colour in the furildioxime layer is proportionate to the amount of nickel present, and was measured on a Bausch and Lomb Spectronic 20 spectrophotometer at 435 m μ . The method used was that proposed by Taylor (1956). A calibration curve was prepared through use of artificial standards, supplied by Mrs. D. Mah.

Copper

Copper was determined semiquantitatively by the colorimetric biquinoline organic extraction method (Appendix table 1), according to a method modified by Mrs. D. Mah and the author. The intensity of the pink colour in the organic layer was measured on a Bausch and Lomb Spectronic 20 spectrophotometer at 546 mu.

Precision and Accuracy of Copper and Nickel Determinations

Copper and nickel determinations were uncontrolled, due to the unavailability of suitable standards. Reproducibility of results was checked by multiple analyses of several samples, and was found to be within 2 percent of the value presented.

Spectrographic Analysis

Qualitative trace element emission spectrographic analysis of three samples of rhyolite were completed by Mr. G. MacDonald of the Geology Department, Carleton University. Nineteen elements were determined as either major, minor, or trace components (Appendix table 4). In addition, the rhyolite and rhyolite breccia samples were compared on a ratio basis to determine approximate differences relative to a common datum. Analyses were done on a Jarrel Ash emission spectrograph and read on an ARL densitometer. The Strontium 2931.8A° line was used as a datum line in relative comparison of the two rock types.

APPENDIX TABLE 1

¹Partial Analyses of Silicate Rocks from Diamond Drill Holes (Wt %)

DDH # and footage	% SiO ₂	% Fe ₂ O ₃	% Na ₂ O	% K ₂ O	ppmCu	ppmNi
671 - 19	47.0	10.45	2.22	.44	7.5	-
34	49.9	9.63	2.94	.12	10	200
59	48.8	10.10	1.20	.04	100	150
67	51.0	7.89	2.20	.24	-	-
74	-	11.14	2.32	.24	75	225
77	45.5	11.11	2.04	.05	25	150
87	47.9	9.50	4.58	.58	125	250
97	47.6	-	1.92	1.00	250	300
99	-	11.12	.46	.14	-	-
107	49.8	11.21	1.88	.04	560	660
116	47.1	11.11	1.54	.05	1000	1000
126	45.5	11.18	.58	.14	1000	750+
136	52.4	11.32	.64	0.0	2.5	800+
170	58.3	10.44	.64	1.0	5.0	100-
198	66.4	5.43	.58	1.16	6.3	100-
223	62.5	4.05	1.34	1.96	375	75
246	75.0+	2.58	1.24	2.70	50	50
260	-	3.38	1.22	1.72	150	100
280	60.8	3.32	1.06	1.66	50	100
300	59.3	4.78	1.60	1.24	10	75
328	56.6	3.41	1.40	2.46	5.0	75
681 - 11	38.7	11.73	1.14	.10	5.0	100
31	43.1	10.95	.04	.10	50	260
40	50.6	-	-	-	75	100
50	50.6	11.17	.74	.05	100	150
85	39.2	11.14	.02	.20	75	1000
100	45.1	11.17	.94	3.30	250	1200
114	41.3	11.14	.02	0.00	300	600
119	44.5	11.43	.40	2.3	5	400
164	-	11.11	.72	.64	500	160
169	-	11.26	.78	.52	0	-
179	50.5	4.52	.40	.38	0	-
189	47.0	5.71	.40	.56	0	400
199	70.0	5.77	1.28	.62	37.5	160
219	61.7	3.43	1.20	1.02	200	-

¹ See Appendix Fig. 1 for diamond drill hole locations.

APPENDIX TABLE 2

Silica Analyses of Surface Samples
(See Appendix Fig. 1 for locations)

Silica (Wt %)	
Md 1	38.6
Md 2	48.7
Md 3	48.5
Md 4	38.2
Md 9	44.9
Md 10	45.7

APPENDIX TABLE 4

Qualitative Spectrographic Analysis of Rhyolite

DDH- footage	Al	Mg	Si	Ga	Ca	V	Cu	Na	Zn	Ti	Ni	Zr	Sr	Co	Fe	Mn	K
681-189	Mc	M	Mc	Tr	M	Tr	Tr	M	Tr	M	Tr	Tr	Tr	Tr	Mc	M	Mc
671-246	Mc	M	Mc	Tr	M	Tr	Tr	Mc	-	M	Tr	Tr	Tr	Tr	M	Tr	Mc
671-328	Mc	M	Mc	Tr	Mc	Tr	Tr	Mc	-	M	Tr	Tr	Tr	Tr	M	M	Mc

Mc - Major component

M - Minor component

Tr - Trace component

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PHILLIPS BAY

FIGURE 2

FIGURE 2

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West Boundary

Fault