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**BULLETIN 143** 

# FERROMAGNESIAN SILICATE MINERALS IN THE METAMORPHOSED IRON-FORMATION OF WABUSH LAKE AND ADJACENT AREAS, NEWFOUNDLAND AND QUEBEC

K. L. Chakraborty

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## PREFACE

Highly metamorphosed iron-formations contain iron- and manganese-rich varieties of amphibole and pyroxene minerals that are uncommon in other metamorphic rocks. The mode of occurrence, composition, and properties of these minerals are of special significance in studies of the amphibole group of minerals as a whole, in understanding the primary nature and metamorphic history of iron-formation, and in the beneficiation and processing of iron ore mined from the metamorphosed iron-formations.

Dr. K. L. Chakraborty, a post-doctorate fellow of the National Research Council from Jadavpur University, India, was attached to the Geological Survey of Canada from November 1961 to January 1963. His study of the composition, optical properties, and X-ray determinations of ferromagnesian silicate minerals from the Wabush Lake area in Labrador, Newfoundland, is reported in this bulletin.

J. M. HARRISON,

Director, Geological Survey of Canada

OTTAWA, December 2, 1963

BULLETIN 143 — Eisen- und magnesiumhaltige Silikatmineralien in der metamorphisierten Eisenformation des Wabushsees und angrenzender Gebiete in Neufundland und Quebec.

Von K. L. Chakraborty.

Einzelheiten über die chemischen und optischen Eigenschaften und die Art des Vorkommens einer grossen Anzahl von eisen- und magnesiumhaltigen und Kalk-silikat-Amphibolen, Pyroxenen, Granaten und einigen assoziierten Karbonatmineralien.

БЮЛЛЕТЕНЬ 143 — Минералы железистомагнезиальных силикатов метаморфической железной свиты оз. Уабуш и прилегающих районов провинций Ньюфаундленд и Квебек. К. Л. Чэкраборти.

Дается описание деталей химических и оптических свойств и условий залегания большого числа железистомагнезнальных и известково-силикатных роговых обманок. пироксенов, гранатов и некоторых других сопутствующих карбонатных минералов.

## **CONTENTS**

## PAGE

Introduction	1
Previous work	1
Scope of investigation	2
Acknowledgments	2
Petrography of the iron-formation	3
Oxide facies	3
Silicate facies	4
Carbonate facies	4
Mineralogy of the iron-formation	5
Separation of minerals	5
The amphiboles	6
Classification	6
Anthophyllite series	7
Cummingtonite-grunerite series	9
Manganoan-cummingtonite	14
Other silicates	16
Common hornblendes	16
Pyroxene group	17
Garnet group	19
Carbonate minerals	19
Anthophyllite-cummingtonite-manganoan-cummingtonite relationship	21
Paragenesis of silicate minerals	25
Summary and conclusion	27
References	28
Appendix	31

Table I.	Optical and chemical data on three anthophyllites	8
II.	Optical data on cummingtonites from Wabush Lake area	9
III.	Optical data on cummingtonites from Mount Wright area	10

## PAGE

Table IV.	Optical data on cummingtonites from Boulder Lake area	10
V.	Refractive index (Nz) of cummingtonites from Wabush Signal	12
VI.	Refractive index $(N_z)$ of cummingtonites from Wabush No. 6	
	deposit	12
VII.	Chemical analyses of five cummingtonites	13
VIII.	Chemical analyses and optical properties of manganoan-cumming-	
	tonites	15
IX.	Optical data on actinolites	16
Χ.	Optical properties and chemical analyses of two diopsides	18
XI.	Optical data on two hypersthenes	18
XII.	Results of carbonate investigation	20

# Illustrations

Plate I.	Prismatic grains of anthophyllite at centre of grain of talc	7
II.	Alternate bands of silicate carbonate and quartz-rich iron-forma-	
	tion	12
III.	X-ray powder photographs of two cummingtonites	14
Figure 1.	Distribution of iron-formation in the southern part of the Labra- dor geosyncline	6
2.	Optical data and indicated chemical composition of 14 members of	
	the cummingtonite-grunerite series, Wabush iron-formation	11
3.	Relative amounts of MgO, FeO, and MnO in cummingtonite- grunerite, anthophyllite, and manganoan-cummingtonite	22
4.	Weight per cent of MnO and FeO in anthophyllites, cumming- tonite-grunerite and manganoan-cummingtonites from Wabush Lake	23
5.	Coefficient of correlation (r) for anthophyllites and manganoan-	
	cummingtonites	24

# FERROMAGNESIAN SILICATE MINERALS IN THE METAMORPHOSED IRON-FORMATION OF WABUSH LAKE AND ADJACENT AREAS, NEWFOUNDLAND AND QUEBEC

#### Abstract

The Wabush iron-formation is a metamorphosed Precambrian ferruginous sediment in the southern part of the Labrador geosyncline. The whole formation is divided into three main lithological units (oxide iron-formation, silicate iron-formation, and carbonate iron-formation) on the basis of mineral assemblage. A large number of ferromagnesian and lime silicate minerals, such as anthophyllite, cummingtonite, manganoan-cummingtonite, hypersthene, diopside, actinolite, and garnet have been formed in these rocks by metamorphic reactions. The chemical and optical properties and modes of occurrence of these minerals have been studied, and their identifications confirmed by X-ray studies.

Siderite and dolomite are the predominant types of carbonate in these rocks. Variations in chemical composition of cummingtonites in different ironformations apparently indicate differences in primary chemical composition of the sediments. The relationship of the anthophyllite, cummingtonite, and manganoan-cummingtonite minerals is established. Anthophyllite and cummingtonite are proven to be two different series with limited isomorphism. Manganoan-cummingtonite has monoclinic symmetry, but its chemical composition and optical properties are more similar to anthophyllite with orthorhombic symmetry than to the cummingtonite–grunerite series. Paragenesis of the silicate minerals was deduced from their chemical composition and textural relationship.

Results of this study suggest that the iron-formation was metamorphosed isochemically with a minimum possible migration of material, and has reached the epidote-amphibolite facies or garnet-staurolite zone of metamorphism. Manganese-bearing anthophyllite and manganoan-cummingtonite are evidently the source of secondary manganese in the iron ores of this region.

#### Résumé

La formation ferrifère Wabush est un sédiment ferrugineux métamorphisé du Précambrien, de la partie sud du géosynclinal du Labrador. L'ensemble de la formation se divise en trois principales unités lithologiques (formation à oxyde de fer, formation ferrifère à silicate et formation ferrifère à carbonate). Un grand nombre de minéraux ferromagnésiens et de minéraux à chaux et à silicate comme l'anthophyllite, la cummingtonite, la manganoan-cummingtonite, l'hypersthène, le diopside, l'actinolite et le grenat se sont formés dans les roches par réactions métamorphiques. On a étudié les propriétés chimiques et optiques et les modes de venues de ces minéraux et on a confirmé leur identification par l'examen aux rayons X.

La sidérite et la dolomie sont les principaux genres de carbonates dans ces roches. Les variations de la composition chimique des cummingtonites dans les diverses formations ferrifères indiquent apparemment des différences dans la composition chimique primaire des sédiments. On a établi les rapports entre l'anthophyllite, la cummingtonite et les minéraux à manganoan-cummingtonite. Il est établi que l'anthophyllite et la cummingtonite sont deux séries différentes à isomorphisme limité. La manganoan-cummingtonite présente une symétrie monoclinique, mais sa composition chimique et ses propriétés optiques ressemblent plus à l'anthophyllite à symétrie orthorhombique qu'à la série à cummingtonite-grunérite. On a déduit la paragenèse des minéraux à silicate de leur composition chimique et de leurs rapports texturaux.

Les résultats de la présente étude portent à supposer que la formation ferrifère a été métamorphisée isochimiquement avec une migration possible de matériaux réduite au minimum et qu'elle est parvenue au faciès à épidoteamphibolite ou à l'état de métamorphisme au grenat-staurolite. L'anthophyllite à manganèse et la manganoan-cummingtonite sont évidemment les sources du manganèse secondaire dans les minerais de fer de la région.

## **INTRODUCTION**

The iron-formation of Wabush Lake and surrounding areas forms the southern part of the metamorphosed Precambrian ferruginous sedimentary series of the Labrador geosyncline. Since the end of the 19th century parts of this formation have been investigated by various Canadian geologists. A recent review of these investigations with detailed description of the geology, stratigraphy, structure, and economic aspect of the areas has been given by Gross (*in preparation*).

The Wabush iron-formation has been divided into two stratigraphic units: the lower Wabush iron-formation, consisting of quartz-carbonate-silicate rocks; and the upper Wabush iron-formation, composed of quartz-specularite-magnetite rocks or the potential orebodies. The whole formation is intricately folded and faulted. The specimens were collected for comparative study by G. A. Gross and the writer from both lower and upper Wabush iron-formation near Wabush Lake, and from the Mount Wright and Boulder Lake areas. The distribution of rocks in these areas is shown on Figure 1. Talc, anthophyllite, cummingtonite-grunerite, manganoan-cummingtonite, hypersthene, diopside, tremolite, actinolite, garnet, and a few other secondary minerals are the important ferromagnesian silicates of this metamorphosed iron-formation.

## **Previous Work**

Cummingtonite-grunerite, hypersthene, diopside, and actinolite are the most abundant and widespread metamorphic silicate minerals of all iron-formations. These minerals, along with quartz, magnetite, and carbonates, have been described by Gross (1955)<sup>1</sup>, Mueller (1960), Klein (1960), and Kranck (1961) from different parts of the Labrador geosyncline. Mueller and Kranck investigated the equilibrium relations in the natural hydrous ferromagnesian silicates on the basis of the distribution of different elements in them. The phase chemistry of different hydrous iron silicafes has been briefly discussed by Yoder (1957). Experimental studies on the system FeO-SiO<sub>2</sub>-H<sub>2</sub>O have been carried out by Flaschen and Osborn (1957) and by Smith (1957). Sundius (1931), Richarz (1927 a, b), and Gruner (1946) described the mineralogy of the cummingtonite-grunerite series from the iron-formations of Sweden and the Mesabi Range. A few manganiferous cummingtonites were described by Sundius (1924) from the iron-formations and eulysitic rocks of Sweden. Richarz (1927) and Sundius (1931) later tried to compare the optical properties and chemical composition of the manganiferous and non-manganiferous cummingtonites. The crystal structures of the monoclinic amphiboles have been worked out by Warren (1930) and Ghose (1961); Rabbitt (1948) has published results of a detailed study on the anthophyllite series.

<sup>&</sup>lt;sup>1</sup> Names and/or dates in parentheses are those of *References* listed at end of report.

#### Ferromagnesian Silicate Minerals

Study of various aspects of the ferromagnesian amphiboles by different workers raised new problems concerning the cummingtonite and anthophyllite series. The relationship between anthophyllite and cummingtonite has been discussed since 1930, when Johansson made a comparative study of these minerals and tremolite. Sundius (1931) and Richarz (1927b) brought forward their arguments regarding the relationship of manganese-rich and manganese-poor cummingtonite. Recently Jaffe, Meijer, and Selchow (1961) described one manganoan-cummingtonite from manganese carbonate rocks of Nsuta, Ghana.

## Scope of Investigation

An examination of the literature cited above indicated that more detailed investigations were needed on the optical and chemical properties, structural patterns, and paragenesis of the ferromagnesian silicate minerals. Accordingly, with the metamorphosed Wabush iron-formation as material, the author has: (1) studied and described the mineral assemblage in each sedimentary facies present; (2) determined variations in optical properties, chemical composition, and X-ray powder patterns of various ferromagnesian silicates present; (3) made precise and accurate determinations of the carbonate minerals in the iron-formation by means of X-ray diffraction, semiquantitative spectrographic analyses, differential thermal analyses, and thermogravimetric analyses; (4) inferred the grade and nature of metamorphism of the rocks; (5) established a new correlation of the relationship of anthophyllite, cummingtonite, and manganoan-cummingtonite; (6) established the paragenesis of the silicate minerals from their textural relationship, chemical composition, and mode of occurrence; and (7) indicated the source of secondary manganese in the iron ores of the Wabush Lake area.

## Acknowledgments

The writer carried out this work at the Geological Survey of Canada as a postdoctorate research fellow sponsored by the National Research Council of Canada. The X-ray determinations and chemical analyses of silicate minerals were done by J. L. Jambor and S. Courville, respectively. A generous grant from the Survey and the facilities offered by different mining companies of Newfoundland and Quebec made the author's field work possible.

The author takes this opportunity to express his gratitude to Dr. G. A. Gross of the Survey who suggested this study and offered helpful criticism, discussion, and encouragement during the progress of the work. Thanks are also due to Dr. K. R. Dawson for his constructive suggestions.

## PETROGRAPHY OF THE IRON-FORMATION

The ferruginous rocks of the Wabush Lake and surrounding areas are classified in three main lithological groups, including the oxide, silicate, and carbonate facies. Gross (*in preparation*) has discussed in detail the various kinds of iron-formations, their classification, and their distribution in the Labrador geosyncline. The author's classification based on mineralogy follows that of Gross. Short descriptions of each of these three groups are given.

The three mineral facies occur as distinct lithological units, interfingering with each other or in places showing transition both along and across the strike directions. Although from the existing mineralogy it is not possible to decipher the primary nature of these rocks, there is little doubt that the Wabush iron-formation is a metamorphosed equivalent of sedimentary iron-formation like that in the Knob Lake Group farther north, where primary facies are preserved. The environment under which these facies may be deposited has been outlined by Krumbein and Garrels (1952), James (1954), and others. The transition or abrupt local changes in different facies is believed to be brought about by slight change in pH and Eh or irregularities in the sedimentary basins. Interfingering, on the other hand, may be caused by regressive and transgressive changes in sea-level.

## **Oxide** Facies

The oxide facies is represented by a thinly banded iron-formation consisting predominantly of quartz, specularite, and magnetite. A little talc, anthophyllite, and cummingtonite also occur as primary constituents in this association, but do not exceed 5 per cent of the total bulk of the rock. Ferrimuscovite was identified with quartz and specularite in the Mount Wright area. The mineral assemblages characteristic of this facies are:

- a. quartz-specularite (with talc, anthophyllite, and very little magnetite);
- b. quartz-specularite-magnetite (specularite and magnetite roughly in equal proportion);
- c. quartz-magnetite-cummingtonite (with very little specularite).

The oxide facies forms most of the upper Wabush iron-formation. The lithological similarity of these rocks to the itabirite formation of Minas Gerais, Brazil (Guild, 1953) is readily apparent. Quartz and iron oxides occur together forming a mosaic-like texture, but there is no sign of reaction between the two. The effect of metamorphism on these rocks is mainly recrystallization of the minerals and increase of grain size. The average quartz grain size in the Wabush and Boulder Lakes areas ranges from 0.15 mm to 0.2 mm, but in the Mount Wright area it is consistently above 0.2 mm.

## Silicate Facies

The iron-formation characteristic of the silicate facies consists mainly of cummingtonite with quartz, magnetite, and garnet. Ferrohypersthene is a common constituent of this mineral assemblage in the Mount Wright area. Cummingtonite grains show two habits, coarse prismatic grains or fine acicular needles. The acicular forms appear to have been completely recrystallized to the coarse forms. Although a schistose fabric is common in these rocks, many of the silicate grains are randomly distributed, forming a coarse felted mass, which transects the crudely defined banding. The silicate facies is the least abundant in this region.

## Carbonate Facies

The iron-formation representing the carbonate facies is more heterogeneous than the other two facies. It grades from coarsely banded quartz-carbonate rock to carbonate-quartz-cummingtonite-magnetite rock, with a number of other silicate minerals like diopside, actinolite, tremolite, phlogopite, etc., appearing in places. Carbonate is predominant and cummingtonite forms 10 to 15 per cent of the rocks. Actinolite, tremolite, and phlogopite are evidently secondary. The following mineral assemblages are represented:

- a. carbonate-quartz;
- b. carbonate-tremolite-quartz;
- c. carbonate-quartz-cummingtonite-magnetite;
- d. diopside-cummingtonite-actinolite-carbonate.

Ferrohypersthene is closely associated with assemblage d in the Mount Wright area. The carbonate facies rocks alternate with thin bands of silicate iron-formation in some parts of the stratigraphic succession.

Small amounts of carbonate, bluish green hornblende, and tourmaline are present as minor constituents in most specimens examined. Biotite and chlorite are also present, but are clearly of retrograde metamorphic origin.

## MINERALOGY OF THE IRON-FORMATION

The metamorphosed iron-formation of Wabush Lake and surrounding areas is composed of a large number of iron oxide and ferromagnesian silicate minerals. Some secondary Mn-oxides have also been reported from these rocks. The oxide minerals were studied by Gross (1955), Knowles and Gastil (1959), and others. Klein (1960) examined the mineralogical properties of the amphiboles, especially cummingtonites. As mentioned earlier, anthophyllite, cummingtonite–grunerite, common hornblendes, and a few pyroxenes (hypersthene and diopside), and garnet form the most important ferromagnesian silicates in the Wabush iron-formation. A variety of manganoancummingtonite occurs with anthophyllite in the oxide iron-formation in the Wabush No. 6 and No. 7 deposits, and also to the south of Little Wabush Lake (Fig. 1). The writer has confined his discussion to the important silicate minerals encountered in these rocks. With the exception of some accessory minerals, all identifications have been confirmed by X-ray powder pattern and chemical analyses.

The highest and the lowest refractive indices of the minerals were determined by liquid immersion methods in sodium light. Optic axial angles were measured directly on a four-axis universal stage and the extinction angles were also checked. The intermediate index of all the samples has been calculated. The accuracy for indices below 1.70 is  $\pm$  0.002 and above 1.70 is  $\pm$  0.005.

## Separation of Minerals

Separation of amphiboles was done using a Frantz isodynamic separator, with the samples crushed to -100+150 mesh. Magnetite and grains containing magnetite inclusions were separated using a strong hand magnet. Carbonates were leached out by hot dilute HCl. A drift tilt of 25 degrees with a cross tilt of 18 degrees and 0.4 to 0.5 ampere current was the most satisfactory setting for the isodynamic separator for separating cummingtonites from quartz. Separation of cummingtonite was easy as it does not occur with anthophyllite or manganoan-cummingtonite. A little higher ampere setting was needed to separate manganoan-cummingtonite from quartz and anthophyllite. Specularite was separated very easily at a lower current (0.25 ampere) at this setting. After treatment in the Frantz separator, impurities were almost negligible, and those that remained were detected under the binocular microscope and easily removed by hand picking. The concentrates from the Frantz separator had very few impurities and were sufficiently clean for refractive index studies. The coarse grain size of the silicate minerals and lack of intergrowth made the separation relatively easy. Anthophyllite occurs in pure bands or in clusters in these rocks. Samples were taken from bands free of manganoan-cummingtonites, and it was not difficult to obtain a stock of mineral that was free of impurities by hand picking under the binocular microscope. Diopside occurs as coarse to very coarse grains and pure crystals of diopside were readily available for chemical and X-ray analyses. After hand picking, portions of the final products were mounted and examined under the petrographic microscope. Inclusions of iron oxide were present in less than one per cent of the silicate grains, and the stock obtained for chemical analysis, X-ray, and optical examinations was better than 99 per cent pure.

## The Amphiboles

## Classification

The amphibole group of minerals are silicates that have either orthorhombic or monoclinic symmetry, and have similar internal structure and external habit. The silicon-oxygen tetrahedra are arranged in such a way as to produce a double chain "inosilicate" structure in which the Si-O ratio is 4:11 (Warren, 1930). The general formula for this group as given by Berman (1937, p. 354) is

(W, X, Y)<sub>7-8</sub> (Z<sub>4</sub>O<sub>11</sub>)<sub>2</sub> (O, OH, F)<sub>2</sub>

where W = Ca; Na, K, and Li in minor amount;

- X = Mg, Fe<sup>++</sup>, Mn<sup>++</sup>; and Al in part;
- Y = Al and Fe<sup>+++</sup> primarily, and sometimes Ti;
- Z = Si mainly and Al in part.

It has been generally accepted that there are three main species comprising the amphibole group. The species are:

1. Anthophyllite: X<sub>7</sub> (Z<sub>4</sub>O<sub>11</sub>)<sub>2</sub> (HO)<sub>2</sub>; orthorhombic;

with X = Mg and Fe and very little Ca;

Z = almost entirely Si; Al sometimes in small amount.

2. Cummingtonite-grunerite: X<sub>7</sub> (Z<sub>4</sub>O<sub>11</sub>)<sub>2</sub> (OH)<sub>2</sub>; monoclinic;

X = Mg, Fe<sup>++</sup> and Mn; Zn is subordinate; Al in minor quantity;

- Z = Si predominantly; Al sometimes in very small amounts.
- 3. Hornblende: W<sub>3</sub> (X, Y)<sub>5</sub> (Z<sub>4</sub>O<sub>11</sub>)<sub>2</sub> (OH, F)<sub>2</sub>; monoclinic;

W = Ca; Na and K in subordinate amounts; Li rare;

- X = Mg, Fe<sup>++</sup>; Mn is rare;
- $Y = Al, Fe^{+++}; Ti is rare;$
- Z = Si mainly; Al in small part.

The amphiboles of the Wabush iron-formation fit into this three-fold classification.

6



Figure 1. Distribution of iron-formation in the southern part of the Labrador geosyncline.

#### Anthophyllite Series

In the Wabush iron-formation anthophyllite was found in two places. In the Smallwood mine (Fig. 1) it occurs with specularite and quartz with a small amount of talc, and in the Wabush No. 6 and No. 7 deposits it is associated with quartz, magnetite, specularite, and a greenish amphibole that has been identified as manganoan-cummingtonite. Both occurrences are restricted to the upper Wabush ironformation. Anthophyllite, mainly a fibrous variety, occurs as very lean, discontinuous bands parallel to the regional foliation. Acicular, elongated prismatic grains are also present but rare. The anthophyllite looks grey, greenish, or pale yellowish brown. In thin sections it is colourless, greenish, or pale brown. The fibrous variety is often found in stellate groups. Talc in fairly coarse grains is a constant associate of anthophyllite and specularite in the Smallwood mine. Anthophyllite has evidently crystallized later than talc in these rocks and large grains of talc show transformation to anthophyllite (Pl. I). The stability field of talc and anthophyllite has recently been experimentally established by Fyfe (1962), who found that over a limited range of conditions between 670° and 800°C at 2,000 bars, talc would convert to anthophyllite and quartz in the presence of water. The texture described here is possibly an example of this reaction that has taken place under natural circumstances.



PLATE I. Prismatic grains of anthophyllite (An) formed at the centre of a big grain of talc (x200 crossed nicols)

#### **Optical Properties and Chemical Composition**

The optical properties and partial chemical analyses of two samples of anthophyllite from Wabush iron-formation are given in Table I. The optical properties were determined from relatively coarse prismatic grains under high magnification.

## Table I

Optical and Chemical Data on Three Anthophyllites

	Sp. 60-GF-55 No. 6 Wabush Deposit	Sp. 62-GFC-74 Smallwood Mine	Anthophyllite, Edwards, N.Y. (Rabbitt, 1948, Table 2, No. 43)
$\begin{array}{c} SiO_2\\ Al_2O_3\\ Fe_2O_3\\ FeO\\ CaO\\ MgO\\ MnO\\ Na_2O\\ K_2O\\ TiO_2\\ H_2O\\ F\end{array}$	55.79 4.01 2.21 7.69 0.10 23.20 2.25	8.57 24.84 2.29	59.29 0.59 0.29 0.06 1.26 30.98 2.77 0.37 0.19 0.03 3.80 0.20
N <sub>x</sub> N <sub>y</sub> N <sub>z</sub> N <sub>z</sub> -N <sub>x</sub> 2V	$ \begin{array}{r} 1.610\\ 1.618\\ 1.624\\ 0.014\\ -86^{\circ} \end{array} $	1.614 1.622 1.626 0.012 74°	1.62

(All analyses are given in weight per cent)

(Analyst: S. Courville)

Rabbitt (1948), after an extensive study of the anthophyllite series, came to the conclusion that identification of anthophyllite, especially the fibrous variety, is not complete without X-ray verification. The writer had the identification of the first sample (Sp. 60-GF-55) confirmed by X-ray powder patterns. The d-spacings and observed intensities are given in the appendix and approximate the spacings listed on the ASTM card 9-455. The diagnostic X-ray diffraction lines of anthophyllite are 3.24 and 3.05.

Rabbitt established that the anthophyllite series is a 3-component one with limited isomorphism in which magnesium, iron, and aluminum are the principal constituents involved. Iron or  $(Fe^{++} + Mn^{++})$  can substitute for magnesium from about 5 per cent to about 50 per cent, and aluminum replaces silicon up to 2 atoms in the unit cell. Besides the oxides of these three essential cations, anthophyllites of the Wabush iron-formation contain appreciable amounts of MnO. Manganese has also been reported in the chemical analysis of anthophyllite from Edwards, N.Y., which Rabbitt described as one of the purest varieties known. The analysis has been cited in Table I of this paper for comparison. Ghose (1962) recently described the distribution of Mg<sup>++</sup> and Fe<sup>++</sup> in some of the ferromagnesian silicates including cummingtonite and anthophyllite. Similar work on the distribution of Mn in the lattice positions of these minerals is still lacking. Considering that manganese is not an essential constituent

of anthophyllite the writer suggests two alternatives as to why it may be present: (1) the high manganese content is normal for an anthophyllite that is in equilibrium with manganoan-cummingtonite; or (2) the manganese-bearing anthophyllite is in a metastable state in these rocks.

## Cummingtonite-Grunerite Series

Members of the cummingtonite-grunerite series are the most abundant silicates in the metamorphosed iron-formation of Wabush Lake and surrounding areas. Although their stability field could not be definitely established (Flaschen and Osborn, 1957), these are minerals widely known from the metamorphosed iron-formations all over the world. In the Wabush iron-formation they occur in all three facies (oxide, silicate, and carbonate), but in different proportions. The optical and chemical properties of the Wabush cummingtonites and their modes of occurrence differ markedly in the three facies. In the oxide facies of iron-formation cummingtonite occurs with quartz and magnetite as small prismatic grains, which are generally elongated parallel to the banding. In the silicate facies cummingtonite occurs in two varieties, as coarse prismatic grains and as fine elongated needles. Cummingtonite in the carbonatequartz mineral assemblage is very coarse grained, poikilitic, and is distributed in the rock without any preferred orientation. Evidence for reaction between carbonate and quartz is not conclusive, but in places small grains of cummingtonite occur at the contact of carbonate and quartz bands or surrounding the carbonate grains.

## **Optical Properties**

Cummingtonites from the three mineral facies of iron-formation differ in colour, from brown (in the oxide facies), pale brown or amber (in the silicate facies), to colourless (in the carbonate facies). The colours are easily differentiated under the binocular microscope and even with the naked eye in mineral concentrate. All three varieties seemed to be nonpleochroic. The prismatic cleavages and lamellar twinning are well developed. The (001) parting was seen in a few grains of cummingtonite associated with carbonate. Optical data of these minerals from three widely separated localities were determined for comparative study (Tables II, III, IV).

	Oxide Facies Silicate Facies Carbonate Facies							
	Sp. 62- GFC-51 (12) <sup>1</sup>	Sp. 57- GF-86 (10)	Sp. 57- GF-84C (9)	60-GF-65 (5)	60-GF-59 (6)	60-GF-W4	62-GF-18 (3)	62-GF-16
Nx Ny Nz Nz-Nx Z ^ C 2 V	$ \begin{array}{r} 1.675\\ 1.696\\ 1.715\\ 0.040\\ 14^{\circ}\\ -86^{\circ} \end{array} $	1.673 1.692 1.708 0.035 15° - 84°	1.670 1.689 1.707 0.037 15° 88°	1.662 1.680 1.696 0.034 17° 89°	1.664 1.683 1.698 0.034 16° - 85°	1.655 1.670 1.687 0.032 20° +86°	1.657 1.673 1.691 0.034 18° +88°	1.661 1.679 1.694 0.033 17° - 87°

Table II

Optical Data	on Cu	mmingtonites	from	Wabush	Lake	Area
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<sup>1</sup> Numbers in brackets refer to positions of points plotted on Fig. 2.

## Table III

	Oxide Facies		Silicate	Silicate Facies			rbonate Fac	ies
	54-19 (14) <sup>1</sup>	54B	54-8A	54-14 <b>B</b>	54-9-2A (7)	54-8 <b>B</b>	M-6-E	54-9-3 (1)
N x N y Nz-N x Z∧C 2V	1.677 1.699 1.718 0.028 14° - 84°	1.671 1.686 1.699 0.028 15° - 86°	1.666 1.677 1.689 0.023 17° - 88°	1.671 1.684 1.696 0.025 17° - 85°	1.665 1.678 1.690 0.025 17° - 85°	1.663 1.679 1.694 0.031 19° -89°	1.662 1.680 1.696 0.034 17° - 88°	1.650 1.662 1.680 0.030 20° +80°

Optical Data on Cummingtonites from Mount Wright Area

<sup>1</sup> Numbers in brackets refer to positions of points plotted on Fig. 2.

#### Table IV

<b>Optical Data on Cummingtonite</b>	s from	Boulder	Lake	Area
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<u> </u>		Nx	Ny	Nz	Nz-Nx	Z∧C	2V
	Sp. 60-GF-54F (13) <sup>1</sup>	1.676	1.699 <sup>2</sup> 1.695	1.717	0.041	14°	- 83°
Oxide Facies	Sp. 60-GF-54K (11)	1.674	1.695 <sup>2</sup> 1.692	1.712	0.038	15°	84°
Silicate Facies	Sp. 60-GF-54A (8)	1.668	1.688 <sup>2</sup> 1.685	1.705	0.037	17°	— 86°

<sup>1</sup> Numbers in brackets refer to positions of points plotted on Fig. 2.

<sup>2</sup> Calculated Ny values.

Tables II, III, and IV show that the cummingtonites from the oxide facies have the highest refractive indices, and those from carbonate facies have the lowest. The cummingtonites in the silicate facies have intermediate values. The optical properties of 14 samples, showing the maximum range of compositional variation, have been plotted in Winchell's diagram (Fig. 2). The samples were numerically numbered for convenience of reference. Cummingtonites from different facies show clearly defined groupings. Those in the carbonate facies range in composition from Fe<sub>55</sub> to Fe<sub>70</sub>, those in the silicate facies from Fe<sub>74</sub> to Fe<sub>82</sub>, and those in the oxide facies from Fe<sub>85</sub> to Fe<sub>88</sub>. These groupings indicate that the compositions of cummingtonites differ in the three facies, but are alike in similar facies in different regions.

To determine whether this interpretation is also true in a limited area, the writer collected samples of cummingtonite systematically from two well-exposed sections. At Wabush Signal (Fig. 1), 40 samples were collected from an approximate area of 200 square feet where alternate bands of carbonate-rich and silicate-rich iron-formation were exposed. The bands are thin, sharply defined, and continuous (Pl. II).

Mineralogy of the Iron-Formation



FIGURE 2. Optical data and indicated chemical composition of 14 members of the cummingtonite-grunerite series from the Wabush iron-formation. Chemical analyses of five samples are also plotted. (Diagram after Winchell, 1951, p. 428)

Samples were collected from each band at an interval of 7 feet. Another suite consisting of 16 samples was collected on the south end of Wabush No. 6 deposit at intervals of 5 feet across a section extending from oxide to carbonate facies with a transitional silicate facies. The highest refractive index ( $N_z$ ) of cummingtonites from these samples was measured (Tables V and VI). The values of  $N_z$  obtained are fairly close and indicate the same range of compositional variation in cummingtonites from closely alternating bands of carbonate and silicate iron-formations as is found in widely separated areas.



PLATE II. Alternate bands of silicate carbonate (dark) and quartz-rich iron-formation. Typical section at Wabush Signal.

## Table V

Refractive Index (N<sub>z</sub>) of Cummingtonites from Wabush Signal

	Silicate Bands									Carb	onate	Bands		
	1	2	3	4	5	6	7	1A	2A	3A	4A	5A	6A	7A
1st Line1	1.700	1.705	1.705	1.707	1.700	1.710	1.705	1.693	1.694	1.692	1.695	1.694	1.692	1.691
2nd Line	1.698	1.705	1.705	1.710	1.705		1.710	1.693	1.696	1.694	1.695	1.692		1.692
3rd Line	1.700	1.702	1.710	1.705	1.700	1.707	1.710	1.693	1.694	1.692	1.695	1.692	1.694	1.692

<sup>1</sup> Lines were chosen across the bands of iron-formation.

## Table VI

Refractive Index  $(N_z)$  of Cummingtonites from Wabush No. 6 Deposit (Every alternate sample was examined)

			Silicate Faci	es		Ca	arbonate Fac	cies
Sample Nos.	11/1	11/3	11/5	11/7	11/9	11/11	11/13	11/16
$N_{z}$	1.698	1.699	1.705	1.710	1.700	1.694	1.696	1.694

#### Chemical Composition

Table VII lists partial chemical analyses of five selected samples of cummingtonites from different members of the Wabush iron-formation. These are recalculated in mole per cent and plotted on Figure 2.

#### Table VII

#### Chemical Analyses of Five Cummingtonites<sup>1</sup>

Provide and the second s									
Sample No. and Location	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	CaO	MgO	MnO	F	Facies
60-GF-54F (13) <sup>2</sup> (Boulder Lake)	51.60	0.62	1.37	38.09	0.00	6.10	0.66	0.02	Oxide
57-GF-84C (9) (White Lake)	46.54	7.64	3.75	30.62	0.14	8.06	0.34	2	Silicate
57-GF-86 (10) (Carol Lake)	51.45	0.00	2.18	35.11	0.00	8.00	0.83		Silicate
60-GF-65 (5) (Wabush Lake)	47.64	4.46	3.22	34.10	0.04	7.11	0.36	,	Carbonate
60-GF-W4 (2) (Luce Lake)	51.46	0.61	0.40	33.01	1.14	10.93	0.58		Carbonate

(Analyses given in weight per cent)

 $^1$  Ti, V, Ba, Sr, Cr, Ni etc. content were checked by spectrochemical method and were found absent or negligible. (Analyst: S. Courville.)

<sup>2</sup> Numbers in brackets refer to sample number used on Figure 2.

The cummingtonites are predominantly ferromagnesian silicates and are very similar to those described by Mueller (1960), Klein (1960), and Kranck (1961) from different parts of the Labrador geosyncline. None of them approaches the iron endmember of the cummingtonite-grunerite series in its optical properties or chemical composition (Fig. 2). Though the compositions of the cummingtonites are similar, it is apparent that the cummingtonites from the oxide facies have the highest iron content, with less iron than those from the silicate facies. Cummingtonites from the carbonate facies have lower iron content and higher lime and magnesia content. This variation in iron content may be due to limitations in the availability of iron in different horizons during the formation of cummingtonite. From James' analyses (1954) the writer extrapolated the average chemical composition of different primary sedimentary facies of iron-formation, which supports this idea. The average iron content in the oxide facies is about 40 per cent, that in the carbonate facies is 25 per cent, and that in the silicate facies varies from 25 to 30 per cent.

Two samples of cummingtonite shown on Table VII contain appreciable amounts of aluminum. This appears exceptional, since Sundius (1933), Rabbitt (1948), Layton and Phillips (1960) believed that aluminum was present in quantity in some anthophyllites, but was rare in cummingtonites. Some of the minerals from Strathy, Sutherland, described by Collins (1942) as cummingtonites are relatively high in aluminum, and are similar to the high aluminum cummingtonites from the Wabush ironformation. The MnO content is very low. The fluorine content was checked in one sample and was found negligible (0.02%). The chemical analysis of the sample 60-GF-65 seems inconsistent with the optical and X-ray data.

#### Ferromagnesian Silicate Minerals

All cummingtonite samples analyzed have been confirmed by X-ray powder patterns. The intensities, d-values, and indices of one sample (57-GF-84C) with high alumina are given in the appendix. The lines from other samples were compared with this and were found almost identical. For the purpose of composition determination, a line in the back reflection has been appropriately marked with an 'x' on Plate III. The sample with highest iron content (60-GF-54F) has the largest cell dimension, and that with lowest iron and highest magnesium content (60-GF-W4) has the smallest cell. This phenomenon can be explained by the substitution of Fe<sup>++</sup> (0.74Å) by Mg<sup>++</sup> (0.66Å) in this series. The FeO : MgO curve on Figure 2, if extended, may be a guide to determine the optical properties and chemical composition of the cummingtonite–grunerite minerals.



PLATE III. Contact prints of X-ray powder photographs of two cummingtonites show variation in cell dimension. a = sp. 60-GF-54F with high iron. b = sp. 60-GF-W4 with high magnesium.

#### Manganoan-Cummingtonite

Manganoan-cummingtonite occurs only in the quartz-specularite-magnetite member of the upper Wabush iron-formation. It is found in the quartz-specularite-magnetite schists of the Wabush No. 6 and No. 7 deposits and also in a similar band south of Little Wabush Lake. In the northern parts of these deposits the manganoan-cummingtonite-bearing bands grade along strike into quartz-specularite-anthophyl-lite schists. The distribution of this pale greyish to light green amphibole gives the rocks a distinctly banded appearance. Klein (1960) recently studied the optical and chemical properties of this mineral in the Wabush No. 7 deposit. Manganoan-cummingtonite is distinctly fine grained, acicular or prismatic. Some needles form stellate groups. Because of the close similarity between these amphiboles and members of the tremolite-actinolite series, it is very difficult to identify them in hand specimen.

### **Optical Properties and Chemical Composition**

In thin section manganoan-cummingtonite is seen to be colourless or pale green. The lamellar twinning is not common, but the (001) parting is found in most of the grains. The optical properties and partial chemical analyses of two of these amphiboles are given in Table VIII, along with a few others from the literature for comparison. The analyses show that the manganoan-cummingtonites are in general higher in MgO and MnO content than the common ferromagnesian cummingtonites. The refractive indices and birefringence are remarkably low in these amphiboles. The extinction angles in the first four samples are much higher than those found in the manganese-poor cummingtonites. Optic axial angles are high and the optic sign is always negative. Richarz (1927a) and Sundius (1931) compared the optical properties of manganese-rich and manganese-poor cummingtonites, and reported lower refractive indices in the former, but they did not put forward an explanation for this unusual phenomenon.

## Table VIII

Chemical Analyses and Optical Properties of Manganoan-Cummingtonites (Analyses given in weight per cent)

	A	В	С	D	Е	F	G
SiO <sub>2</sub>	53.00		53.70	57.1	51.96	52.98	50.74
$AI_2O_3$	5.81		0.75		0.44	0.26	0.88
TiO <sub>2</sub>			0.005				0.06
$Fe_2O_3$	5.72		2.16		0.39	0.60	1.80
MgO	17.39	19.98	19.1	19.1	9.87	13.58	10.57
FeO	5.44	9.64	3.63	1.2	22.51	21.93	24.13
MnO	7.29	5.22	16.8	19.2	7.65	8.03	7.38
Na <sub>2</sub> O			0.22				0.22
CaO	1.50		1.12	1.5	4.98	0.29	2.00
K <sub>2</sub> O			0.01				0.08
$H_2O$			2.21	1.9	2.17	2.36	1.94
$P_2O_5$			0.04				
CO <sub>2</sub>			1		0.14	0.09	
F							0.07
			99.79	100	100.11	100.12	99.87
Nx	1.632	1.628	1.630	1.628	1.650	1.650	1.655
Nv	1.643	1.641	1.644	1.642	1.670	1.665	1.671
Nz	1.655	1.651	1.654	1.650	1.685	1.679	1.685
Nz-Nx	0.023	0.023	0.024	0.022	0.035	0.029	0.030
Z∧C	21°	21°	21°	22°	15°	16°	15.4°
2V	-87°	-83°	$-82^{\circ}$	-74°	-81°	—87°	-85.3°
				1			

A. Sp. 57-GF-WICI South of Little Wabush Lake. Wabush iron-formation. (Analyst: S. Courville.)

B. Sp. 62-GFC-26A Wabush deposit No. 6. Wabush iron-formation. (Analyst: S. Courville.)

C. Klein (1960, p. 53). Wabush deposit No. 7. Wabush iron-formation.

D. Jaffe, et al. (1961, p. 650). Nsuta, Ghana.

E. Sundius (1924, p. 157). Brunsjögruvan, Sweden.

F. Sundius (1924, p. 157). O. Silvergruvan, Sweden.

G. Sundius (1931, p. 334). Uttersvik, Sweden.

Ferromagnesian Silicate Minerals

One sample of manganoan-cummingtonite (A, in Table VIII) was verified by X-ray powder patterns. The measured and calculated d-spacings, observed intensities, and indices are given in the appendix. The magnitude of the cell dimensions was determined by the Weissenberg Camera and data were adjusted to match the X-ray powder pattern. The pattern shows monoclinic symmetry and agrees well with the data of manganiferous cummingtonites described by Klein (1960) and Jaffe (1961). It is seen from Table VIII that the refractive indices of the manganiferous cummingtonites do not show appreciable changes with increase or decrease of Mn.

## Other Silicates

A large number of ferromagnesian and lime silicates were formed along with anthophyllite and cummingtonites in the Wabush iron-formation. Among these the common hornblendes, pyroxenes, and garnets are important.

## Common Hornblendes

## Actinolite

Actinolite occurs with the cummingtonite-diopside-carbonate assemblage in the lower Wabush iron-formation. The mineral was easily identified by its pale green colour. In thin section it is seen to be pale greenish or yellowish and distinctly pleochroic. Actinolite formed coarse prisms and has undoubtedly replaced cummingtonite in these rocks. Unreplaced colourless relicts of cummingtonite are fairly plentiful in the centres of green actinolite grains. Lamellar twinning and (001) partings are not common, but are present in some grains, perhaps as relict forms preserved from cummingtonites. Optical properties of two samples of actinolite are given in Table IX. The optical data indicate that the minerals are "ferroactinolites" and rich in iron.

## Table IX

Specimen No. and Locality	Colour and Pleochroism	Nx	Ny	Nz	Nz-Nx	z c	2V
62-GF-19 Wabush Lake	x = colourless y = pale green z = green	1.650	1.658 <sup>1</sup> 1.660	1.666	0.016	15°	-88°
54 A Mount Wright	x=colourless or pale yellow y=yellowish green z=green	1.638	1.650	1.662	0.024	16°	— 87°

## **Optical Data on Actinolites**

<sup>1</sup> Calculated Ny value.

## Tremolite

This mineral is present in the lower Wabush iron-formation associated with carbonate and quartz and rarely with cummingtonite. Both coarse prisms and asbestiform varieties can be identified. The crystals are generally white or pale greenish, and colourless in thin section. Lamellar twinning was seen in a few grains. Tremolite is closely intergrown with carbonates and appears to have formed from them. The optical properties of one sample (60-GF-62) from Wabush Lake area were determined as follows:

$N_x = 1$	1.612	$N_z - N_x$	=	0.017
$N_y = 1$	1.6211	$Z \wedge C$	=	20°
	1.619	2V	=	$-88^{\circ}$
$N_z = 1$	1.629			

<sup>1</sup>Calculated Ny value

#### Hornblende

Blue-green hornblende is a common amphibole in metamorphosed iron-formations and has been described by Richarz (1927b), Miles (1943), and others from different parts of the world. This variety of hornblende is present as very small grains in most members of the Wabush iron-formation, but its paragenetic relationship with other silicate minerals is not clear. In only one place in Wabush No. 6 deposit was it found as a thin band in quartz-specularite schist. There it is coarsely crystalline, dark green, and is closely associated with quartz. Its optical properties are as follows:

271	7		1				
$\mathbf{P}$	10	n	cv	ч.	$\alpha i$	CZ	n
	10	$\mathcal{O}$	~~	674	11	01	rı.

x = pale greenish yellow	$N_x = 1.642$	$N_z - N_x$	= 0.019
$_{y} = olive-green$	$N_y = 1.655$	$Z \wedge C$	= 20°
$_{z}$ = deep bluish green	$N_z = 1.661$	2V	$= -66^{\circ}$

#### **Pyroxene Group**

Pyroxenes are an important group of minerals in the lower Wabush iron-formation. Two varieties of pyroxenes, diopside and hypersthene, could be identified in these rocks. Diopside is present both in the Wabush Lake and Mount Wright areas, but hypersthene is found only in the latter.

#### Diopside

This mineral occurs as conspicuous coarse, green porphyroblastic crystals, associated with cummingtonite, actinolite, and carbonates. The crystals have grown across the cummingtonite prisms and rarely contain rotated anhedral inclusions of that mineral. The formation of diopside, therefore, apparently followed the crystallization of cummingtonite. As there is no evidence of replacement between diopside and cummingtonite or diopside and carbonates, the paragenesis of diopside can only be guessed.

The diopside in the Wabush iron-formation is green and non-pleochroic in thin section. Grains are large, prismatic, and show poikilitic texture. Prismatic cleavages

#### Ferromagnesian Silicate Minerals

at right angles are well developed and easily detected in the basal sections. The optical properties of two samples and the chemical analyses of one are given in Table X. Both samples are rich in iron and nearer to hedenbergite (Ca Fe  $Si_2O_6$ ) in composition.

## Table X

Optical Properties and Chemical Analyses of Two Diopsides (Analyses given in weight per cent)

			-		· · · · · · · · · · · · · · · · · · ·								
Sample No. and Location	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Nx	Ny	Nz	Nz-Nx	Z∧C	2V
60-GF- W4 Luce Lake	51.56	0.32	1.69	19.23	8.89	16.94	0.34	1.715	1.721 <sup>1</sup> 1.725	1.740	0.025	44°	+60°
54-6-E Mount Wright								1.712	1.717	1.732	0.020	43°	+59°

(Analyst: S. Courville)

<sup>1</sup> Calculated Ny value

## Hypersthene

Hypersthene occurs as small, elongated crystals closely associated with cummingtonite, garnet, and quartz in the silicate facies of the Wabush iron-formation. It is also found with the cummingtonite-diopside-actinolite-carbonate assemblage in the carbonate facies.

Hypersthene is intergrown with cummingtonite along direction of crystal elongation. The intergrowth is so complicated that mineral separation for chemical analysis was practically impossible. Hypersthene is identified in thin section by its parallel extinction, pleochroism, and other optical properties. Table XI shows the optical data of two hypersthene samples.

## Table XI

Facies	Specimen No.	Pleochroism	Nx	Nz	Nz-Nx	2V	Ny
Silicate Mount Wright	38	x=pale yellowish brown y=pale greenish brown z=pale green	1.735	1.755	0.020	-66°	1.749
Carbonate	54-9-3	Pale brown	1.723	1.740	0.017	— 52°	1.736
Carbonate East of Mount Wright	54-9-3	Pale brown Very weakly pleochroic	1.723	1.740	0.017	— 52°	1.73

### Optical Data on Two Hypersthenes

The approximate composition of the hypersthenes was ascertained by plotting the optical properties on Winchell's enstatite-ferrosilite diagram (Winchell, 1951, p. 406). The composition of hypersthene from the silicate facies was  $Mg_{25}$  Fe<sub>75</sub>, and that from the carbonate facies was  $Mg_{37}$  Fe<sub>63</sub>. Both the samples have a high iron content and fall in the ferrohypersthene region of Winchell's diagram.

The weak and varying intensity of pleochroism of ferrohypersthenes in these rocks is peculiar and needs some explanation. The explanation offered in some older text books indicating that intensity of pleochroism increases with increase in iron content in the enstatite-hypersthene series obviously does not hold, according to the writer's observations, for the series as a whole. It does not seem possible as yet to ascribe strong pleochroism to high content of Fe, Mn, or Ti. Perhaps more quantitative measurements of pleochroic properties might lead to some possible chemical explanation of its intensity.

## Garnet Group

Garnet is rare in the Wabush iron-formation. Only one variety, intermediate in composition between spessartite and almandite, is present in the silicate facies of the iron-formation.

Garnet occurs as coarse porphyroblastic grains with cummingtonite, quartz, and magnetite. Both in hand specimen and in thin section the mineral is yellowish pink, the pink being more prominent. The grains are coarse, euhedral, and poikilitic. Like diopside, garnet appears to have pushed aside earlier formed cummingtonite crystals during crystal growth. Relict microbanding was seen in some of the grains. A sample of garnet from the Boulder Lake area had a refractive index of 1.820, and a cell dimension of 11.559  $\pm 0.005$  Å.

## **Carbonate Minerals**

The carbonate minerals occur with quartz, cummingtonite, and magnetite in a major lithologic unit of the Wabush iron-formation. As previous workers have not reported the composition of these carbonates, the author undertook accurate determinations of the composition and proportion of the carbonate minerals in this formation. Such an investigation was needed in order to understand the paragenesis and stability fields of different carbonate and silicate minerals. As the temperatures of formation of the carbonate minerals are well known (Kulp, *et al.*, 1951), their identification helps to evaluate the metamorphic condition of these rocks.

Seven samples with minimum quartz, magnetite, and silicate minerals were selected from the Wabush Lake area. The samples were crushed to -100 + 150 mesh. Magnetite was separated by using a strong hand magnet. Bromoform separation was used successfully to remove part of the quartz. The samples were then run in the Frantz isodynamic separator to remove the silicate minerals, as described previously. A complete separation of quartz from the carbonates seemed impossible.

#### Ferromagnesian Silicate Minerals

As a preliminary step the concentrated carbonate stock was examined under the microscope, and was found to be a complex mixture of different carbonates of varying refractive indices and colours. Because it is not always possible to distinguish the members of the carbonate family under the ordinary petrographic microscope, and also because there is considerable overlapping in refractive indices owing to large-scale elemental substitution in these minerals, the author did not depend on the optical data for their conclusive identification. The techniques used for the specific identification of these minerals included differential thermal analysis, thermogravimetric analysis, X-ray diffraction, and semiquantitative emission spectroscopy. The investigation was carried out in the Mines Branch, Department of Mines and Technical Surveys, Ottawa, under the direction of Dr. N. F. H. Bright (Bright, 1962). The results are shown on Table XII.

## Table XII

Specimen No.	Mineral Assemblage Before Concentration	Minerals After Concentration (All approximate values)
60-GF-55	Quartz, specularite magnetite, anthophyllite, carbonate, little chlorite, and talc	Siderite (Fe, Mn) Co <sub>3</sub> , 60%; Mn is significant Ankerite (Ca, Fe (CO <sub>3</sub> ) <sub>2</sub> ), 35%; and quartz
60-GF-62	Carbonate, quartz, tremolite, magnetite, chlorite	Siderite, 85%; rest is quartz
60-GF-65	Carbonate, cummingtonite, quartz	Calcite (Ca CO <sub>3</sub> ), 45%; dolomite (Ca, Mg (CO <sub>3</sub> ) <sub>2</sub> ), 40%; and quartz
60-GF-66A	Carbonate, quartz, magnetite, chlorite, phlogopite	Ankerite, 20%; dolomite, 10%; siderite (with significant Mn), 5%; and quartz
60-GF-66B	Carbonate, quartz, magnetite, cummingtonite, chlorite, and tourmaline	Quartz is predominant; ankerite dolomite  10%
60-GF-W5	Carbonate, cummingtonite, quartz, with little tremolite	Siderite (Mn quite low), 40%; dolomite and quartz, 10%
60-GF-W6	Carbonate, quartz, with little phlogopite	Ankerite, 35%; siderite, 25%; magnesite (MgCO <sub>3</sub> ) and quartz, 10%

**Results of Carbonate Investigation** 

As shown by Table XII, siderite, dolomite and ankerite are the most abundant carbonate minerals of the Wabush iron-formation. Calcite and magnesite are rare or insignificant in quantity.

## Anthophyllite-Cummingtonite-Manganoan-Cummingtonite Relationship

Anthophyllite-cummingtonite-grunerite can be regarded as phases in the system MgO-FeO-SiO<sub>2</sub>-H<sub>2</sub>O. Because of the similarity in composition of these three minerals, earlier workers considered the two series as isodimorphous. Eskola (1936) cited the occurrence of anthophyllite and cummingtonite in the same rocks of the Orijarvi region and stated they were polymorphic, but it is interesting to note that Eskola's cummingtonite contains 3.96 per cent alkalis, whereas the equivalent anthophyllite contains a negligible quantity. Johansson (1930) showed the difference between the orthorhombic anthophyllite and monoclinic cummingtonite lattice. Sundius (1933) denied that the two minerals are isodimorphous and showed that anthophyllites contain 6 to 9 per cent more alumina and ferric oxide than the similar cummingtonites. Rabbitt (1948), and Layton and Phillips (1960) discussed this problem in great detail and came to the conclusion that anthophyllite is essentially a threecomponent system involving magnesium, iron, and aluminum, whereas cummingtonites are ferromagnesian silicates in which manganese and calcium are usually present in significant quantities. Boyd (1959) investigated the system Mg7Si8O22 (OH)<sub>2</sub>-Fe<sub>7</sub>Si<sub>8</sub>O<sub>22</sub>(OH)<sub>2</sub> and tried to synthesize both orthorhombic and monoclinic amphiboles. No amphibole richer in iron than about Mg<sub>40</sub> Fe<sub>60</sub> could be synthesized. Although both anthophyllite and cummingtonite can be represented by the general formula (Mg, Fe)<sub>7</sub> Si<sub>8</sub>O<sub>22</sub> (OH)<sub>2</sub>, the commonly occurring anthophyllites are magnesiarich, whereas most cummingtonites are iron rich. Natural anthophyllites are restricted to the range from a pure Mg end-member to a composition of about  $Mg_{40}$  Fe<sub>60</sub>. Natural cummingtonites extend from the pure Fe end-member to about Fe<sub>25</sub> Mg<sub>75</sub>. It seems, therefore, that a gap exists in the isomorphous series at the Fe end of anthophyllites and at the Mg end of cummingtonites. The writer investigated a large number of samples from the Wabush iron-formation, but could not find any cummingtonite richer in magnesium than Fe<sub>55</sub> Mg<sub>45</sub>.

Manganiferous cummingtonites were reported by Sundius (1924) from the Swedish iron-formations and from eulysitic rocks. The same mineral group has since been restudied by Sundius (1931) and by Richarz (1927b). These manganiferous cummingtonites are all rich in iron. Recently Jaffe, Meijer, and Selchow (1961) reported one manganoan-cummingtonite from manganese carbonate rocks of Nsuta, Ghana, which contains as much as 19.2 per cent of MnO. These workers regarded these minerals as members of the cummingtonite-grunerite series, and indicated that they are formed by the substitution of ferrous iron by manganese. The manganoancummingtonites reported by the writer and Klein (see Table VIII) from the Wabush iron-formation are interesting in that they occur with anthophyllites in the same beds. In thin sections the two minerals form intergrowths and can be distinguished by their extinction angles, slight differences in refractive indices, birefringence, and colour. Chemical analyses of the manganiferous cummingtonites in Table VIII show that they are rich in magnesium, which is rather unusual for natural cummingtonites. The lower refractive indices in these minerals is also remarkable. Both Richarz (1927a) and Sundius (1931) tried to correlate the optical properties of the high and low manganese

#### Ferromagnesian Silicate Minerals

cummingtonites and came to the conclusion that there is a difference between the Mn-poor and Mn-rich members of the series. The X-ray data of manganoan-cumming-tonites fit best with those of cummingtonite, but are not an exact match. Cell dimensions are also a little smaller.

Anthophyllites from Wabush iron-formation (Table I) contain some Mn. The analyses of manganoan-cummingtonite (A and B in Table VIII) are similar to the analyses of these anthophyllites, with the possible substitution of Mg by Mn, which suggests that these manganoan-cummingtonites may be related to the anthophyllites, rather than to the cummingtonites. In order to verify this interpretation, and also to furnish a more complete picture of the MnO: FeO: MgO ratios in some of these amphiboles, Figure 3 was prepared, using the following analyses: anthophyllites from Table I, and Rabbitt (1948, Table II, Nos. 29 and 45); cummingtonites from Table



Note: Numbers and letters refer to sample indentification on Tables I, VII, & VIII



VII, Klein (1960, p. 42), Mueller (1960, Table II, No. DH-3), and from Kranck (1961, p. 179); and manganoan-cummingtonites from Table VIII. The groupings of the points on Figure 3 seem to be significant. Cummingtonites show up as Fe-Mg amphibole with little MnO, the anthophyllites fall to the Mg corner, and the manganoan-cummingtonites approach the ideal Mg-Mn amphibole. Anthophyllites and manganoan-cummingtonites from the Wabush iron-formation are closely spaced in the diagram. It appears that as Mn enters into anthophyllite it tends towards manganoan-cummingtonite composition and apparently there exists a linear relationship.

To be more precise about this relationship, the writer plotted MnO against FeO content of anthophyllites, cummingtonite-grunerites and manganoan-cummingtonites (Fig. 4). Data were taken from all published literature (Sundius, 1924, 1931; Bowen and Schairer, 1935; Collins, 1942; Miles, 1943; Rabbitt, 1948; Mueller, 1960; Klein, 1960; and Kranck, 1961) and also from Tables I, VII, and VIII of this paper, showing maximum variation in composition. All samples containing more than 3 per cent MnO were plotted as manganoan-cummingtonites. Next, the coefficient of correlation (r) for all these points was calculated, following the procedure of Dixon and Massey (1957, p. 201); this came to -0.27.



FIGURE 4. Diagram showing the weight per cent of MnO and FeO in anthophyllites, cummingtonite-grunerite and manganoan-cummingtonites from Wabush Lake samples and analyses reported in literature.

#### Ferromagnesian Silicate Minerals

Taking only anthophyllites and manganoan-cummingtonites on Figure 5, the coefficient of correlation was calculated, which gave the value of r = 0.50. All but two samples lie very near the mean line of correlation. The same amount of correlation between these two groups of minerals was obtained with a negative inclination of the line when MnO was plotted against MgO. The value of r is much reduced as the ferromagnesian cummingtonites are taken into consideration. Therefore the manganoan-cummingtonites, at least the high magnesian ones, have a higher degree of correlation with the anthophyllites. As there is no evidence of replacement between anthophyllite and manganoan-cummingtonite in the Wabush iron-formation, the writer suggests that manganoan-cummingtonite is a manganiferous analog of anthophyllite. A similar relationship exists between hypersthene and pigeonite (Bowen and Schairer, 1935; Kuno and Nagashima, 1952), where Ca plays the critical role. As pointed out by Layton and Phillips (1960), both Mn and Ca, because of their larger atomic radii (0.83Å and 1.03Å) compared to Fe++ (0.74Å) and Mg++ (0.66Å), prefer a monoclinic symmetry. Therefore gradual substitution of Mg++ by Mn in the anthophyllite lattice may, at a certain stage, be accompanied by a change from orthorhombic symmetry to monoclinic. The peculiar refractive indices and high magnesia content



FIGURE 5. Diagram showing the coefficient of correlation (r) for anthophyllites and manganoan-cummingtonites.

of manganoan-cummingtonites can also be better explained in this way. Instead of becoming lower, the refractive indices in fact rise with the increase of Mn in the anthophyllite composition.

## Paragenesis of Silicate Minerals

The origin of silicate minerals in iron-formation is a difficult problem. Various suggestions have been made by previous workers as to the mechanism of formation of cummingtonites. The Wabush iron-formation is generally considered to be the metamorphosed equivalent of a cherty silicate iron-formation such as that in the Knob Lake area. At Knob Lake, siderite, quartz, minnesotaite, hematite, magnetite, and talc are present in abundance, which may be assumed to be the primary minerals in these rocks. In the Wabush iron-formation a large number of high temperature. silicate minerals like anthophyllite, cummingtonite, hypersthene, diopside, actinolite, etc., have been formed by metamorphic reactions. Although there is still insufficient information to reconstruct accurately the metamorphic history of these rocks, the writer has formed the following conclusions about the paragenesis of the minerals, based on the mode of occurrence, textural relations, and chemical composition.

Anthophyllite occurs with specularite, quartz, and talc. From its relation with talc (Pl. I), there is no doubt that it is formed by the breakdown of talc. The necessary reaction was suggested by Fyfe (1962) from his experimental study:

7 Mg<sub>3</sub>Si<sub>4</sub>O<sub>10</sub> (OH)<sub>2</sub> = 3 Mg<sub>7</sub>Si<sub>8</sub>O<sub>22</sub> (OH)<sub>2</sub> + 4SiO<sub>2</sub> + 4H<sub>2</sub>O Talc Anthophyllite

Cummingtonites are present in all three facies of the Wabush iron-formation. and can form by metamorphism of primary iron silicates, or by reaction between siderite and quartz or quartz and magnetite. In the silicate facies of iron-formation, cummingtonite occurs as sharp continuous bands without any evidence of replacement or gradational margins. Within these bands the cummingtonite is well crystallized. These bands or layers may be considered as stratigraphic horizons. In the transitional oxide facies small cummingtonite crystals occur with quartz and magnetite aligned with the regional foliation. No sign of reaction between quartz and magnetite has been observed. Cummingtonites in these rocks are therefore believed to be derived from primary silicates (minnesotaite) by simple recrystallization. In the carbonate facies of iron-formation coarsely crystalline cummingtonites are arranged in a random fashion They are also found between carbonate and quartz bands or around the carbonate minerals. Optical data (Fig. 2) and chemical analyses (Table VII) show that these cummingtonites are comparatively poor in iron and rich in lime and magnesia. Although there is no direct evidence of siderite-quartz reaction, it seems that carbonates played some part in the formation of cummingtonites in these rocks. The metamorphic destruction of carbonates and combination of the cations with silica is strictly comparable to the development of tremolite and diopside in metamorphosed limestone and dolomite, and is referred to as silication.

Hypersthene is found closely intergrown with cummingtonite in both the silicate and carbonate facies of the iron-formations in the Mount Wright area (Gross, 1955)

#### Ferromagnesian Silicate Minerals

The chemical composition of hypersthene, as indicated by optical data, agrees very well with the composition of cummingtonites from corresponding facies. Hypersthene is therefore believed to have formed by the structural reconstitution of cummingtonite without any appreciable addition or subtraction of iron. In the carbonate bands where enough Ca is available, diopside and actinolite crystallized simultaneously with hypersthene.

## SUMMARY AND CONCLUSION

The Wabush iron-formation is a metamorphic banded ferruginous rock of sedimentary origin. In this report it has been divided into lithological facies on the basis of characteristic mineral assemblages that are derived from primary sedimentary minerals. The mineralogical compositions of the rocks show that the grade of metamorphism in the Wabush and Boulder Lakes areas has reached the epidote-amphibolite facies or garnet-staurolite zone. Farther south, however, in the Mount Wright area, metamorphism is of slightly higher intensity, as revealed by the coarseness of quartz grains and silicate minerals, and the presence of hypersthene. On the basis of the present investigation, the writer concludes that the iron-formation was metamorphosed isochemically with a minimum possible migration of elements. Each layer, however thin it might be, acted as a closed system during progressive metamorphism. in the manner suggested by Yoder (1957), and retained its bulk chemical composition practically unaltered. These layers mostly show evidence of recrystallization, with cummingtonite, anthophyllite, hypersthene, diopside, etc., appearing in areas that reflect gradual increase of pressure and temperature. The difference in composition of cummingtonites in different types of iron-formations indicates a variation in primary chemical composition. A similar interpretation for compositional variations of stilpnomelane was reached by James (1954).

This study has also contributed some new evidence on the paragenesis of the silicate minerals. The abundance of siderite in the Wabush iron-formation suggests that it may be stable up to the epidote-amphibolite facies of metamorphism. It is hoped that the talc-anthophyllite, and anthophyllite-cummingtonite-manganoan-cummingtonite relationship will suggest new channels of investigation regarding their stability fields. The distribution and role of Mn in the formation of these minerals is of further interest.

Secondary manganese oxides are reported from the iron orebodies south of Little Wabush Lake, which are situated at a lower elevation than the Smallwood mine and Wabush 6 and 7 deposits. The average Mn content in the orebodies of Wabush Lake and surrounding areas according to surface samples does not exceed 1 per cent, except in Wabush deposits No. 6 and No. 7, where manganese content may vary locally from 2 to 8 per cent. These deposits, as mentioned before, contain abundant manganoan-cummingtonites and manganese-bearing anthophyllites. It is possible that these minerals are also the source of manganese in the orebodies to the south.

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## APPENDIX

The d-spacings, intensities and cell dimensions of the amphiboles were measured from X-ray powder pattern using Fe radiation, Mn filter, and camera diameter = 57.3 mm.

Antho	phyllite	Anthophyllite			
(Sp. 60-GF-55. No	o. 6 Wabush Deposit)	(ASTM Ca	rd 9-455)		
I (est.)	d (meas.)	d -	I _		
10	9.32	9.3	25		
7	8.26	8.9	30		
$\frac{1}{2}\mathbf{B}$	5.06	8.26	55		
1	4.80	7.48	7		
5	4.54	5.04	13		
5	4.13	4.90	9		
4	3.84	4.62	13		
4	3.41	4.50	25		
6	3.23	4.13	20		
5	3.18	3.90	13		
8	3.04	3.65	35		
2	2.96	3.36	30		
6	2.725	3.24	60		
3	2.595	3.05	100		
5	2.493	2.87	20		
1/2	2.350	2.84	40		
2	2.281	2.74	20		
1	2.232	2.68	30		
3	2.169	2.59	30		
$\frac{1}{2}$	2.125	2.54	40		
1	2.076	2.434	13		
1	2.020	2.318	20		
$\frac{1}{2}$	1.939	2.290	20		
$\frac{1}{2}$	1.858	2.252	13		
12	1.839	2.174	9		
		2.142	30		
		2.074	9		
		2.060	9		
		1.991	15		
		1.875	11		
		1.839	20		
		1.734	30		

## Cummingtonite (Sp. 57-GF-84C. West of White Lake)

I (est.)	d (meas.)	hkl.	I (est.)	d (meas.)	hkl.
2	9.15	020	4	1,660	461
10	8.33	110	2	1.634	480, 1.11.0
$\frac{1}{2}$	5.17	001	2	1.596	153
1/2	4.84	111	1	1.581	402
ī	4.62		1	1.553	600
1	4.55	040	3	1.521	0.12.0
4	4.13	220	1/2	1.509	551
3	3.86	131	$\frac{1}{2}$	1.496	372
3	3.46	131	4	1,475	502
4	3.26	240	ĩ	1.466	3.11.0
7	3.06	310	$\frac{1}{2}$	1.434	4.10.1
1	2.99	221	4	1.403	642, 661
7	2.756	330	2	1.381	512
4	2.628	061	1	1.366	1.11.2
4	2.503	202	$\frac{1}{2}$	1.353	
$\frac{1}{2}$	2.395	261	$\frac{1}{2}$	1.333	
$\frac{1}{2}$	2.369	350	1	1.328	662
$\frac{1}{2}$	2.309	_	$\frac{1}{2}$	1.315	004
2	2.292	351	3	1.300	2.12.2
ł	2.240	421		1.274	
3	2.215	312		1,251	
5	2.189	261		1,232	
2	2.096	202		1.184	
1 2	2.071	400, 081		1.156	
2	2.029	331		1.066	
2	1.990	190		1.0415	
2	1.900	402		1.0393	
1	1.949	402		1.0147	
2	1.906	422		0.9983	
2	1.881	191			
2 1	1.834	460			
2	1.020				
1	1.790	3/1			
2	1.710	272			
2	1./05	512			
1	1.685	512			

# Manganoan-cummingtonite

# (Sp. 57-GF-W.I.C.I. South of Little Wabush Lake)

I (est.)	d (meas.)	d (calc.)	hkl.
MS	9.02	9.03	020
S	8.32	8.26	110
W	4.83	4.84	111
М	4.51	4.51	040
Μ	4.13	4.13	220
Μ	3.85	3.86	131
М	3.42	3.42	131
Μ	3.24	3.24	240
S	3.07	3.05	310
Μ	2.96	2.957	221
S	2.72	2,723	151

## Manganoan-cummingtonite-Continued

I (est.)	d (meas.)	d (calc.)	hkl.
VW	2.65	2,659	331
MW	2,60	2,601	061
М	2.51	2.511	202
VW	2.36	2.351	350
MW	2.286	2.294	171
W	2 249	2 248	421
11/	2.247	2.240	312
W	2.231	2.230	171
M	2.170	2.169	261
W	2,076	2,074	202
W	2.019	2.021	222
VW	1.980	1.982	370
W	1.958	1.959	402
VVW	1.911	1.908	352
W	1.860	1,863	191
VW	1.815	1.806	191
W	1.797	1.791	312
VVW	1.782	1.776	530
VVW	1.749	1.750	203
MW	1.694	1.692	512
VW	1.673	1.673	551
М	1.648	1.644	461
W	1.616	1.616	1.11.0
MW	1.587	1.588	153
VW	1.569	1.565	402
VW	1.554	1.549	600
VVW	1.541	1.542	422
VVW	1.531	1.526	620
W	1.511	1.508	570
W	1.503	1.504	0.12.0
W	1.483	1.482	602
W	1.453	1.450	3.11.0
VW	1.426	1.425	4.10.1
Μ	1.404	1.401	661
W/MW	1.372	1.368	512
W/VWB	1.347	1.348	1.11.2
VWB	1.330	1.329	662
W/VW	1.300	1.301	0.12.2
MW	1.290	1.290	2.12.2
W/VW	1.276	1.273	751
výw	1.262	1.263	4.12.0
VW	1.255	1,255	404
VW	1.219	1.215	602
VVW	1.198		
VVW	1.191		
MW	1.182		
VVW	1.115		
W	1.111		
W	1.087		
VVW	1.080		
VVW	1.075		
W	1.057		
MW	1.036		

33

## Manganoan-cummingtonite-Concluded

I (est.)	d (meas.)	d (calc.)	hkl.
	· · · · · · · · · · · · · · · · · · ·		
MW	1.030		
W	1.022		
W	1.012	S =strong	
W	1.001	W =weak	
MW	0,989	M = medium	
MW	0,982	VW=very weak	
W	0.978	B = broad	

Cell dimensions of this manganoan-cummingtonite have been calculated:

$a_0 =$	9.53 Å	
$b_0 =$	18.05 Å	$eta = 102.83^\circ$
$c_0 =$	5.31 Å	

Calculated spacings are in harmony with monoclinic symmetry, space group = C2/m.

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