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METAMORPHISM OF IRON FORMATIONS ON THE
MELVILLE PENINSULA, NORTH WEST TERRITORIES

by

^{Harold}
David Watkins

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

Department of Geology
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The undersigned hereby recommend to the Faculty of
Graduate Studies acceptance of this thesis,

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MELVILLE PENINSULA, NORTH WEST TERRITORIES",

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ABSTRACT

Metamorphosed Precambrian oxide facies iron formations occur on East and West Melville Peninsula associated with basic, pelitic and carbonate rocks. They have been deformed by folding and strike-slip faulting, and are intruded by granitic plutons.

Mineral assemblages in the West Melville iron formation and associated rocks are typical of garnet zone metamorphism. Stability limits of Fe-rich actinolite, Fe-chlorite, and cummingtonite-grunerite, all of which occur in the iron formation, impose a maximum upon the physical conditions of metamorphism.

The reactions:

$5 \text{ ferroan dolomite} + 8 \text{ quartz} + \text{H}_2\text{O} \rightleftharpoons \text{tremolite} + 3 \text{ calcite} + 7\text{CO}_2$ and; $\text{actinolite} + 3 \text{ calcite} + 2 \text{ quartz} \rightleftharpoons 5 \text{ salite} + \text{H}_2\text{O} + 3 \text{ CO}_2$; the former from a carbonate outcrop, the latter from a nearby iron formation; suggest a temperature of metamorphism of 480°C at 2000 bars total pressure.

A slightly lower grade of metamorphism on East Melville Peninsula is suggested by the absence of garnet, finer grained rocks, and the mineral assemblage, quartz-ankerite-calcite-grunerite.

Amphiboles in the iron formations are commonly zoned and contain exsolution lamellae. Coexisting amphiboles are grunerite

and cummingtonite paired with actinolite and hornblende. Electron microprobe analyses of five amphibole pairs demonstrate a miscibility gap of 8.9 weight percent CaO between grunerite and actinolite and suggest a small miscibility gap of 3.3 weight percent Al_2O_3 between actinolite and hornblende. The same analyses indicate the maximum solubility of Al_2O_3 , Na_2O , and CaO in the grunerite structure to be 0.3, 0.7, and 0.9 weight percent respectively under the metamorphic conditions on West Melville Peninsula and slightly less at the lower metamorphic grade in the east. Actinolite-grunerite pairs show strong fractionation of Fe-Mg; actinolite having a higher ratio of $\text{Mg}/\text{Mg} + \text{Fe}_{\text{total}}$. However, fractionation of Fe and Mg is near unity when aluminous phases are present.

Microprobe analyses of two chlorites confirm the expected dependence of refractive index and birefringences on the $\text{Mg}/\text{Mg} + \text{Fe}_{\text{total}}$. This ratio increases in chlorites and amphiboles in the iron formation with increasing P_{O_2} . The P_{O_2} in the iron formation is indicated by magnetite and magnetite-hematite assemblages and is probably a function of the original environment of deposition.

It is thought that minnesotaite, stilpnomelane, and greenalite, with minor carbonate and excesses of quartz and iron oxides constitute the precursors of the present iron formations. Some of the reactions considered to have lead to the present assemblages include:

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INTRODUCTION

The area studied in this thesis is on Melville Peninsula in the eastern Arctic within the District of Franklin, approximately 1500 miles north of Montreal, Quebec (Fig. 1).

The geology of the Precambrian terrain of Melville Peninsula is not well known. The only previous work in the area is a reconnaissance map by W. W. Heywood of the Geological Survey of Canada (1967). Discovery of a major iron formation with economic potential prompted a more detailed assessment of the geology of the region and provided the writer the opportunity to work in an undescribed area. Two months of mapping the iron formation yielded new data on the stratigraphy, structure, petrography and mineralogy of the region. Occurrences of iron formation on either side of the peninsula are referred to as the East and West Melville Iron Formations (Fig. 6). An effort has been made to relate the two occurrences structurally and to indicate differences in metamorphic grade.

A detailed study of the mineralogy and phase relationships in the iron formation and adjacent rocks defines the approximate limits of temperature and pressure of metamorphism and suggests the probable behaviour of volatile components during metamorphism. Because of the sensitivity of iron oxide minerals to changes in oxygen fugacity, it was possible to illustrate the dependence of the silicate mineralogy on variations in oxygen fugacity.

Coexisting amphibole pairs in the iron formation were studied and the compositional gaps between the cummingtonite-

FIGURE 1: LOCATION OF AREA INVESTIGATED IN THIS THESIS

actinolite-hornblende series are defined under the conditions prevalent during metamorphism. The distribution of elements between an amphibole-pyroxene pair is also described.

METHODS OF STUDY

INTRODUCTION

The mapping of the area was carried out by D. Underhill and the writer during July and August, 1969, as part of a preliminary exploration and sampling program by Borealis Exploration Limited. The geology was mapped on air photograph overlays. These photos were used to compile base maps. Because of the proximity of the area to the magnetic north pole, and the magnetic nature of the minerals, attitudes and measurements that normally are done by compass were visually estimated by aligning the feature with obvious physiographic phenomena. A representative suite of samples was collected for detailed optical, chemical and X-ray studies.

SAMPLE PREPARATION

Parts of specimens were crushed and sized to -60, +125 mesh to determine refractive indices of some non-opaque minerals. Magnetite was removed with a hand magnet; other grains of various minerals were selected by hand under a binocular microscope.

Thin sections of the rock specimens were made for petrographic and textural studies. Polished sections were made for the

identification of opaque minerals.

Electron probe analyses were performed on some polished thin sections. Garnets were carefully separated for chemical analyses. Specimens were crushed to -150, +200 mesh and passed several times through a separatory funnel using bromoform as the heavy liquid medium. Then magnetite was pulled out with a hand magnet and the crushed material was passed several times through an isodynamic separator. Under the binocular microscope it appeared to be free of impurities, but the garnets were all observed to have common, fine, quartz inclusions in thin section and it is probable that some quartz contamination remained. These same specimens were used for X-ray work on the garnets.

OPTICAL METHODS

Amphibole crystals were selected under the binocular microscope and mounted on a spindle stage where the γ refractive index was determined. Refractive indices of chlorites and garnets were determined on cleavage fragments. Refractive index values below 1.700 were determined using standard immersion oils in steps of 0.002. Visually estimated volumes of two consecutive oils were mixed to produce a graduation of 0.001. A monochromatic sodium light source was used and the temperature was controlled at 22°C. Index oils were checked on a refractometer. For refractive indices greater than 1.700, plane polarized light and oils that were graduated in steps of 0.005, were used.

Plagioclase compositions were estimated in thin sections on the flat stage using the Michel-Levy statistical method.

Carbonates were identified using staining techniques outlined by Warne (1962).

CHEMICAL ANALYSES

Chemical analyses of amphiboles, pyroxenes, chlorites, and biotite were produced with an M.A.C. electron microprobe operated at 20 KV and at a specimen current of 0.03 microamps and at 0.02 microamps for carbonates. The analyses were performed by A. G. Plant on the probe at the Geological Survey of Canada in Ottawa.

A partial chemical analysis of garnet was done by atomic absorption (Mg, Ca) and titration (Fe total, Mn). The analyses were performed by Cal Murray at Carleton University.

X-RAY METHODS

Garnet samples were X-rayed to determine the cell edge parameter to confirm identification. The sample was mixed with a silicon standard and exposed to cobalt radiation for 24 hours.

GENERAL GEOLOGY

GENERAL STATEMENT

Precambrian rocks of Archean age, possibly in part of Archean age, have possibly undergone two periods of folding. They were metamorphosed, granitized, and locally intruded by granitic

and pegmatitic rocks. Metamorphosed sedimentary and volcanic rocks on both sides of Melville Peninsula may be downfolded remnants of a once continuous and extensive unit (Anhaeusser, et al., 1969). Heywood (1967) introduced the term, Prince Albert Group, for this distinctive assemblage which comprises several map units (Table 1).

STRATIGRAPHY

THE PRINCE ALBERT GROUP

The Prince Albert Group comprises a succession of Aphebian or Archean metamorphosed sedimentary and volcanic rocks (Heywood, 1967). Greenstones and amphibolites (unit 1), derived from intermediate to basic volcanic rocks, are the oldest rocks in the group and are possibly the oldest rocks in the entire region. Thin layers of acid volcanic, tuffaceous, and sedimentary rocks occur within this unit but have not been mapped separately.

Rock unit 2 consists of quartzite, quartz-biotite schist, garnet-biotite schist, sericite schist, quartz-feldspar gneiss, and schistose conglomerate that probably overlies the greenstone and amphibolite. Layers of metavolcanic rock are common within unit 2. The contact between units 1 and 2 is gradational and placed where metasediments become dominant. The composition of the metasediments varies along strike.

Iron formation (unit 3) conformably overlies the metasediments. The transition from metasediments to layered quartz-magnetite iron formation is usually sharp. In a few areas the contact is grada-

TABLE 1

TABLE OF FORMATIONS¹

ERA	GROUP	MAP UNIT	L I T H O L O G Y
A R C H E A N A N D / O R A P H E B I A N		10	diabase sills and dikes
	Intrusive into quartzite, granite, gneisses, and Prince Albert Group		
		9	quartzite, minor conglomerate
	unconformity		
		8	granite
	Intrusive into Prince Albert Group		
		7	migmatite
		6	granitoid gneiss
		5	layered gneiss
		4	gabbro, peridotite, serpentinite
Intrusive into Prince Albert Group			
A R C H E A N	Prince Albert Group	3	iron formation
		2	metasediments-quartzite, quartz-biotite schist, garnet-mica schist, marble
		1	greenstone and amphibolite

Units 5-7 are of uncertain age and have tentatively been placed in their present position on the basis of speculated regional correlation by W. W. Heywood. The possibility that they constitute an older basement cannot be ruled out.

tional over several tens of feet. Metasediments that overlie the iron formation are indistinguishable from those beneath it.

BASIC AND ULTRABASIC ROCKS

Sills and dikes of peridotite and serpentized peridotite with talc lenses (unit 4 a) occur within the Prince Albert Group. Some exceed a half mile in length and attain widths of several hundred feet.

Gabbro (unit 4 b) forms near vertical sills up to 1000 feet wide in metasedimentary rocks and iron formation on East Melville Peninsula. Contacts are usually fine grained and strongly sheared. Inclusions of iron formation, greenstone, and quartzite are common within the gabbro. On the west side of the Peninsula metagabbro and amphibolite represent unit 4 b.

The basic and ultrabasic intrusions are probably ophiolitic, judging by their association with eugeosynclinal sedimentary and volcanic rocks.

GRANITIC AND GNEISSIC ROCKS

A wide variety of granitic and gneissic rocks underlie most of the area adjacent to the Prince Albert Group.

The contact between layered gneiss (unit 5) and the Prince Albert Group was not observed. The contact between granitoid gneiss and the Prince Albert Group is steeply dipping and strongly sheared. Migmatite (unit 7) contacts with the greenstone belt are sheared and relatively sharp. The migmatite has possibly been derived from units 5 and 6 and clear boundaries cannot be established between these units.

Granitic rocks (unit 8) develop as small sills and dikes and as large plutonic masses. Apparently tabular granitic bodies have been possibly emplaced in the core of some antiforms. Massive granitic plutons with cross cutting contacts disrupt the Prince Albert Group and units 5 and 6. Numerous small dikes and quartz veins characterize the contact zone. The plutons contain inclusions of iron formation, metasediments, and greenstone.

APHEBIAN SEDIMENTARY AND INTRUSIVE ROCKS

On the west side of Melville Peninsula, gently to moderately dipping quartzite (unit 9) unconformably overlies steeply to vertical dipping greenstone, iron formation, gneiss, and granite. The basal unit contains layers and lenses of pebble conglomerate. South of the main iron formation, the base is a highly bleached, friable, pebbly zone about 50 feet thick, that may represent a preserved regolith.

Diabase dikes (unit 10), up to 120 feet wide and striking east to southeast, intrude all Precambrian rocks in the area.

STRUCTURAL FEATURES OF THE IRON FORMATION

GENERAL STATEMENT

The proximity of the map area to the earth's magnetic pole and the capacity of the iron formation to swing a compass needle within a distance of several miles, rendered this instrument useless. Time was not available to construct an accurate means of

measuring attitudes because of the reconnaissance nature of the field program. Thus, all attitudes were estimated or plotted on air photos by lining up topographic features. This method introduced significant errors in the data.

The central part of Melville Peninsula consists of layered gneissic to granitic rocks trending northeasterly and generally dipping steeply. The major units of iron formation are located in two of three belts of greenstone, amphibolite, and metasedimentary rocks. These trend northeast and are steeply dipping. The region is cut by steeply dipping to vertical faults which strike westerly to northwesterly. West-northwest striking, near vertical diabase dikes also transect the whole region.

MESOSCOPIC STRUCTURES IN THE WEST MELVILLE IRON FORMATION

Primary textures and structures were rarely observed, and all were too deformed to aid in top determination. Bedding in the iron formation is probably defined by the alternating laminae of quartz and magnetite. In adjacent metasediments and nearby greenstones and amphibolites, bedding varies in thickness from 1 foot to massive. Schistosity and gneissosity also appear to be parallel or subparallel to bedding. Attitudes of all these features are shown on the geological maps (Maps 1-4). They serve to delineate structural trends and indicate the structural conformity of most of the rock types.

Laminae in the iron formation in some zones are strongly con-

torted. Where S and Z shapes were viewed down plunge, the hinge lines are plotted on the geological map. Most of the folds are tight to isoclinal. Small folds have axes that are near vertical or near horizontal. Those with steeply plunging attitudes seem to be dominant. Some of the contortions of the laminae may be interference patterns.

In one area, quartz-magnetite laminae were observed to trace out concentric series of rings. Bedding surfaces showed two sets of intersecting lineations. Both sets plunge steeply; one trends northerly, the other northwesterly. Pebbles found in conglomerate adjacent to the northern iron formation (Fig. 2) are stretched. Elongation is parallel to the axes of the steep folds in the area.

MEGASCOPIC STRUCTURES - WESTERN REGION

Major isoclinal folds and vertically dipping faults are the dominant structures in the western region (Fig. 2). In the southern part, iron formation defines a series of isoclinal folds plunging steeply southwesterly.

The northernmost area of iron formation defines an isoclinal fold plunging steeply to the northeast. Large folds in the central portion of this zone are suggestive of interference structures. The southern end sweeps around to an easterly striking zone dipping moderately to the north.

Vertical or near vertical faults cut across these structures in a west-northwest direction.

FIGURE 2: AERIAL DISTRIBUTION OF IRON FORMATION ON
ON WEST MELVILLE PENINSULA

Measurements and calculations summarized in the following table describe approximately the movement of some of these faults.

FAULT	SEPARATION (in feet)		SENSE OF MOVEMENT
	HORIZONTAL	VERTICAL	
Buckley Mountain	700	200	left-handed
Borealis	1150	950	right-handed
Kolimigoolik	3000	-	right-handed
Underhill	550	-	right-handed

Quartzite (unit 9) in the southern end of the region unconformably overlies granitic and gneissic rocks and rocks of the Prince Albert Group. They are however, cut by the west-northwest fault system and gently folded about northwest trending axes. The cross bedding and graded bedding in this unit indicate that it lies right side up.

STRUCTURE OF THE EASTERN IRON FORMATION

The black magnetite and white quartz laminae probably represent sedimentary layers. These laminae are intricately folded and contorted in some areas. Meta-gabbro has been intruded into the belt subparallel to bedding attitudes. Inclusions of iron formation and quartzite are common in the meta-gabbro. Strong shear zones commonly develop near gabbro contacts.

Boudinaged quartz layers are observed in iron formation. Steeply dipping fractures, almost perpendicular to bedding, cause the iron formation to break into blocky chunks. A near horizontal fracture commonly accompanies this feature.

The belt of iron formation, associated metasediments and metavolcanic rocks is vertical to steeply dipping along most of its strike length of over 30 miles. A major fold occurs at the southwestern extremity. Several warps in the trend of the belt appear to have approximately the same sense of asymmetry as this large fold. Numerous small folds with near vertical or near horizontal axes occur in places.

A series of vertically dipping faults striking west-northwest cuts the iron formation.

The lateral separation can be estimated by using the iron formation as a marker and measuring the distance it is offset by faulting. The separation ranges to a maximum of 12,000 feet.

INTERPRETATION OF STRUCTURAL FEATURES

The megascopic structure of the western iron formation suggests two periods of deformation. Ring structures and contorted small scale folds that are possibly interference structures caused by two superimposed phases of deformation support this interpretation.

The sense of asymmetry of mesoscopic and megascopic folds in the southwestern iron formation suggests that the iron formations

in this area form an antiform-synform pair (Fig. 2). Bedding attitudes further corroborate this interpretation.

Bedding and fold hinge line attitudes were plotted on an equal-area projection in an effort to separate superimposed structural features. From the southwestern region, poles to bedding plot as a strong girdle through the central part of the projection (Fig. 3). Some fold axes plot perpendicular to the plane described by the girdle. The distribution of data represents a major fold plunging south-southwesterly at approximately 20 degrees.

Other attitudes from the same area are plotted on figure 4. Poles to bedding form a partial girdle around the outer edge of the projection. Small fold hinge lines, although somewhat scattered, plot in the central part of the projection. The distribution of the poles to bedding indicate folding on a steep axis defined by the maximum of small fold hinge lines (Fig. 4).

A plot of axes of small folds from the northwestern iron formation indicates a grouping of axes with an axial plunge of about 75 degrees northerly (Fig. 5). The plot of poles to bedding confirms the plunge. This direction also corresponds to the direction of elongation of deformed pebbles adjacent to the iron formation. Several small folds with near horizontal axes were observed but not measured within the same domain.

The shape of the fold near the central part of the map-area possibly results from interference of two phases of deformation. The broad fold in the southern part of this zone may be a re-

FIGURE 3: Contoured plot of 26 poles to bedding from major fold in southern part of the western region of the iron formation on West Melville Peninsula. Dots represent minor fold hinge lines. Contour interval: 1 percent.

FIGURE 4: Contoured plot of 27 poles to bedding from the southwestern region of the iron formation on West Melville Peninsula. Squares represent minor fold axes. Contour interval: 1 percent.

FIGURE 5: Plot of 12 minor fold hinge lines from the northern region of the iron formation on West Melville Peninsula.

sult of local intrusion (Map 1).

The limited data available possibly indicate that originally flat lying sedimentary rocks were folded first about a near horizontal axis and contemporaneously or subsequently refolded about a near vertical axis, giving rise to the present geometry of the iron formation.

Insufficient data are available to interpret the structure of the iron formation on East Melville Peninsula. The vergence of folds in the eastern iron formation is opposite to that of folds in the western iron formation. The east and west iron formation show vergence towards the southwest (Fig. 6). These iron formations appear to be parts of the same stratigraphic unit and define a major peninsula wide fold. Granite and migmatite have intruded the nose of the fold and destroyed direct evidence of the connection (Fig. 6). Small folds on both sides of the peninsula appear to have a similarity in the attitudes of their axial planes and there is a suggestion of refolding. However, the data are insufficient to be conclusive.

PETROGRAPHY

METAMORPHOSED BASIC ROCKS

Basic rocks constitute approximately two-thirds of the metamorphosed Prince Albert Group. These rocks have probably been derived from several sources, including:

1. basic tuffs, which alternate concordantly
with pelitic schists,
2. lavas which form thick extensive masses,
3. sills and dikes.

Neither relict minerals nor relict textures can be used to differentiate the sources of these amphibolites. However, the original differences are unimportant in terms of metamorphic mineralogy, as all types have converged to a common assemblage.

Metamorphism of the basic rocks appears to be somewhat similar in grade to the middle zone B of Shido (1958) and the epidote-amphibolite facies assemblages of James (1955).

Mineral assemblages observed are as follows:

- a) blue green hornblende-plagioclase, with or
without epidote, quartz, brown biotite and
sphene,
- b) actinolite-plagioclase-quartz,
- c) actinolite-chlorite-plagioclase-quartz,
- d) blue green hornblende-plagioclase-biotite-
epidote-chlorite.

Any of the above assemblages may contain opaque minerals.

Assemblages of type (a) constitute the major part of these rocks.

Blue green hornblende is the major constituent of most of these rocks. It is strongly pleochroic with α : yellow green, β :

medium green, γ : blue-green. The grains are generally euhedral and prismatic and have a preferred orientation (Plate 1). Less commonly, hornblende forms porphyroblastic plates with an irregular outline and a sieve texture (Plate 2). The hornblende is set in a matrix of equigranular plagioclase. The plagioclase is oligoclase or andesine that may or may not be twinned. Many of the plagioclases show zonal structure with a more calcic rim.

Epidote is common as euhedral grains. Sphene is common as granular aggregates. Fine plates of biotite are pleochroic brown. Chlorite occurs as shredded plates around biotite. It is usually of random orientation and cuts across the foliation. The orientation of chlorite is not considered to be attributable to the main metamorphic event.

METAMORPHOSED CARBONATE ROCKS

A minor unit of carbonate rock crops out on West Melville Peninsula. Ferroan dolomite, the principal constituent, and calcite were identified by staining with Alizarine red-S and potassium ferricyanide (Warne, 1962). Tremolite, quartz, chlorite, and biotite were identified optically. Chlorite and biotite are found in discrete bands and lenses and their texture indicates they are independent phases of the carbonate rock.

Assuming the components CO_2 and H_2O are in excess and ignoring important differences in Fe and Mg substitution, the composition of the carbonate rock and its constituent minerals can be

expressed in terms of the three components CaO, MgO + FeO, and SiO₂ (Fig. 7). The development of this assemblage can be represented by the reaction:

Since all these minerals are present in textural equilibrium, it is reasonable to assume that the metamorphic grade was sufficient to reach this reaction line. At equilibrium, four crystalline phases and a fluid phase coexist. Considering CaO, (MgO + FeO) SiO₂, H₂O, and CO₂ as the components of a simplified system, the phase rule:

$$F = C - P + 2$$

indicates the system has two degrees of freedom. Therefore the equilibrium temperature has a unique value if the fluid pressure P_f and the mole fraction (X) of the gas are specified. Experimental evidence (Skippen, 1971) indicates the limits under which this reaction can occur (Fig. 8). At an arbitrarily selected P_f of 2000 bars, the reaction occurs in an iron free system between 458°C and 510°C. A decrease in P_f causes a decrease in the temperature at which the reaction goes on (Fig. 8). The effect that iron has on this reaction is not known, but it is considered likely that it would cause a slight drop in the temperature of reaction (Skippen, personal communication).

METAMORPHOSED PELITIC ROCKS

The chief constituent minerals of the metasedimentary suite are: quartz, biotite, almandine, plagioclase, muscovite, chlorite, and amphibole. Some potassic feldspar and rarely epidote are observed. Mineral assemblages observed are as follows:

- a) quartz-biotite-hornblende-plagioclase, with
or without almandine
- b) quartz-biotite-chlorite-almandine-plagioclase,
with or without hornblende
- c) quartz-biotite-chlorite-muscovite-plagioclase
- d) quartz-biotite-chlorite-muscovite-almandine
- e) quartz-plagioclase-biotite-chlorite-muscovite-
almandine-epidote
- f) quartz-plagioclase-potash feldspar-biotite-
muscovite
- g) quartz-chlorite with or without muscovite

Any of the above assemblages may contain opaque minerals. Pleochroic brown biotite is common in most of the sedimentary rocks. Plagioclase (oligoclase-andesine) is also an important constituent. Twinning and zoning are common. Zones are commonly sharp enough to yield a Becke line. The inner zone is more sodic than the outer zone suggesting that the metamorphism of the area was progressive. Potash feldspar, where present, usually shows the clear quadrille twinning of microcline. Hornblende is blue green and

pleochroic. These features are consistent with the mid zone B metamorphism of Shido (1958).

These assemblages are characteristic of garnet zone metamorphism. Garnets were studied in more detail to find if they yield evidence compatible with this metamorphic grade.

GARNET

Garnets up to 6 mm in diameter are common in schistose rocks adjacent to the West Melville iron formation. The common assemblage is garnet + biotite + quartz $\pm$ chlorite $\pm$ plagioclase $\pm$ muscovite $\pm$ magnetite. Fine-grained quartz inclusions are common and show the crystals did not rotate during or after formation. Garnets occur as both euhedral and anhedral grains.

Garnets of the pyrospite series, especially those rich in almandine, are found typically in pelitic schists. Their systematic appearance in low to medium grade rocks of a progressive metamorphic series is so impressive that it has long been used as an index mineral (Barrow, 1893).

Physical parameters have been measured and partial chemical analyses carried out on garnets from three localities on West Melville Peninsula to determine their composition. Partial chemical analyses are shown in Table 1(b) together with refractive index and unit-cell edge. X-ray powder diffraction data used to calculate unit cell dimensions are shown in Table 1(a).

The analyses are sufficiently accurate to indicate that

TABLE 1(a)
X-ray Powder Diffraction Data for Garnets

hk1	TH33		X60E		W50E	
	Calculated dhkl(A)	Observed dhkl(A)	Calculated dhkl(A)	Observed dhkl(A)	Calculated dhkl(A)	Observed dhkl(A)
211	4.726	4.767	4.727	4.747		
222	3.342	3.347	3.343	3.344	3.341	3.342
400	2.894	2.893	2.895	2.891	2.893	2.896
420	2.589	2.586	2.589	2.582	2.588	2.589
332	-	-	2.469	2.467	2.468	2.470
422	2.363	2.363	2.364	2.362	2.363	2.364
510	2.270	2.271	2.271	2.269	2.270	2.271
521	2.114	2.112	2.114	2.113	2.113	2.116
440	2.047	2.046	2.047	2.046		
611	1.878	1.878	1.879	1.877	1.878	1.878
444	1.671	1.671	1.671	1.671	1.671	1.671
640	1.605	1.605	1.606	1.606	1.605	1.606
642	1.547	1.546	1.547	1.547	1.547	1.549
800	1.447	1.447	1.447	1.448	1.447	1.445
840	1.294	1.294	1.295	1.295		

almandine is the dominant component present, suggesting garnet zone or higher grade metamorphism. Furthermore, the grossular content is very low. Therefore the composition is not compatible with garnets from either the chlorite or biotite zone.

Stability fields of garnets of various compositions have been experimentally determined: almandine (Yoder, 1955; Hsu, 1968), spessartine, (Hsu, 1968), grossular (Yoder, 1950), and pyrope, (Boyd, England, 1962). However, the phase relations of garnet present in multi-phase assemblages are not sufficiently known to determine either pressure or temperature without careful consideration of the composition and stability of coexisting phases (Evans, 1965).

METAMORPHOSED IRON FORMATION

The iron formation of east and west Melville Peninsula consists primarily of banded quartz-magnetite of the oxide facies. The principal oxide is magnetite with lesser amounts of hematite. Subsidiary amounts of silicates and carbonates occur within the unit. Amphiboles, including coexisting pairs of members of the tremolite, cummingtonite, and hornblende series are common. Other silicates include chlorite, biotite, and muscovite. Ankerite and calcite constitute the carbonate minerals. Assemblages are given in detail in Table 8.

Measurement of quartz grains in contact with no minerals other than quartz indicated that the average grain size is 3 times

TABLE 1(b)

Partial Garnet Analysis

	<u>TH33</u>	<u>X60E</u>	<u>W50E</u>
SiO ₂ (est)	38.00	38.00	38.00
Al ₂ O ₃ (est)	24.48	22.27	22.18
FeO	23.80	27.39	30.23
MgO	1.49	1.36	0.98
MnO	10.21	3.60	1.08
CaO	<u>2.72</u>	<u>2.88</u>	<u>2.88</u>
Total	97.70	95.50	96.35

(est) = estimated (Deer, Howie, and Zussman, 1966)

Ref. Index	1.810	1.810	1.810
Unit Cell Edge	11.577	11.580	11.574

(Analyses of C. Murray, Carleton University laboratory)

larger in iron formation on West Melville than on East Melville.

Considerable emphasis has been placed on the study of the Melville iron formations because:

1. the economic implications of these deposits,
2. the unique conditions under which these deposits were metamorphosed allows clear definition of amphibole miscibility gaps and gives insight into the behaviour of components and phases during metamorphism.

INTRODUCTION TO THE AMPHIBOLES

Amphiboles have a wide chemical variation reflecting an elaborate arrangement of cation sites of contrasting size and differing surrounding atomic configurations. These structures can accommodate all the major cations of the earth's crust and mantle. Amphiboles are of widespread occurrence and may be sensitive indicators of the physical environment of crystallization. If physical conditions of crystallization for a large number of different amphibole bearing rocks can be determined, the observed variations in amphibole compositions and structural states might be understood and subsequently employed to indicate physical conditions in other rocks lacking in other indicative minerals.

The amphiboles all show the same internal structure and possess the same external habit. Silicon tetrahedra are arranged to produce a double chain (insosilicate) structure in which the

Si:C ratio is 4:11. The general formula for this group as found in Ernst (1968) is:

with W = Ca, Na, minor K, sometimes Li

X = Mg, Fe⁺⁺, Mn⁺⁺, Al in part

Y = Al, Fe⁺⁺⁺, Ti

Z = Si principally, Al in part.

Extensive studies indicate four generally accepted series comprising this group:

1. Anthophyllite series - $X_7(Z_4O_{11})_2(OH)_2$

X = Mg, Fe; Mg/Fe large; Ca subordinate

Z = Si almost entirely; Al in small amounts.

2. Cummingtonite-grunerite series - $X_7(Z_4O_{11})_2(OH)_2$

X = Mg, Fe⁺⁺;

Z = Si.

3. Tremolite-actinolite series - $W_2X_5(Z_4O_{11})_2(OH)_2$

W = Ca, minor Na;

X = Mg, Fe⁺⁺, minor Al;

Z = Si, minor Al.

4. Hornblende series - $W_3(X,Y)_5(Z_4O_{11})_2(OH,F)_2$

W = Na, Ca never >2, minor K, rarely Li;

X = Mg, Fe⁺⁺, Mn⁺⁺;

FIGURE 9a: Refractive indices (γ) of Mg-Fe amphiboles from the western Melville Iron Formation, (diagram adapted from Deer, Howie and Zussman, 1966).

FIGURE 9b: Refractive indices (γ) of calcium Mg-Fe amphiboles from the Melville Iron Formation (diagram adapted from Deer, Howie and Zussman, 1966).

Y - Al, Fe⁺⁺⁺, Ti;

Z = Si, lesser Al.

Groups 2, 3 and 4 are important constituents of the Melville iron formation and are treated in detail.

CUMMINGTONITE - GRUNERITE SERIES

Iron - magnesian amphiboles of the cummingtonite-grunerite series are common in both the East and West Melville iron formations. In the East Melville iron formation they are generally fine-grained, acicular, randomly oriented, twinned and beige to brownish in colour. In the West Melville iron formation they are generally medium-grained and acicular to broad prismatic in habit and display only moderate twinning. They tend to be a brownish to pale green colour in hand specimen and are locally oriented parallel to lineations or to laminations.

The known range of composition of (Mg-Fe) amphiboles extends from minerals containing approximately 30 percent of the $\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$ component to the $\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$ end member. Cummingtonite describes minerals containing 30 to 70 percent $\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$ and grunerite is used for more iron rich members (Deer, Howie, Zussman, 1966; Ernst, 1968). The refractive indices vary linearly with composition. The refractive index (γ) was determined to indicate the approximate range of compositions in the iron formation (Fig. 9a). Analytical data (Table 2) are also plotted, where available. Few

determinations were possible because of:

1. the zoned nature of many grains,
2. the fine grain size in many areas,
3. excessive twinning in many of the grains.

TABLE 2

Variation in γ refractive indices of members of the
cummingtonite-grunerite series in
iron formation on Melville Peninsula.

Sample No.	Mineral	γ refractive index $\pm$ 0.001	Location
Y240	Grunerite	1.702	Map 1
TP.1	Cummingtonite	1.685	300' east of TP3 (Map 1)
X500	Cummingtonite	1.672	Map 1
W10	Cummingtonite	1.689	Map 1

STABILITY OF CUMMINGTONITE-GRUNERITE SERIES

Little experimental evidence is available to describe the stability fields of end members of this series. Calcium-bearing grunerite has been synthesized between 450°C and 595°C at 1000 bars H₂O pressure and 80 bars CO₂ pressure. Intermediate Ca-bearing cummingtonite-grunerites were obtained at higher temperatures (Schurmann, 1966).

Some general statements regarding the stability of cumming-

tonite-grunerite are available from field studies. The assemblages; hypersthene + hedenbergite + cummingtonite-grunerite $\pm$ fayalite and; cummingtonite-grunerite + hornblende or actinolite have been described in metamorphosed iron formations (Gunderson, Schwartz, 1962). Higher grade rocks contain abundant fayalite; lower grade or retrograde rocks contain more hydrous Fe-Mg silicates such as minnesotaite, stilpnomelane and nontronite. Cummingtonite-grunerite also appears in middle grades of metamorphosed mafic igneous rocks of relatively low pressure terrains (Shido, 1958). Grunerite is described as the key mineral of intermediate intensity metamorphism of iron formation. Its appearance slightly precedes that of garnet in argillaceous rocks and approximately corresponds to the garnet isograd (James, 1955). The appearance of grunerite is also used as an isograd in contact metamorphosed iron formation and corresponds to middle grade conditions of metamorphism (French, 1968).

TREMOLITE - ACTINOLITE SERIES

Members of the tremolite-actinolite series are common in the West Melville iron formation. They are fine to medium-grained, green to dark green in colour and acicular to short and prismatic or nematoblastic.

Variations in refractive indices of members of this series are mainly related to the replacement of Mg by Fe. As a consequence, the composition can be estimated by determining the refractive

index. Refractive indices were determined of amphiboles from various localities to determine the approximate range of compositions in the iron formation (Fig. 9b). Where analytical data are available the exact composition is indicated. Substitution of Si by Al and of OH by F can cause up to 15 mol. percent error in estimates of composition based on refractive indices.

TABLE 3

Variation in some optical properties of tremolite-actinolite
from West Melville iron formation

Sample No.	Mineral	γ refractive index ± 0.001	Pleochroism		Location
			α	γ	
Y560	actinolite	1.682	pale green	dark green	see map 1
TP3	actinolite	1.648	colourless	pale green	see map 1
TP4	actinolite	1.660	colourless	pale green	150 ft. west of TP3
W10	actinolite	1.650	colourless	pale green	see map 1
W260	tremolite	1.638	colourless	colourless	250 ft. west of W10

W260 occurs with hematite and magnetite. All other assemblages from magnetite iron formation.

STABILITY OF TREMOLITE-ACTINOLITE SERIES

Considerable experimental evidence is available on the stability of end members of the tremolite-actinolite series. Although end members are not present in assemblages on West Melville Peninsula, some amphiboles are close enough to justify certain conclusions.

Although tremolite normally has a very wide stability range, severe limitations can be placed on it in certain assemblages. The association tremolite-calcite-quartz is observed stably co-existing in TP3. The upper stability limit of this assemblage is closely defined by a curve (Fig. 8). At a total fluid pressure of 3000 bars, this assemblage can exist to a maximum of 564°C. The tremolite of this assemblage, however, contains a certain amount of iron (Table 3) which will probably lower its stability to an unknown extent. The total fluid pressure which is not known can also cause a variation in the location of the curve of maximum stability.

Ferroactinolite has a severely restricted thermal stability range compared to the maximum stability limit of tremolite (Fig. 10). At 3000 bars fluid pressure ferroactinolite is stable to a maximum of 543°C (assuming $P_{\text{fluid}} = P_{\text{H}_2\text{O}}$). A decrease in the total fluid pressure to 500 bars reduces its stability further to 437°C (Ernst, 1966). Under osmotic conditions the stability of hydrous minerals would be confined to even lower temperatures.

Because ferroactinolite contains iron, predominantly as the

FIGURE 10: Comparison of the high temperature stability limits for tranolite (Boyd, 1959) and ferrotremolite (Ernst, 1966) defined by magnetite-wustite.

FIGURE 11: F_{O_2} -T diagram at 3000 bars fluid pressure;
field boundaries dashed when locations are
calculated or inferred, (after Ernst, 1966).

h = hematite	me = magnetite	f = fluid
a = andradite	ft = ferrotremolite	q = quartz
hp = hedenbergitic pyroxene		i = iron

ferrous iron, oxygen fugacities in excess of those defined by the assemblage magnetite + quartz + fayalite also cause a drastic reduction in the stability range of ferroactinolite (Fig. 10).

Because of these restrictive conditions and because an unusual bulk composition high in FeO and CaO but low in Al_2O_3 and MgO is required for the formation of ferroactinolite, it is most uncommon to find members of the series in which the replacement of Mg by Fe is greater than 50 percent (Deer, Howie, and Zussman, 1966).

Near appropriate conditions are observed for the formation of ferroactinolite in the area of specimen Y560. Actinolite in this specimen has an Mg/Mg + Mn + Fe ratio of 23.9 (Table 5). Thus the F_{O_2} -T diagram (Fig. 11) indicates approximately the stability limits for the assemblage quartz-magnetite-actinolite of specimen Y560.

COEXISTING AMPHIBOLES

Chemical analyses and atomic reductions of five coexisting amphibole pairs are given in Table 5. Inspection of the analysis shows that many analyses totals lie between 96.20 and 98.5 percent. Water of crystallization normally constitutes 1.5 to 2.0 wt. percent but analyses for water cannot be done on the probe. Consequently, atomic reductions are made on the basis of 23 oxygens.

CHEMOGRAPHIC RELATIONS OF THE AMPHIBOLES

The graphical representation of amphibole assemblages has long been a major problem (Winchell, 1945; Ernst, 1968; Robinson and Jaffe, 1969) because of the composition range and the great number of different substitutions. To describe common amphiboles to a first approximation the components SiO_2 - Al_2O_3 - Fe_2O_3 - TiO_2 - FeO - MnO - MgO - CaO - Na_2O - H_2O are required. This list may be reduced to 4 components: $(\text{FeO}+\text{MgO}+\text{MnO})$ - CaO - Al_2O_3 - Na_2O provided the following assumptions are made:

1. Assume SiO_2 is present in excess as the phase quartz.
This condition is met in all specimens examined.
2. Ignore the important crystal chemical differences between MgO and FeO .
3. Ignore Fe_2O_3 and TiO_2 . In each specimen TiO_2 is a negligible component. The Fe_2O_3 component enters into a separate oxide phase (magnetite, specularite, or both) but does not usually enter into the silicates extensively.
4. Treat H_2O as a perfectly mobile component controlled by the activity of H_2O of the environment. By ignoring coupled Na/Na substitution of the A and M(4) sites as in richerite and assuming that all Na substitution is compensated by Al in four-coordination as in edenite or in six-coordination as in glaucophane it is possible to represent the amphiboles in terms of

the three components ($\text{Al}_2\text{O}_3\text{-Na}_2\text{O}$), CaO , (FeO-MgO+MnO) at the apices of a triangle (Fig. 12) (Robinson and Jaffe, 1969).

TABLE 4

Estimated Modes of Specimens Containing Analyzed Amphiboles
from Melville Peninsula, Northwest Territories.

	West Melville			East Melville		
	Y240	Y560	TP3	W10	C600	AE1F
Grunerite	20	5		10	16	5
Actinolite		15	17	5		
Hornblende	5				4	15
Biotite		2		4	2	
Chlorite	5			6		
Stilpnomelane	10					
Quartz	35	23	30	40	53	20
Carbonate			X		5	20
Salite			5			
Hematite			X			
Magnetite	25	55	45	35	20	40
Pyrite	X	X			X	
Pyrrhotite	X	X		X	X	X
Apatite	X		3	X		

X = less than 1%

DESCRIPTION OF SPECIMENS IN TABLE 4

Y240 - medium to fine grained laminae of quartz, magnetite and silicate from .01 - .2 inches in thickness. All minerals are in mutual contact. Grunerite is colourless, and has multiple twinning. Hornblende is pleochroic from pale green to pale blue green. Extremely fine lamellae of a calcic amphibole are present in some grunerite grains (Plate 3). Stilpnomelane and chlorite appear to be secondary. They tend to be randomly oriented and transect layering (Plate 4).

Y560 - medium grained magnetite-rich iron formation with thin layers of green silicate minerals. Amphiboles are sharply zoned (Plate 5) with strongly pleochroic green ferroactinolite rims and colourless grunerite cores. Fine exsolution lamellae parallel to (101) are common in the grunerite (Plate 5). Grunerite lamellae are not common in the actinolite. Biotite seems to be slightly altered. All minerals in the assemblage are found in mutual contact.

TP3 - medium-grained magnetite rich iron formation with thin green layers of quartz and silicate minerals. Salite occurs as isolated irregular masses in optical continuity within a matrix of fine fibrous amphibole (Plate 6).

Coarser crystals of tremolite penetrate these masses. Hematite occurs as patchy zones of alteration on some magnetite grains. Carbonate grains were observed in contact with tremolite, quartz and magnetite.

W10 - medium-grained iron formation with quartz rich and magnetite rich layers varying from .05 to .3 inches in thickness. Grunerite and actinolite occur as discrete grains, and rarely zoned with pale green actinolite rims around colourless grunerite. Very fine exsolution lamellae are present in some grunerite parallel to (101). Chlorite and biotite are locally finely intergrown. All minerals occur in mutual contact.

AE1F - very fine-grained, thinly laminated iron formation. Amphiboles are commonly zoned with green hornblende rims and colourless grunerite cores. Zoning although rarely sharp and usually diffuse appears transitional from colourless to green amphibole (Plate 7). Exsolution lamellae parallel to (101) are common in both amphiboles. Xenoblastic quartz and carbonate and idiomorphic magnetite impart a granoblastic texture to the rock. All mineral species are in mutual contact.

C600 - fine-grained iron formation with quartz and silicate-

rich layers and magnetite-rich layers varying from very thin to .4 inches in thickness. Some grunerite forms a rim of acicular crystals radiating out from individual magnetite grains (Plate 8). Clusters of grunerite are commonly associated with a carbonate mineral (Plate 9). Hornblende occurs as zones in, or rims around some grunerite crystals. All minerals have mutual contacts.

PHOTOGRAPHS OF THIN SECTIONS,
POLISHED SECTIONS, AND HAND SPECIMENS OF ROCKS
FROM MELVILLE PENINSULA

PLATE 1: Amphibolite with planar orientation of
amphibole grains. Magnification x 20.

PLATE 2: Poikiloblastic amphibole with quartz
"eyes" in amphibolite. Magnification x 20.

PHOTOGRAPHS OF THIN SECTIONS,
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PLATE 1: Amphibolite with planar orientation of
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PLATE 2: Poikiloblastic amphibole with quartz
"eyes" in amphibolite. Magnification x 20.

PLATE 3: Zoned amphibole pairs from sample Y560.

Magnification x 50.

PLATE 3a: X-ray scan of Ca exsolution lamellae in
amphibole from sample Y560.

PLATE 3: Zoned amphibole pairs from sample Y560.

Magnification x 50.

PLATE 3a: X-ray scan of Ca exsolution lamellae in
amphibole from sample Y560.

PLATE 4: Stilpnomelane and chlorite transecting
layering, sample Y240. Magnification x 50.

PLATE 5: Sharply zoned amphiboles, with pleochroic
actinolite rims and grunerite cores (Y560).
Magnification x 50.

PLATE 4: Stilpnomelane and chlorite transecting
layering, sample Y240. Magnification x 50.

PLATE 5: Sharply zoned amphiboles, with pleochroic
actinolite rims and grunerite cores (Y560).
Magnification x 50.

PLATE 6: Isolated irregular masses of salite showing
optical continuity with fibrous amphibole (TP3).
Magnification x 50.

PLATE 7: Transitional zoning in AELF from colourless
to green amphibole. Magnification x 100.

PLATE 6: Isolated irregular masses of salite showing optical continuity with fibrous amphibole (TP3).
Magnification x 50.

PLATE 7: Transitional zoning in AE1F from colourless to green amphibole. Magnification x 100.

PLATE 8: Grunerite in C600 forms a rim of acicular crystals radiating out from magnetite.

Magnification x 100.

PLATE 9: Clusters of grunerite in C600 associated with carbonate mineral. Magnification x 50.

PLATE 8: Grunerite in C600 forms a rim of acicular
crystals radiating out from magnetite.
Magnification x 100.

PLATE 9: Clusters of grunerite in C600 associated
with carbonate mineral. Magnification x 50.

PLATE 10: Magnetite and quartz separated by reaction rim
of grunerite in sample C340. Magnification x 50.

PLATE 11: Banded magnetite-quartz iron formation
(sample Y240).

PLATE 10: Magnetite and quartz separated by reaction rim
of grunerite in sample C340. Magnification x 50.

PLATE 11: Banded magnetite-quartz iron formation
(sample Y240).

PLATE 12: Banded hematite-quartz iron formation
(sample TP3).

PLATE 13: Pyrrhotite "birds eye" texture in magnetite
(C340). Magnification x 50.

PLATE 12: Banded hematite-quartz iron formation
(sample TP3).

PLATE 13: Pyrrhotite "birds eye" texture in magnetite
(C340). Magnification x 50.

PLATE 14: Skeletal magnetite in specularite from
TH-45. Magnification x 50.

PLATE 14: Skeletal magnetite in specularite from
TH-45. Magnification x 50.

TABLE 5

Electron Microprobe Analyses of Coexisting Amphiboles

	Sample Y240 West Melville		Sample Y560 West Melville		Sample W10 West Melville		Sample C600 East Melville		Sample AE1F East Melville	
	grun.	hblde.	grun.	act.	grun.	act.	grun.	hblde.	grun.	hblde.
SiO ₂	51.6	44.0	49.2	51.8	53.4	53.9	51.2	41.0	51.2	47.9
TiO ₂	Tr	0.1	Tr	Tr	0.0	0.0	Nd	Nd	0.0	0.0
Al ₂ O ₃	0.2	9.2	Tr	0.1	0.0	0.3	0.1	14.8	Tr	3.6
FeO	37.3	26.1	42.0	28.9	33.2	19.4	39.1	26.2	37.0	26.1
MnO	0.8	0.2	0.3	0.1	1.2	0.2	0.3	0.2	0.5	0.2
MgO	7.1	4.2	4.1	5.1	10.2	12.0	5.1	1.8	8.4	7.5
CaO	0.5	11.6	0.8	9.7	0.7	11.8	0.3	11.1	0.8	11.1
Na ₂ O	0.0	1.0	0.6	1.2	0.0	0.3	0.1	1.0	0.2	1.0
K ₂ O	0.0	0.3	Tr	0.3	0.0	0.1	Tr	0.6	0.0	0.2
	97.5	96.7	97.0	97.2	97.7	98.0	96.2	96.7	98.1	97.6

Analyses performed by A. G. Plant at the Geological Survey of Canada

grun. = grunerite; hblde. = hornblende; act. = actinolite

TABLE 5 (cont.)

Numbers of Ions on the Basis of 23 Oxygens

Charge Assaying	Y240		Y560		W10		C600		AE1F	
	+46.0	+45.8	+45.9	+45.8	+45.9	46.0	46.0	+45.8	+45.9	+45.8
Fe=FeO	-46.0	46.0	-46.0	-0.1	-46.0	46.0	46.0	-46.0	-46.0	-46.0
Si	8.10	6.92	8.01	8.09	8.06	7.97	8.20	6.45	7.99	7.43
Al IV	0.00	1.08	0.00	0.00	0.00	0.03	0.00	1.55	0.00	0.57
Al VI	0.04	0.62	0.00	0.02	0.00	0.02	0.02	1.20	0.00	0.09
Ti	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	4.90	3.43	5.72	3.77	4.27	2.40	5.24	3.45	4.83	3.39
Mg	1.66	0.98	1.00	1.19	2.34	2.64	1.22	0.42	1.96	1.73
Mn	0.11	0.03	0.04	0.01	0.16	0.03	0.04	0.03	0.07	0.03
Ca	0.08	1.95	0.14	0.62	0.12	1.87	0.05	1.87	0.13	1.84
Na	0.00	0.31	0.19	0.36	0.00	0.09	0.03	0.31	0.06	0.30
K	0.00	0.06	0.00	0.06	0.00	0.02	0.00	0.12	0.00	0.04
Mf/Mg+Mn+Fe										
Total	24.93	22.15	14.73	23.86	34.56	52.18	18.74	10.83	28.53	33.70

Because of the components chosen figure 12 portrays coupled Al/Al substitution more or less completely but not Na/Al substitution. This is reasonable, however, in view of the minor quantities of Na_2O in consideration. An examination of the composition relations (Fig. 12) leads to the following observations:

All the grunerite samples plot in a tightly packed group at the (FeO+MgO+MnO) corner of the triangle. Actinolite and hornblende plot in a linear fashion near the same corner. The association grunerite-actinolite is cut out where alumina is available to amphibole by the association of grunerite and hornblende. The short gap between actinolite W10 and hornblende AE1F can be interpreted in three ways:

1. there is a continuous range of compositions between the actinolite and the hornblende series and the division of the two taken at $\text{Si} \leftrightarrow \text{Al IV}$ replacement of 0.5 atoms per formula unit (Deer, Howie, and Zussman, 1966) is truly an arbitrary one.
2. the distance between the two points outlines a miscibility gap.
3. failure to determine Fe^{+++} component may produce an artificially high number of Al IV atoms per formula unit. Consequently, it is possible that hornblende AE1F is actually an aluminous actinolite

and may lie short of any miscibility gap that might divide the two series.

As alumina becomes available to amphiboles it goes preferentially to the calcic member of the pair. Only a very small amount enters the grunerite and there appears to be no systematic relation between total Al_2O_3 and the amount present in grunerite. This suggests grunerite can accept only small amounts of Al in its lattice and that there is no continuous variation between grunerite and anthophyllite. The latter requires a more alumina rich environment before it can form.

Grunerite, coexisting with hornblende or actinolite also shows very low Na and Ca substitution. Excess Ca present in the grunerite shows up as very fine exsolution lamellae. Lamellae in grunerite that were barely discernible under high magnification were scanned to confirm the presence of calcium (Plate 3a). It is probable that excess Al is also exsolved in these lamellae where grunerite coexists with hornblende giving them a composition approximately the same as the coexisting grains of hornblende.

Fig. 13 is a graphical representation of the weight percent of the oxides CaO , Al_2O_3 , and Na_2O found in grunerite coexisting with hornblende or actinolite. These values are compared with maximum values as reported by Klein (1968). CaO and Al_2O_3 are much lower in the specimens from Melville iron formation than the maxima reported by Klein. This could be attributed to:

1. relatively low temperature of formation
2. bulk rock composition

3. both of these factors.

Calcium bearing exsolution lamellae in grunerite (Plate 3) as well as coexisting hornblende or actinolite may be considered as calcium-saturating phases. Coexisting carbonate, stilpnomelane, or plagioclase may be thought of as additional calcium-saturating phases where they occur. High calcium-bearing cummingtonites reported are generally from volcanic rocks, and may result from an increased solubility of CaO related to the high temperature of formation of volcanic amphiboles. Thus the low CaO component in grunerite from the iron formation is interpreted as indicating a relatively low temperature of formation.

Grunerites with high Al_2O_3 are also mainly from volcanic rocks. Lamellae in grunerite coexisting with hornblende are probably an Al saturating phase. Chlorite and stilpnomelane are also alumina saturating phases in some specimens. However, these saturating phases do not occur in all the specimens. Thus the low Al_2O_3 content can be attributed to relatively low temperatures of formation where Al saturating phases are present, and to a depletion of Al in the environment where they are not.

The Na_2O content of the grunerite analyses in Table 5 is also shown in Figure 13. With one exception, these also are lower than the maximum value reported by Klein (1968) for Na_2O in cummingtonite with coexisting hornblende, suggesting a relatively low or moderate temperature of formation. The grunerite with the high Na_2O content coexists with actinolite that is also relatively high in Na_2O (Table 5). This probably reflects an environment relative-

FIGURE 13: Weight percent CaO , Al_2O_3 , Na_2O
in grunerite coexisting with
hornblende or actinolite.

Melville Iron Formation

Maximum values in literature
(Klein, 1968)

ly rich in Na_2O . The Na_2O content of 0.6 weight percent is probably approaching the maximum amount of Na substitution in grunerite. A cummingtonite-magnesioriebeckite pair is reported to have 0.7 weight percent Na_2O in the cummingtonite (Klein, 1968).

Mg-Fe SUBSTITUTION

In order to examine the different roles of MgO and FeO it is necessary to expand the number of components to treat these two separately. They may be combined with CaO to form the triangle CaO, MgO, FeO in which appears an "amphibole quadrilateral" (Klein, 1968, Fig. 3). This provides excellent representation of grunerite-actinolite pairs (Fig. 14) but has a drawback in that it obscures the importance of Al/Al substitution in hornblende. Since this is best shown in the triangle $(\text{Al}_2\text{O}_3\text{-Na}_2\text{O})$, CaO, $(\text{FeO}+\text{MgO}+\text{MnO})$ this triangle can be expanded to form a tetrahedron $(\text{Al}_2\text{O}_3\text{-Na}_2\text{O})$, CaO, MgO, $(\text{FeO}+\text{MnO})$. The orientation of the lines in such a tetrahedron is best seen by a projection from the composition of an ubiquitous phase as shown in Thompson (1957). For this study, a projection from the anorthite point in the system $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-CaO-Na}_2\text{-MgO-(FeO+MnO)}$ onto the plane CaO-MgO- $(\text{FeO}+\text{MnO})$ was chosen (Figure 15). The resulting projections are true phase diagrams only if the following conditions are met: (1) the assemblage contains quartz, (2) the assemblage contains plagioclase, (3) plagioclase composition has no influence on the amphibole compositions, and (4) other components

Figure 14

Distribution of Ca, Mg, Fe (total)
between coexisting actinolite
grunerite and hornblende.

- grunerite
- actinolite
- ▲ hornblende

are negligible. Requirement (2) is not fulfilled but the projections nevertheless are useful for comparing assemblages.

The Mg-Fe distribution between grunerite and coexisting actinolite or hornblende is expressed by the ratio $100 \text{ Mg}/\text{Mg} + \text{Mn} + \text{Fe}_{\text{total}}$ at the bottom of Table 5. This same distribution is shown graphically in Fig. 15. In the actinolite-grunerite pair the calcic amphibole has a much higher $\text{Mg}/\text{Mg} + \text{Mn} + \text{Fe}_{\text{total}}$ ratio than the coexisting grunerite. The fractionation is very pronounced, but slightly more so in Y560 where essentially no aluminous phases are present, than in W10, where alumina is present in chlorite and to a minor extent in the actinolite. In assemblages AE1F and Y240, Fe-Mg partitioning is almost unity. In AE1F, hornblende is the only aluminous phase present. It has a slightly higher $\text{Mg}/\text{Mg} + \text{Mn} + \text{Fe}_{\text{total}}$ ratio than the coexisting grunerite. In Y240, hornblende, chlorite, and stilpnomelane are present as aluminous phases, and the $\text{Mg}/\text{Mg} + \text{Mn} + \text{Fe}_{\text{total}}$ ratio of the calcic amphibole is slightly lower than that of the coexisting grunerite. The highly aluminous hornblende in C600 has a much lower $\text{Mg}/\text{Mg} + \text{Mn} + \text{Fe}_{\text{total}}$ ratio than the coexisting grunerite.

As some of the amphiboles are aluminous their graphical representation in Fig. 14 is only partial. Fig. 15 considers $(\text{Al}_2\text{O}_3 - \text{Na}_2\text{O})$ as a fourth component and provides a basis for comparison. Grunerite and actinolite plot in almost the same position but hornblendes fall nearer to the $(\text{FeO} + \text{MnO})$ corner of the triangle. There is a tendency for tielines to fan toward more iron rich hornblendes with increasing iron content of the amphibole pair.

This trend is not observed in grunerite coexisting with actinolite in non-aluminous assemblages.

Ferric iron is found only in small quantities in grunerite but may be a more important constituent of calcic amphiboles (Deer, Howie, and Zussman, 1966). Subtraction of Fe^{+++} from Fe total would therefore tend to pivot tielines to the left as the $\text{Mg}/\text{Mg}+\text{Fe}$ ratio of the calcic amphibole would tend to be increased, while remaining the same in the coexisting iron-magnesium amphibole.

CHLORITE

Chlorite is a common constituent of the West Melville iron formation and is commonly the only aluminous phase present. Therefore it has been examined in some detail.

The two variables Si and total Fe are the principal factors influencing the optical properties of unoxidized chlorites. The refractive indices increase with increasing iron and decreasing silicon content and the birefringence decreases from positive through zero to negative values as iron or silicon increase (Deer, Howie, and Zussman, 1966). Magnesian chlorites are generally optically positive while iron chlorites have a negative sign. Optical properties have been determined (Table 6) and plotted (Fig. 16) to estimate the $\text{Fe}/\text{Fe}+\text{Mg}$ ratio and Si content.

FIGURE 16: Measured optical properties of chlorites from West Melville Iron Formation (diagram adapted from Hey, 1954).

TABLE 6

Measured Optical Properties From Chlorites of
the West Melville Iron Formation

Sample	Refractive index (B)	Bire- fringence	SIGN	$\frac{\text{Fe tot}}{\text{Fe+Mg}}$	Location
Y20	1.644	.005	-	.73	220 feet east of Y240
Y240	1.643	.005	-	.73	see map 1
TP1	1.650	.006	-	.78	300 feet east of TP3
TP9	1.601	.010	-	.43	300 feet west of TP3
X200	1.588	.008	-	.33	300 feet east of X500
X500	1.616	.004	-	.49	see map 1
X1000	1.651	.004	-	.78	500 feet west of X500
W10	1.645	.002	-	.77	see map 1
W260	1.601	.009	-	.44	250 feet west of W10

Electron probe analyses and atomic reductions on the basis of 28 oxygens were made on chlorites from two of these specimens (Table 7).

The chemical analyses are in fair agreement with the optical data. Most of the chlorites are iron rich and cluster in one part of Figure 16. In each case, magnetite is the coexisting oxide phase. A second, smaller group of chlorites is relatively low in iron and plots in a different area of the diagram. In these cases, the associated oxide phases are both magnetite and hematite. This indicates a tendency to decrease the quantity of ferrous iron in chlorite as the partial pressure of oxygen is increased. (Assuming the chlorites to be a univariant assemblage as a function of P_{O_2} in a system with a variance of 3 in which temperature and pressure are fixed. This assumption seems warranted by the assemblages (Table 8). The correlation of chlorite composition with the coexisting iron oxide phase is readily explained because hematite should coexist with a relatively magnesium rich chlorite as the chlorite structure can accept only limited amount of ferric iron. The correlation indicates the importance of oxidation in petrogenesis.

STABILITY OF IRON RICH CHLORITE

Much experimental work has been done on the synthesis and breakdown of magnesian and ferrous end members of the aluminous chlorite series. Because of the common occurrence of the assemblage iron chlorite-quartz, some of this experimental data is use-

TABLE 7

Chlorite Analyses

	Y240(wt.%)	W10(wt.%)
SiO ₂	23.4	24.8
Al ₂ O ₃	18.8	18.6
FeO	38.7	34.0
MnO	0.2	0.2
MgO	7.1	11.4
H ₂ O ₂ (est.)	<u>11.8</u>	<u>11.0</u>
	100.0	100.0

(est.) = estimated

Number of Ions on the Basis of 28 Oxygens

Si	5.32	5.42
Al ^{IV}	2.68	2.58
Al ^{VI}	2.36	2.21
Fe _{total}	7.36	6.22
Mn	0.04	0.04
Mg	2.41	3.72
$\frac{\text{Fe tot}}{\text{Fe+Mg}}$	0.75	0.63

ful to indicate the upper limits of temperature and pressure attained during metamorphism of the iron formation.

The Mg-chlorite, clinochlore, is the most stable member in the chlorite series. Its stability limit has been defined by Yoder (1952) and Fawcett (1964) and is indicated in Figure 17. The upper stability limit of Mg-chlorite+quartz is considerably lower (Figure 18). The probable effect of iron in reducing the stability of chlorite must not be overlooked. Turnock (1960) determined the upper stability of daphnite (Fe-chlorite) and showed it to be lower than the corresponding magnesian chlorites (Fig. 18). However, iron chlorites can exist in equilibrium with quartz at their upper stability limits (Turnock, 1960; Fawcett, Yoder, 1966) because they react to form a silica saturated assemblage. The magnesian chlorites react to produce assemblages undersaturated with respect to silica.

The influence of the Fe/Mg ratio on the stability of intermediate chlorites is not yet known. On the assumption that there is a linear variation of the upper stability temperature of chlorite+quartz between the chlorite end members, line D has been drawn to correspond to an Fe/Mg ratio of 4:1 (Fig. 18). This gives a possible maximum stability limit of 625°C at 2.5 kilobars for the iron rich chlorite-quartz assemblages of the Melville iron formation, where they are in a magnetite-hematite assemblage which indicates a high P_{O_2} .

FIGURE 17: Stability of Mg-Chlorite after Yoder (1952).

FIGURE 18: Upper temperature stability limits for chlorites.

- (A) Fe chlorite breaks down to quartz-bearing assemblage at high P_{O_2} (magnetite-hematite buffer).
- (B) Fe chlorite stability limit at low P_{O_2} (magnetite-wustite buffer).
- (C) Mg chlorite stability limit.
- (D) Upper stability limit of chlorite with Fe/Mg ratio of 4:1 in magnetite-hematite (high P_{O_2}) assemblage.

(after Turnock, 1960)

STILPNOMELANE

Stilpnomelane is found in one part of section Y240. It occurs as radiating clusters and fine scales that cut across bedding and other mineral grains (Plate 4) and normally grows at the expense of chlorite. The textural relations suggest it is not part of the original prograde assemblage but is the product of a later metamorphic event. All the stilpnomelane observed in this study has the pleochroic formula: α = golden yellow; $\beta = \gamma$ = deep brown-black, indicating high $\text{Fe}^{+++}/\text{Fe}^{++}$.

The occurrence of ferri-stilpnomelane has been attributed by some writers (Brown, 1967) to the secondary oxidation of ferro-stilpnomelane. This study has yielded some supporting evidence for this concept:

1. specimens with stilpnomelane show signs of incipient weathering, principally in the occurrence of goethite;
2. stilpnomelane shows no tendency to form in rocks formed under high P_{O_2} as indicated by the presence of hematite. It occurs only in association with magnetite.

Experimental evidence (Brown, 1967) indicates that ferri-stilpnomelane is reduced to ferro-stilpnomelane between 410-460°C at $P_{H_2O} = 2\text{Kb}$ and P_{O_2} in the magnetite field near the magnetite-hematite boundary. This suggests that ferri-stilpnomelane was not stable during metamorphism but is a product of post

metamorphic oxidation of primary ferro-stilpnomelane.

The occurrence of stilpnomelane is commonly attributed to an originally high Fe_2O_3 content of the host rock or high P_{O_2} during metamorphism. In this instance, it appears more likely to have formed under low P_{O_2} to accommodate a bulk composition with a high Fe/Mg+Al ratio as indicated by the analyzed coexisting amphiboles and chlorite (Tables 6, 7).

PETROGENESIS

PHASE RULE CONSIDERATION

Mineral stabilities are dependent on the composition of vapour phases with which they are in equilibrium (Thompson, 1955). Mineral assemblages have been studied to determine the composition of coexisting vapour and to decide whether the chemical potential of volatile components such as H_2O , CO_2 and O_2 are controlled by the mineral assemblage or specified externally (Zen, 1963).

Iron formations are particularly useful for some studies because of the response of minerals to variations of P_{O_2} (Eugster, 1959).

Most of the mineral assemblages in the iron formation that were examined show no textural features that are indicative of replacement, alteration, or reaction. (Exceptions are samples Y240 and TP3. See above for discussion.) By applying Gibbs' phase rule the variance is 2 or more in all assemblages; this is consistent with their being equilibrium assemblages. In this calculation

of the variance only the major components (Table 8) were used. It was unnecessary to appeal to minor components to make the variance 2 or more. The assemblages, their variance, and systems to which they belong are indicated in Table 8.

The small quantities of mica and hornblende and the lack of assemblages bearing almandine, aluminosilicates, or feldspars indicate Al_2O_3 is not a critical component in the iron formation. Another illustration of the minor importance of the Al_2O_3 component is provided by the assemblage magnetite-quartz-riebeckite. The sodium, because of the lack of Al_2O_3 to form Na-Al silicates such as feldspar, combined with Fe^{+++} to form the Na- Fe^{+++} amphibole, riebeckite.

COMPOSITIONS OF COEXISTING GRUNERITE AND CARBONATES

The East Melville iron formation contains the assemblages grunerite-ankerite-calcite and grunerite-calcite with magnetite and quartz as additional phases. This rock may be described approximately by the seven components CaO , MgO , FeO , SiO_2 , H_2O , CO_2 and O_2 . If equilibrium exists between the six phases grunerite, ankerite, calcite, quartz, magnetite, and vapour, the Gibbs Phase Rule ($F+P = C + 2$) indicates that the system will have three degrees of freedom. It is reasonable to assume that the closely spaced samples studied formed at approximately the same temperature and total pressure; thus if the fugacity of one volatile component is specified inside the system, the compositions of co-

TABLE 8

Mineral Assemblages of Iron Formations

	WEST MELVILLE														EAST MELVILLE							
Sample No.....	Y20	Y240	Y440	Y560	TP1	TP3	TP4	TP9	TH25	TH45	TH46	X200	X500	X1000	W10	W260	AE1F	A50	A320	C200	C340	C600
<u>PHASES</u>																						
magnetite	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
hematite							x	x	x	x	x	x				x						
pyrite	x	x	x	x	x																	x
pyrrhotite	x	x	x	x	x								x		x			x	x		x	x
quartz	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x
grunerite	x	x	x	x	x								x		x			x	x		x	x
actinolite	x		x			x	x			x						x	x					
hornblende		x	x												x						x	x
riebeckite																				x		
chlorite	x	x			x			x				x	x	x	x	x						
biotite	x		x	x											x	x	x		x		x	x
muscovite											x		x	x		x						
stilpnomelane			x	x																		
calcite							x											x	x		x	x
ankerite																					x	x
epidote									x													
pyroxene							x															
plagioclase																						x
apatite	x		x		x				x			x				x	x					
No. of Phases (excluding apatite)	8	8	8	7	6	6	3	5	3	5	4	5	6	5	7	7		7	6	3		6
<u>COMPONENTS</u>																						
SiO ₂	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	x	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗
FeO	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x
MgO	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x		x	x		x	x
CaO	x	x	x	x		x	x	x		x					x	x	x	x	x		x	x
Al ₂ O ₃	x	x	x	x	x			x		x	x	x	x	x	x	x		x	x		x	x
Na ₂ O			x																	x		x
K ₂ O	x		x	x							x		x	x		x	x		x		x	x
O ₂	x	x	x	x	x	⊗	x	x	x	⊗	⊗	⊗	⊗	x	x	x	x		x	x	x	x
CO ₂						⊗												⊗	⊗	x	⊗	⊗
S	⊗	⊗	⊗	⊗	⊗								x		x			⊗	x		x	x
H ₂ O	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x		x	x	x	x	x
No. of Components	9	9	9	9	7	7	6	7	3	8	6	7	8	7	9	8		9	10	5	10	10
VARIANCE	3	3	3	4	3	3	5	4	2	5	4	4	4	4	4	3		4	6	4	5	6
x = phase present ⊗ = phase present and buffered																						

existing phases are uniquely determined.

Ankerite and calcite were distinguished in thin sections of sample C600 by staining techniques (Warne, 1962) but the ankerite composition was not determined.

If the assumption of equilibrium at a specified temperature, total pressure, and chemical potential of one volatile component is made, the assemblage grunerite-ankerite-calcite-quartz is invariant and the grunerite-calcite-quartz assemblage is univariant. Thus, variations in the composition of coexisting grunerite and calcite are to be expected.

The composition of grunerite coexisting with calcite is more magnesian than that of grunerite coexisting with two carbonates at approximately the same metamorphic grade (Fig. 19). French (1968) indicates that grunerite-calcite-quartz occurs at a slightly higher metamorphic grade than grunerite-ankerite-calcite-quartz, and that grunerite from the former association becomes relatively enriched in iron (Fig. 19). This is the reverse of the compositional trend observed in this study.

Compositional data from more grunerite-carbonate assemblages are necessary to illustrate whether the system has reached equilibrium.

COEXISTING AMPHIBOLE AND PYROXENE

The assemblage clinopyroxene-actinolite-calcite-quartz-magnetite-hematite is observed in the West Melville iron formation. Electron probe analyses of the pyroxene-amphibole pair were carried

Figure 19

Composition of coexisting
carbonates and grunerite
from East Melville Iron
Formation.

TABLE 9

Analyses of Carbonates Coexisting with Grunerite

(For grunerite analyses, see Table 5.)

Sample No.	C600(wt.%)	AE1F(wt.%)
FeO	4.9	1.9
MnO	0.3	0.14
MgO	0.6	0.3
CaO	49.2	52.5
CO ₂ (a)	<u>45.0</u>	<u>45.2</u>
Total	100.0	100.04

(a) = assumed

Numbers of Ions on the Basis of 6(O)

Mg	0.034	0.020
Fe _{tot}	0.141	0.057
Mn	0.013	0.009
Ca	1.753	1.860
C	2.043	2.040

out and atomic reductions were made on the basis of 6 oxygens for pyroxene and 23 oxygens for the amphibole (Table 10). These data are plotted on a triangular diagram with CaO, FeO, and MgO at the corners (Fig. 20). The actinolite is slightly enriched in iron with respect to the salite.

Substantial textural evidence indicates pyroxene has been produced by the following decarbonation and dehydration reaction:

The approximately balanced reaction is as follows:

The three textural features supporting this reaction are:

1. there is a spatial relationship between actinolite and salite.
2. calcite is not common and is normally found in contact only with quartz or magnetite. It occurs rarely in contact with actinolite, and never with salite, suggesting proximity to the reaction line.
3. areas where pyroxene occurs are quartz free, suggesting that quartz has been consumed in the reaction.

The reaction has stopped going to the right because one of the reactants (calcite) has been used up. Consequently the above textures and minerals have been preserved.

The temperature at which this reaction occurs is dependent on the Fe/Mg ratio and the total pressure and mole fraction of CO_2 in the system. An approximation of the range of values at which the reaction can occur can be inferred from Figure 7.

MOBILITY OF CO_2 AND H_2O

In multivariant mineral assemblages which include one or more components capable of extensive substitution of one component for another it is very difficult to prove that the rock has been a completely closed system. The activities of the different components and the bulk composition are variable and it is difficult to say whether bulk compositions or an externally controlled water pressure controlled mineral compositions. Because assemblages appear to be related to bulk compositions does not preclude diffusion in and out of the system.

No buffer assemblages for H_2O or CO_2 were observed on Melville Peninsula (with the possible exception of specimens containing two carbonates). This is a necessary condition if H_2O and CO_2 activities are to be controlled externally (Butler, 1969).

A complete reaction has probably taken place between the original carbonate and quartz to form the presently observed silicate assemblage. The occurrence of quartz-grunerite-calcite,

TABLE 10

Analysis of Coexisting Amphibole and Pyroxene (Sample TP3)

	Amphibole (wt.%)	Pyroxene (wt.%)
SiO ₂	56.70	52.50
Al ₂ O ₃	0.10	0.00
FeO	11.30	10.10
MnO	0.10	0.10
MgO	17.00	11.80
CaO	<u>13.30</u>	<u>35.00</u>
	98.50	99.50

(Analyses by A.G. Plant at the Geological Survey of Canada.)

Numbers of ions on the basis of:

	23 Oxygens	6 Oxygens
Si	8.015	1.995
Al ^{IV}	0.000	0.000
Al ^{VI}	0.017	0.000
Fe	1.336	0.321
Mn	0.012	0.003
Mg	3.582	0.668
Ca	2.015	1.018
100 Mg/Mg + Fe	72.66	67.54

actinolite-grunerite-calcite, and quartz-salite-actinolite-calcite, with calcite present only in small amounts is evidence for CO_2 having been able to leave the system. However, the assemblage quartz-ankerite is seen locally with no trace of a reaction between them to form a ferromagnesian silicate, indicating CO_2 was not free to diffuse out, or behaved as an inert component.

OXIDATION STATE AND ELEMENT DISTRIBUTION

Magnetite and hematite (specularite) are indicators of the relative oxidation states of the assemblages in which they occur. When magnetite and hematite occur in the same assemblage, the activity of O_2 is defined as a univariant function of temperature. The pertinent reaction for this association is:

Quartz-magnetite-specularite rocks are common in the West Melville iron formation. Several assemblages studied contain magnetite and specularite coexisting with silicate minerals. In each specimen, the $\text{Mg}/\text{Mg}+\text{Fe}$ ratio of the silicates (amphiboles and chlorite) was much higher than the same ratio in silicates coexisting with magnetite (Table 11). Thus, it is concluded that the Mg content of the ferromagnesian silicates, and aluminous and calcic iron-magnesian silicates increases with increasing activity of O_2 in

the environment.

It is apparent that wide variations in the activity of oxygen occurred during metamorphism in the West Melville area. It is implicit in this that oxygen was not free to diffuse throughout the iron formation. The oxidation state was probably controlled within each assemblage by that assemblage and must be a function of the original environment of deposition. The limited mobility of oxygen is also illustrated by the association of magnetite and specularite in thin alternating bands.

Magnetite was the only iron oxide observed in the East Melville iron formation. This could imply either a uniform environment of deposition, or that oxygen was free to diffuse throughout the entire unit.

A PROPOSED MODEL OF METAMORPHISM

Information needed to reconstruct the metamorphic history of the Melville iron formation in its entirety is not available. However, from textural and analytical data a possible model is suggested for phase changes.

It has been concluded that the iron formation was a closed system with respect to O_2 . This implies that the degree of oxidation of the various assemblages in the iron formation has remained essentially constant during the change from sedimentary conditions to the present garnet zone metamorphic grade. James

TABLE 11

Mg/Mg + Fe_{tot} of amphiboles and chlorites in
assemblages bearing magnetite + hematite and magnetite only

Sample	Mineral	Oxide phase	Mg/Mg + Fe _{tot}
Y20	chlorite	magnetite	.27
240	chlorite	magnetite	.27
TP1	chlorite	magnetite	.22
X1000	chlorite	magnetite	.22
W10	chlorite	magnetite	.23
TP9	chlorite	magnetite + hematite	.57
X200	chlorite	magnetite + hematite	.67
W260	chlorite	magnetite + hematite	.56
W10	actinolite	magnetite	.68
TP4	actinolite	magnetite	.56
Y560	actinolite	magnetite	.26
W260	tremolite	magnetite + hematite	.85
TP3	actinolite	magnetite + hematite	.73

(1955) describes magnetite-pyrite, magnetite-carbonate, magnetite-hematite, and magnetite-iron silicate (greenalite, minnesotaite, stilpnomelane) assemblages in practically unmetamorphosed iron formation in the Lake Superior region. Assemblages in the Melville iron formation show many characteristics that indicate they have been derived from assemblages similar to those described by James (1955).

Quartz, magnetite, and hematite are the only original minerals still present after metamorphism. Quartz has probably resulted from the recrystallization of chert. These minerals are present in excess and may be produced or consumed in reactions leading to the present silicate assemblages.

An estimate of the bulk composition of the silicate bands was made for specimens in which analytical data of minerals are available (Table 12). The proportion of each mineral was estimated visually and weighted by the appropriate factor to arrive at a bulk composition. For those minerals in each assemblage that were not analysed, an approximate composition was taken from the literature.

When these compositions are compared with analyses of unmetamorphosed iron formation reported in the literature (Gross, 1965; James, 1966; French, 1968) several features are apparent:

1. the Al_2O_3 content of the assemblages is very low. Thus chlorites are eliminated as important precursors to the present assemblage.

TABLE 12

Estimated Bulk Composition of Silicate Component
of Iron Formation Specimens

	Y240 (wt.%)	Y560 (wt.%)
SiO_2	51.00	51.59
Al_2O_3	2.29	0.79
FeO	38.29	33.28
MnO	0.30	0.15
MgO	7.21	5.13
CaO	1.18	7.03
Na_2O	0.51	0.98
K_2O	<u>0.05</u>	<u>1.01</u>
	100.83	99.96

2. the CaO content varies significantly implying the presence of original carbonate in some areas, and its absence in others. The absence of carbonate in the present assemblages indicates metamorphism has been sufficiently severe to cause its disappearance.

The assemblage preceding the minerals presently observed is inferred to be minnesotaite, stilpnomelane, and greenalite, locally accompanied by a carbonate, possibly ankerite or siderite, and invariably with excess quartz and iron oxide. Numerous reactions are cited in the literature that could cause such an assemblage to reach its present state (Mueller, 1960; Kranck, 1961; Hashimoto, 1968). It is not the purpose of this dissertation to speculate on these silicate reactions.

Textural evidence is available in the East Melville iron formation to suggest some of the precursors of assemblages observed here.

At some localities magnetite is separated from quartz by acicular grunerite radiating from the magnetite grain (Plates 8 and 10) suggesting the reaction:

In carbonate bearing iron formation grunerite develops by the general reactions:

1. $7 \text{ ankerite} + 8 \text{ quartz} + \text{H}_2\text{O} \rightleftharpoons \text{grunerite} + 7 \text{ calcite} + 7\text{CO}_2$
2. $7 \text{ siderite} + 8 \text{ quartz} + \text{H}_2\text{O} \rightleftharpoons \text{grunerite} + 7\text{CO}_2$

The reactions were written using analyses of grunerite and calcite from samples AE1F and C600 to calculate the composition of the early carbonate

1.

2.

(residual $\frac{1}{2}$ C)

In specimen AE1F (reaction 1) fibrous grunerite is spatially related to coarsely crystalline white calcite. These areas are depleted in quartz. Small amounts of calcite are observed in fibrous patches of grunerite (reaction 2). These areas are also notably depleted in quartz.

Both of these reactions represent a reduction in molar volume of about 15 percent, which is consistent with increasing grade of metamorphism. Furthermore, an examination of the changes in molar volume indicates the ratio in which the products should be found

to one another

Reaction 1:

Molar

volume

(cc)

Ratio grunerite:calcite = 278 : 7 x 37

= 1.1 : 1

Reaction 2:

Molar

volume

(cc)

Ratio grunerite:calcite = 278 : 37

= 7.5 : 1

The ratio of grunerite to calcite was checked in thin sections by point counting these minerals. Eight hundred points were counted in each specimen by traversing perpendicular to the bedding plane, giving the following results:

Reaction 1 (AE1F) grun:calcite = 1:1

Reaction 2 (C600) grun:calcite = 5:1

A good correlation is observed between theoretical and actual data. The observed ratio in reaction 2 is somewhat low. This is attributed to the possibility of some original calcite being present in the rock. The molar volume evidence corroborates

textural evidence to support the occurrence of the proposed reactions.

CONCLUSIONS ABOUT AMPHIBOLES

Under the physical conditions of the proposed model of metamorphism certain conclusions can be drawn about the composition of some amphiboles.

Actinolite and hornblende probably form a continuous solid solution series with the distinction being an arbitrary amount of Al_2O_3 (hornblende containing greater than 0.5 atoms per formula weight). However, the possibility of a very small miscibility gap cannot be completely eliminated without more analyses that account for both ferrous and ferric iron.

Analyses of coexisting cummingtonite with actinolite or hornblende and other saturating phases of CaO , Al_2O_3 and Na_2O permit definition of the miscibility gap between coexisting pairs of amphiboles and the maximum weight percent of these components that can be taken into the grunerite structure under conditions of crystallization existing during metamorphism.

TABLE 13

Maximum solubility of components in grunerite under
conditions of metamorphism prevalent in Melville
iron formation.

Component	Max. wt. %
CaO	0.9
Al_2O_3	0.3
Na_2O	0.7

It is hoped that further and more detailed studies of this nature will define precise solubility limits in amphiboles and relate them to specific conditions of metamorphism. The common amphibole has the potential of a formidable tool in the unraveling of metamorphic history.

CONCLUSION

A Comparison of East and West Melville Iron Formations

Evidence indicates the iron formation on West Melville Peninsula has been metamorphosed to the garnet zone. Iron formation on East Melville Peninsula is lower grade and probably in the biotite zone. A summary of pertinent data follows:

Textural Evidence

Quartz in iron formation on West Melville is more coarse grained than in the east, although bulk compositions and layering of quartz and magnetite are similar.

Assemblages in Basic and Pelitic Rocks

Mineral assemblages in basic and pelitic rocks on West Melville Peninsula are typical of garnet zone metamorphism. Assemblages in these rock types on East Melville Peninsula are similar but lack garnet.

Substitution in Grunerite

The components CaO , Al_2O_3 , and Na_2O appear to be slightly more soluble in grunerite from West Melville Peninsula than in grunerite from the east, suggesting a higher grade of metamorphism

in the west (Table 14).

TABLE 14

Range of solubility of components in grunerites from
East and West Melville Peninsula

Component	Range of solubility in wt. %	
	West Melville	East Melville
CaO	0.5 - 0.8	0.3 - 0.8
Al ₂ O ₃	0 - 0.2	Tr - 0.1
Na ₂ O	0 - 0.6	0.1 - 0.2

Carbonate Reactions

Evidence of two reactions involving carbonate minerals is
present on West Melville:

As reaction 1 occurs in a carbonate rock and reaction 2 occurs
in iron formation it is probable that the reactions occurred with

different ratios of $\text{CO}_2:\text{H}_2\text{O}$ present. A temperature of 480°C at total pressure of 2000 bars is then compatible with both reactions (Fig. 8) and also within an acceptable range for garnet zone metamorphism.

The assemblages quartz-grunerite-ankerite-calcite and quartz-grunerite-calcite present on East Melville Peninsula suggest a slightly lower grade than the above reactions. Furthermore, these assemblages suggest an increase in the grade of metamorphism from south to north in the eastern iron formation (Map No. 4).

Assuming the reaction

as proposed in the model of metamorphism, samples AE1F and A50 (location on Map 4) have only the reaction products present in the assemblage (Table 8), implying the reaction has gone to completion. Samples C200 and C600 (Map 4) contain both products and reactants (Table 8) suggesting proximity to the reaction line and consequently, a slightly lower metamorphic grade.

The range of physical conditions of metamorphism under which these reactions can go on is compatible with the upper stability limits inferred from the other mineral phases present, including Fe-chlorite-quartz (Fig. 18), ferroactinolite (Fig. 10) and cummingtonite-grunerite.

The east and west iron formations are similar in petrography, both being members of the oxide facies. The western area is higher in metamorphic grade. Because of the immense reserves of potential iron ore in the iron formations it is assured that more

detailed work will be done in the area. More data will undoubtedly reveal a complex history.

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MAP NUMBER ONE

LEGEND

- CENOZOIC**
- PLEISTOCENE AND RECENT**
 - 11** Glacial drift and overburden
- APHEBIAN**
- 10** Diabase dikes and sills
 - 9** Quartzite including local basal conglomerate
- ARCHEAN AND/OR APHEBIAN**
- PRINCE ALBERT GROUP**
- 3** Iron formation
 - 2** Metasedimentary rocks including:
 - a Quartzite
 - b Quartz-biotite schist
 - c Pebble conglomerate with schistose matrix
 - d Garnet-biotite schist
 - e Quartz feldspar gneiss
 - f Sericite schist
 - g Marble
 - 1** Greenstone and amphibolite
- CONTACTS**
- Contact defined
 - - - Contact approximate
 - ... Contact assumed
- STRUCTURES**
- ++ Bedding; inclined, vertical
 - ++ Foliation; inclined, vertical
 - ~ Fold axis; dragfold, multiple fold, vergence shown
 - Lincation
 - Fault

GEOLOGICAL MAP OF IRON FORMATION OCCURRENCES WEST MELVILLE PENINSULA NORTHWEST TERRITORIES

10,000 FEET

LEGEND

- GENOZOIC**
- PLEISTOCENE AND RECENT**
 - II Glacial drift and overburden
- APHEBIAN**
- 10 Diabase dikes and sills
 - 9 Quartzite including local basal conglomerate
- PRINCE ALBERT GROUP**
- 8 Granitic rocks massive to slightly foliated
 - 7 Migmatite, locally includes 5, 6, 8
 - 6 Granitic gneiss
 - 5 Layered gneiss
 - 4 Mafic and ultramafic rocks
 - a Peridotite, serpentinite
 - b Gabbro
- ARCHEAN AND/OR APHEBIAN**
- 3 Iron formation
 - 2 Metasedimentary rocks including;
 - a Quartzite
 - b Quartz-biotite schist
 - c Pebble conglomerate with schistose matrix
 - d Garnet-biotite schist
 - e Quartz feldspar gneiss
 - f Sericite schist
 - g Marble
 - 1 Greenstone and amphibolite
- CONTACTS AND STRUCTURES**
- Contact defined
 - Contact approximate
 - Contact assumed
 - Bedding; inclined, vertical
 - Foliation; inclined, vertical
 - Fold axis; dragfold, multiple fold, vergence shown
 - Lineation
 - Fault

MAP NUMBER TWO

GEOLOGICAL MAP

OF
IRON FORMATION OCCURRENCES

WEST MELVILLE PENINSULA
NORTHWEST TERRITORIES

LEGEND

PLEISTOCENE AND RECENT
 II Glacial drift and overburden

APHEIAN
 1 Diabase dikes and sills
 2 Quartzite including local basal conglomerate

3 Granitic rocks massive to slightly foliated
 4 Migmatite, locally includes S, G, & B
 5 Granitic gneiss
 6 Layered gneiss
 7 Mafic and ultramafic rocks
 a Peridotite, serpentinite
 b Gabbro

PRINCE ALBERT GROUP

1 Iron formation
 2 Metasedimentary rocks including:
 a Quartzite
 b Quartz-biotite schist
 c Pebble conglomerate with schistose matrix
 d Garnet-biotite schist
 e Quartz feldspar gneiss
 f Sillite schist
 g Marble
 h Greenstone and amphibolite

~ Contact defined
 ~ Contact approximate
 ~ Contact assumed
 ++ Bedding; inclined, vertical
 ++ Foliation; inclined, vertical
 ~ Fold axis; dragfold, multiple fold, vergence shown
 \ Lincation
 ~ Fault

GEOLOGICAL MAP

OF
 IRON FORMATION OCCURRENCES

WEST MELVILLE PENINSULA
 NORTHWEST TERRITORIES

0 4000
 FEET

MAP NUMBER FOUR

LEGEND

PLEISTOCENE AND RECENT

Glacial drift and overburden

DIABASE

Diabase dikes and sills

QUARTZITE

Quartzite including local basal conglomerate

IRON FORMATION

Granitic rocks massive to slightly foliated

Migmatite, locally includes 5, 6, 8

Granitic gneiss

Layered gneiss

Mafic and ultramafic rocks

a Peridotite, serpentinite

b Gabbro

PRINCE ALBERT GROUP

Iron formation

Metasedimentary rocks including:

a Quartzite

b Quartz-biotite schist

c Pebble conglomerate with schistose matrix

d Garnet-biotite schist

e Quartz feldspar gneiss

f Sericite schist

g Marble

Greenstone and amphibolite

Contact defined

Contact approximate

Contact assumed

Bedding; inclined, vertical

Foliation; inclined, vertical

Fold axis; dragfold, multiple fold, vergence shown

Lineation

Fault

GEOLOGICAL MAP

OF
IRON FORMATION OCCURRENCES

2 of

LEGEND

- PLEISTOCENE AND RECENT**
- (II) Glacial drift and overburden
- DIABASE**
- (10) Diabase dikes and sills
 - (9) Quartzite including local basal conglomerate
- PRINCE ALBERT GROUP**
- (8) Granitic rocks massive to slightly foliated
 - (7) Migmatite, locally includes 5, 6, 8
 - (6) Granitic gneiss
 - (5) Layered gneiss
 - (4) Mafic and ultramafic rocks
 - a Peridotite, serpentinite
 - b Gabbro
 - (3) Iron formation
 - (2) Metasedimentary rocks including:
 - a Quartzite
 - b Quartz-biotite schist
 - c Pebble conglomerate with schistose matrix
 - d Garnet-biotite schist
 - e Quartz feldspar gneiss
 - f Sericite schist
 - g Marble
 - (1) Greenstone and amphibolite

- ~ Contact defined
- ~ Contact approximate
- ~ Contact assumed
- ++ Bedding; inclined, vertical
- ++ Foliation; inclined, vertical
- ~ Fold axis; dragfold, multiple fold, vergence shown
- ~ Lincation
- ~ Fault

GEOLOGICAL MAP OF IRON FORMATION OCCURRENCES EAST MELVILLE PENINSULA NORTHWEST TERRITORIES

10000 FEET