CHEMICAL PETROLOGY OF METAMORPHIC IRON FORMATIONS AND ASSOCIATED ROCKS IN THE MOUNT REED AREA IN NORTHERN QUEBEC

by

Svante Hakan Kranck

B.Sc., McGill University (1953)
M.Sc., McGill University (1955)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1959

Signature of Author____
Department of Geology and Geophysics, May 18, 1959

Certified by____
Thesis Supervisor

Accepted by____
Chairman, Departmental Committee on Graduate Students

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

PART I

I INTRODUCTION

The Mount Reed area is located at the south end of the Labrador Trough about 150 miles north-northwest of Seven Islands, Quebec. The area is underlain by high-grade metamorphic rocks mainly of sedimentary origin, including iron formation and dolomitic marble. In this paper are presented the results of a study of the phase equilibria among the silicate minerals in the iron formation, mainly ferrohypersthene, ferroaugite, and cummingtonite. The study is based on chemical analyses of coexisting minerals.

The writer had opportunity to spend three summers in the Mount Reed area in the employ of the Quebec Cartier Mining Company and through the cooperation of the company was able to collect specimens for the chemical study. The chemical analyses were performed at the Department of Geology of Massachusetts Institute of Technology using the rapid silicate analysis methods developed by Shapiro and Brannock (1956) of the United States Geological Survey.

High-grade metamorphic iron formations have been described earlier mainly from Minnesota and Sweden. The iron formations at the eastern part of the Mesabi range have been contact metamorphosed by the Duluth gabbro with the development of pyroxene and grunerite. These rocks have been described in papers by Grout and Broderick (1919), Grout (1919), and Richarz (1929). In Sweden the so-called eulysites probably are of similar origin as the silicate iron formation here described. Works on eulysites include papers by Palmgren (1916), von Eckermann (1922), Carstens (1924), Sundius (1924), Geijer (1925), Lindroth (1926), and Tilley (1936).

The Mount Reed silicate iron formations differ from the eulysite and the metamorphic rocks of the Mesabi Range by the absence of fayalite and by the abundance of ferrohypersthene and calcite. The mineral assemblages of the Mount Reed area include the association quartz-ferrohypersthene-ferroaugite-cummingtonite-calcite. The assemblage is interesting both because of the association hypersthene-calcite, so far unknown in geological literature (Ramberg 1952b page 154), and because the low variance of the assemblage indicates that the rocks in the course of the regional metamorphism were closed to the volatile components H_2O and CO_2.

II THE SETTING OF THE IRON FORMATION

The iron formation in the Mount Reed area is exposed mainly along the axial traces of isoclinal synclines which have been refolded along transcurrent fold axes. The thickness of the iron formation is in the order of 200 feet when not thickened or stretched as a result of the deformation. It is underlain by quartzite and marble and an unknown thickness of biotite-muscovite-migmatite-gneiss. Another thick sequence of gneiss overlies the iron formation. The regional geology is described in more detail elsewhere (Kranck 1959).

The field work disclosed three different facies of iron formation, namely, quartz-specularite iron formation, quartz-magnetite iron formation, and quartz-silicate iron formation. Most of the presently commercial ore deposits are located in the first mentioned type. Transitional facies between specularite and the magnetite iron formation on one hand and the magnetite and silicate iron formation on the other hand are common.

III QUARTZ SPECULARITE IRON FORMATION

The quartz-specularite iron formation is best developed at Jeannine Lake where an open pit mine is now under development. The formation consists almost entirely of quartz and specularite. The rock is in part massive, in part well foliated. Where the foliation has been distorted into drag folds large segregations of solid coarse-grained specularite have formed along the fold crests. The only minor constituents are magnetite, finely disseminated all through the rock, and in places clusters of actinolite and diopside together with some calcite.

IV QUARTZ MAGNETITE IRON FORMATION

The quartz-magnetite-iron formation is similar to the specularite iron formation except that the oxide is in the form of magnetite. Transitional rock types with specularite intermixed with magnetite also are common. The magnetite iron formation as a rule is finer grained. Where no specularite is present, layers of silicates commonly are found intermixed with the oxide layers, producing brownish stains on the weathered surface.

V THE SILICATE IRON FORMATION

The silicate iron formation shows a much greater variety in composition and lithology than the oxide iron formations. The facies locally includes layers of ferrodolomite and then more properly should be classified as carbonate-silicate iron formation. However, since there is good evidence that a major part of the silicates is derived from carbonates, no attempt has been made to differentiate the carbonate and the silicate facies. The main mineral constituents of the silicate iron formation are quartz, ferrohypersthene, grunerite-cummingtonite, ferroaugite, calcite, and locally magnetite. Iron silicates mixed with magnetite usually are high in manganese and sodium. They include such minerals as arfvedsonite and aegrine-hedenbergite.

The silicate rock usually is well banded. The banding is produced by varying proportions of the different mineral constituents and presumably directly reflects the original bedding. The banding is brought out particularly on the weathered surface, where quartz-rich resistant layers stand up over rusty brown-weathered carbonate-silicate-rich beds.

The texture of the silicate rocks consists of a granular, medium-grained, xenoblastic mixture of the different constituents. Cummingtonite sometimes appears to be replacing ferrohypersthene. Otherwise no replacement textures are evident that would indicate disequilibrium in the rock.

Chemical analyses have been performed of silicate minerals from two separate areas located about thirty miles apart. The southern source area is around Blough Lake at longitude 68° 00' latitude 51° 55', the northern area around Hobdad Lake at longitude 67° 30' latitude 52° 20'. The mineral assemblages found in both areas are very similar, so that the degree of metamorphism probably is about the same in the two areas.

VI THE CHEMICAL ANALYSES

The analyses were made by photometric methods, as first described for use in silicate analyses by Brannock and Shapiro (1956). The deviation between duplicate analyses seldom exceeds 3 per cent and generally is much less. The main sources of error lie either in the preparation of the solutions or in the presence of inhomogeneities in the samples. The reproducibility of measurements in a single solution generally is extremely good in all the procedures used. The greatest advantage of the method is that each analysis can be checked over and over again both by making duplicate solutions and by running each solution several times. Thereby the risk of major analytical errors is eliminated.

The main difficulties were encountered in the analysis of small amounts of aluminum in the presence of large amounts of iron. Iron tends to interfere in the photometric test for aluminum under these conditions. The analyses for aluminum may therefore not be as reliable as the other analyses. H_2O has not been determined, so accordingly the amphibole and chlorite analyses do not add up to 100 per cent.

VII SIGNIFICANCE OF THE CHEMICAL ANALYSES

The main purpose of the chemical analyses is to find out how the different elements distribute themselves between the different phases. The most significant components in the analysed minerals are FeO, MgO, and CaO. From the analyses one can draw some conclusions about the FeO-MgO-CaO system at the temperature and pressure conditions present in the Mount Reed area at the time of the metamorphism.

Fig. 3 represents a plot of the FeO-MgO-CaO ratios of the different minerals together with the tie-lines of the different mineral assemblages. Five phases are represented in the diagram, namely hyperathene, cummingtonite, anthophyllite, actinolite-hornblende, and diopside-augite. Other components such as Al_2O_3, Na_2O, and H_2O also affect the stability relationships of the minerals represented, and the stability relationships of the different minerals can not be completely represented on this diagram. However, some significant features of the phase chemistry of the minerals can be demonstrated. The following points should be noted.

1. The minerals appear to be at least in approximate equilibrium as shown by the fact that the tie lines between the different mineral pairs are nearly parallel. The only exceptions are the hypersthene-ferroaugite pairs of B1-6 and B1-21. It is possible that in some cases the FeO/MgO ratios still reflect the compositions of the carbonates from which the hypersthenes and ferroaugites formed.

2. Cummingtonite is slightly more magnesium-rich than the hypersthene it is in equilibrium with, at least in the more iron-rich assemblages. Towards the magnesium side the hypersthene-augite and cummingtonite-augite tie lines appear to become almost parallel, indicating that a coexisting cummingtonite and hypersthene in this compositional range may have about the same FeO/MgO ratio.

The lower FeO/MgO ratio in cummingtonite as compared to hypersthene agrees with the general rule that the high temperature phase is higher in magnesium (Ramberg 1952).

3. The general rule among pyroxenes and amphiboles seems to be that the phase higher in calcium has a lower FeO/MgO ratio than the phase lower in calcium. This relationship has been noted earlier to be valid for igneous pyroxenes (Hess 1949). Also, a compilation of analysed pyroxene pairs made by Muir and Tilley (1958) shows that the same relationship is valid for magnesium-rich metamorphic pyroxenes. Eskola(1950) finds that cummingtonite has a higher FeO/MgO ratio than the coexisting hornblende.

4. The immiscibility gap between calcium pyroxene on one hand and hypersthene and cummingtonite on the other hand is about 42 mole per cent in the Mount Reed area.

5. The mineral pairs of F-1 and R-7 shows that the range of miscibility of CaO and FeO/MgO is about 11 mole per cent in low-alkali-amphiboles.

VIII THE ORIGIN OF THE SILICATE IRON FORMATION

The silicate iron formation is thought to have originated partly from carbonate iron formation, partly from primary silicate iron formation. The unmetamorphosed iron formations of the Knob Lake area further north which probably represent unmetamorphosed equivalents to the Mount Reed iron formations include both greenalite minnesotaite, siderite, and ferrodolomite (Perrault 1955). Greenalitepresumably formed partly directly from minnesotaites, partly by reaction between minnesotaite, siderite, and quartz.

Ferrohypersthene probably formed both as a reaction product between quartz and siderite and at somewhat lower temperatures by reaction between greenalite, siderite, and quartz. The presence of grunerite would decrease the partial pressure of CO_2 and therefore make siderite unstable at lower temperatures. Some ferrohypersthene apparently also formed from ferrodolomite as will be shown in the discussion below.

The formation of ferroaugite represents a more difficult problem. It most likely formed as a reaction product between ferrodolomite and quartz. The problem is that both calcite, ferroaugite, and ferrohypersthene are present in most assemblages. One would expect ferrodolomite to decompose in the presence of quartz either to ferroaugite and CO_2 gas or to ferrohypersthene and calcite but not to ferroaugite, calcite and ferrohypersthene at once.

A clue to the solution of the problem may be offered by the fact that ferrohypersthenes coexisting only with calcite generally seem to have a higher FeO/MgO ratio than those coexisting both with ferroaugite and calcite. This is shown by four partial analyses of such hypersthenes giving 40.5 weight per cent, 40.4 per cent, and 44.8 per cent respectively as the FeO content of the minerals. This fact gives support to the idea that the carbonates decompose to ferrohypersthene-calcite at high FeO/MgO ratios, to ferroaugite-CO_2 in rocks with low FeO/MgO ratios and within an intermediate range to ferrohypersthene-ferroaugite-calcite. This state of affairs would exist if the stability relationships among the minerals was as shown in Fig. 14 immediately above the stability field for dolomite-quartz. However, this interpretation cannot represent the whole truth since the composition of coexisting hypersthene and hedenbergite is not fixed.

It is possible that ferroaugite forms metastably over a certain range of FeO/MgO ratios. It is also possible that two reactions take place in accordance with a phase relationship such as is shown in diagram 11. First ferrodolomite reacts with quartz to form ferroaugite and CO_2 gas. Later on at higher temperatures any CO_2 left in the rock reacts with ferroaugite to form calcite and ferrohypersthene. The possible instability of pure ankerite and the possible stability of fayalite-quartz at the extreme FeO side of the diagram has been ignored for sake of simplicity.

IX THE ROLE OF THE VOLATILE COMPONENTS

The role of the volatile components is studied here by using methods introduced by Thompson and earlier by Korzhinsky (see Thompson 1959).

Gibb's phase rule states that

$$\text{Variance} = n + 2 - \phi$$

The variance of a system equals the number of independently variable components less the number of phases plus two. By variance is meant the number of intensive variables which can be altered independently without bringing about the disappearance of a phase or the formation of a new one.

In the Mount Reed iron formations five phases are commonly present, namely ferrohypersthene, ferroaugite, cummingtonite, calcite, and quartz. The phases are composed of six components namely FeO, MgO, CaO, SiO_2, CO_2 and H_2O. Therefore the variance is $6 + 2 - 5 = 3$. Therefore, in order to define the state of the system we would have to define temperature, pressure, as well as the activity of one component. However, because of the extensive solid solution between FeO and MgO in ferromagnesian minerals these components in most cases are not independently variable, thus reducing the components to five. In such cases the variance is reduced to two, so the number of phases equals the number that would be expected in a rock closed to all components including the volatiles. The possibility exists, however, that the FeO/MgO ratio of the minerals in the ferrohypersthene-ferroaugite-cummingtonite-calcite-quartz assemblage at least partly reflects the externally controlled activity of one volatile component. In such a case the FeO/MgO ratio of the minerals should be relatively constant within a given area since the activity should not vary over too great a range if diffusion has been effective. This would be the case, particularly if the diffusion has been driven by regional activity gradients such as would be determined by temperature and pressure gradients or the gravity field.

If the system was open to CO_2, the composition of the hypersthene coexisting with ferroaugite and calcite would be controlled by the CO_2 partial pressure as determined by the conditions of the environment. Hypersthene of higher iron content would coexist only with calcite, and hypersthene lower in iron would coexist only with ferroaugite in accordance with the diagram of Fig. 14. It was mentioned in the discussion of the formation of ferroaugite that the high-iron hypersthene apparently generally does coexist only with calcite. This fact may be taken as evidence for a system open to CO_2. However, the alternative explanation for this fact was offered earlier; namely, that augite very high in iron is not stable in the presence of carbonates. The analysed mineral assemblages B1-3, B1-6, and B1-21 originating less than 300 feet from each other shows that the FeO/MgO ratio of ferrohypersthene and ferroaugite coexisting with calcite is quite variable, so that local activity gradients of CO_2 must be present in the area. Therefore, although diffusion of CO_2 driven by local activity gradients cannot be disproved, it is obvious that long distance diffusion has not taken place.

Again the cummingtonite-ferrohypersthene assemblage strongly indicates that the rock has been closed to H_2O. At each temperature and pressure and activity of H_2O the composition of coexisting ferrohypersthene and ferroaugite should be fixed in accordance with Fig. 15 provided of course the activity of water was such that they would coexist at all. The analyses of cummingtonite and hypersthene generally show quite similar FeO/MgO ratios. This fact may be interpreted to indicate that the activity of water is externally controlled and thus long distance diffusion is possible. However, it seems improbable that the activity of water should be exactly the same in the analysed specimens from the Blough Lake area (analyses A-8, A-30) and the Hobdad Lake area (analyses H-7, H-9) respectively, two areas 30 miles apart. It becomes still more improbable when it is considered that in other places in the Blough Lake area hypersthenes richer in magnesium are present despite the fact that if the activity of water was uniform more magnesium-rich rocks should contain only cummingtonite.

It appears more probable that the coexistence of cummingtonite and hypersthene is controlled by the amount of water present and that the constant composition of the minerals arises from the fact that the bulk composition of the rocks is quite constant and favors a hypersthene and cummingtonite of this composition. This becomes still more probable when it is considered that several other hypersthenes, partially analysed, which do not coexist with cummingtonite also have a FeO/MgO ratio in the same range.

Again it should be noted that in the case of multivariant mineral assemblages which include one or more phases capable of extensive substitution of one component for another, it is very difficult to prove that the rock system has been completely closed. In such an assemblage both the partial pressure and the bulk composition are continuously variable, so that it may be difficult to say if the bulk composition or an externally controlled water pressure determined the mineral compositions. Also, the fact that the assemblages appear to reflect the bulk composition does not preclude diffusion in and out of the system provided the activity gradients driving the diffusion are of local nature. Such activity gradients are influenced by the bulk compositions of the rocks in the immediate neighbourhood and probably are not much different in any case from the partial pressures in the system as determined by the bulk composition.

However, in the above discussion it has been assumed that CO_2 and H_2O may act as independently variable components. It should be pointed out that if a gas phase is present the partial pressure of CO_2 will increase with a decrease of the partial pressure of H_2O provided of course that the total pressure of the gas phase is fixed. In such a case, if the system is closed to one volatile component it must be closed to the other as well. In discussing the formation of the ferrohypersthene-ferroaugite-calcite assemblage it was concluded that ferroaugite reacted with CO_2 gas to form ferrohypersthene and calcite. If this interpretation is correct, a gas phase must have been present at one time together with ferrohypersthene, ferroaugite, and in some cases cummingtonite. The CO_2/H_2O ratio of this volatile phase was fixed in the presence of cummingtonite for each MgO/FeO ratio. Since the variance of the system would not allow the pressure of the volatile phase to vary independently of the lithostatic pressure, the pressure on the volatile phase presumably equalled the pressure on the solid phases. Thus this line of argument also favors a system closed to all components.

X CONCLUSIONS

The analyses presented in this paper show that the mineral assemblages of the silicate iron formation in the Mount Reed area are at least in approximate equilibrium. The general rule has been found to hold that the FeO/MgO ratio always is lower in the calcium-bearing pyroxenes and amphiboles than in the pure ferromagnesian minerals. It also was found that cummingtonite generally has a lower FeO/MgO ratio than the coexisting hypersthene.

There is no support for the idea that volatile components can freely diffuse through the rocks. The partial pressures of all components appear to be determined by the bulk composition of the rocks rather than by the physical conditions of the environment. The most important consequence of this idea is that the temperatures at which the different reactions take place are determined by equilibria in a closed system where the pressure of the volatile phase equals the rock pressure. It is of course too early to say whether this is a general rule in metamorphic reactions. However, the possibility still should be considered that the reason H_2O commonly can be disregarded as a component in the graphical study of grades of metamorphism is the old classical idea that volatiles are always present in the rocks rather than the more recently advanced idea that rocks are open to volatile components.

XI ACKNOWLEDGEMENTS

The writer wants to express his great appreciation to Mr. L. J. Severson, president of the Quebec Cartier Mining Company, and to Dr. R. W. Marsden, manager of explorations of the Oliver Iron Mining Company, for permission to publish information obtained in the Mount Reed area in this paper. The company generously furnished time and transportation for the collection of the rock specimens.

At Massachusetts Institute of Technology the encouragement and advice given by Professor H. W. Fairbairn in the course of the laboratory work and in the preparation of the thesis was of very great value to the writer. The help of Professor W. H. Pinson, Mr. A. Brownlow and Mr. W. Phinney in straightening out some of the laboratory procedures also is appreciated. The theoretical approach used in the study is a direct application of methods developed by Professor J. B. Thompson in lectures at Harvard University. The writer wants to thank Professor Thompson for discussions about the problems dealt with in the paper.

PART II

CHAPTER 1

INTRODUCTION

Petrologists have in recent years become increasingly aware of the importance of physico-chemical laws in understanding the mode of genesis of igneous and metamorphic rocks. A large number of papers have been published discussing the principles involved and showing how they would explain the formation of different types of rocks. The theory of such processes as isochemical metamorphism, metasomatism, partial anatexis, contact metamorphism, and assimilation now are well understood, and we can by applying physico-chemical principles predict a great deal about the type of mineral assemblages each such process would produce. The high pressure work going on in Washington and elsewhere has done a great deal to clarify the stability relationships of the different rock-forming minerals.

So far, however, very few attempts have been made to apply this new knowledge in the field by taking a suite of rocks and deducing what processes could have been significant in its formation through a detailed study of its chemistry and mineralogy. Despite all the speculation about the processes that are involved in metamorphism there is at the present time a great shortage of significant mineralogical data on which such speculation can be based.

In the present paper an attempt is made to look at the rocks in the Mount Reed area in northern Quebec as a physicochemical system and to show how Gibb's phase rule can be applied to gain a better understanding of the factors involved in the formation of the rocks.

The Mount Reed area is underlain by a sequence of high grade metamorphic rocks including migmatite gneiss, amphibolite, dolomitic marble, and iron formation. Main emphasis has been placed on the iron silicates, mainly hypersthene, ferroaugite and cummingtonite, since their relatively simple chemical composition makes them especially suitable for a study of this kind. Some mineral assemblages from the mafic rocks also have been studied to gain information about the more magnesian end members of the system studied. From the information gathered and from information available in the literature some conclusions have been drawn about the relative stability relationships of the different ferro-magnesian minerals and about how they may be affected by changes in temperature, pressure, and partial pressure of the volatiles. Particular emphasis has been placed on the study of the role of the volatiles H_2O and CO_2, since the assemblages of the silicate iron formation commonly contain both these components. One of the great controversies among theoretical petrologists at the present time is whether rocks in the course of regional metamorphism are open or closed to these components (Thompson 1955, Yoder 1959). It is hoped that the present study will lead us nearer towards the solution of this problem.

CHAPTER 2

FIELD WORK

The writer spent three summers in the Mount Reed area, from 1955 to 1957 inclusive, employed by the Quebec Cartier Mining Company. The work consisted partly of detail mapping of iron ore deposits, partly of more regional surveys of the iron formation. In the course of the regional work the writer had opportunity to gain some idea about the regional structure and stratigraphy. The main part of the suite of rocks on which the thesis work is based was collected in the fall of 1957 after the writer had become familiar with the rock types in the area. The company generously gave time and transportation for this project.

CHAPTER 3

LABORATORY WORK

The laboratory work was carried out in the Department of Geology at Massachusetts Institute of Technology and was supported by a grant from the National Science Foundation. The work consisted mainly of chemical analysis of minerals using the rapid silicate analysis methods developed by the United States Geological Survey (Shapiro and Brannock 1956). These methods are a powerful new tool in petrological research. They are fast, reasonably precise and accurate, and can be mastered by any geologist. Thirty-six complete mineral analyses were performed, mostly in duplicate, as well as a number of partial analyses. A Beckman photometer (Model B) and a Perkin-Elmer flame photometer were used, the latter for alkali metals only. The methods used are described in a laboratory report by Brownlow and Phinney. The main difficulty was encountered in the analysis of small amounts of aluminum in the presence of large amounts of iron. Iron tends to interfere in the photometric test for aluminum under these conditions. The values for Al_2O_3 therefore may not be as accurate as the analyses for the other components. In the separation of the different minerals from each other the Frantz magnetic separator was of great help, although in the case of specimens containing disseminated magnetite complete separation could not be accomplished without handpicking. All samples were subjected to a final cleaning by handpicking. The minerals which could be separated out without too much difficulty were analysed in duplicate. Several standards including W-1 and G-1 were used to check the standard solutions.

CHAPTER 4

THE MOUNT REED-MOUNT WRIGHT AREA - LOCATION AND ACCESSIBILITY

Lat.   Long

Mount Reed is located on longitude 52° 02' and latitude 68° 07' and Mount Wright on longitude 67° 20' and latitude 52_o 45' in northern Quebec. The mountains are the two most prominent land marks in an area which lately has become of prominence because of the discovery of a number of large iron ore deposits. The properties of the Quebec Cartier Mining Company are located in a broad belt stretching from Mount Wright southward to Jeannine Lake, about 10 miles south of Mount Reed. Jeannine Lake is the site of an iron ore deposit now under development. Other deposits are located at Mount Reed and Mount Wright.

Only a few years ago the area was accessible only by plane. Now an access road connects Jeannine Lake with Shelter Bay on the Gulf of St. Lawrence and within a few years a railroad will follow the same route.

The northern part of the area has a typical Canadian Shield topography with gently rolling hills separated by glacial drift plains, muskegs and lakes. The area is well forested except in areas devastated by fire. Around Jeannine Lake as one approaches the Manicougan Mountains the topography becomes more rugged.

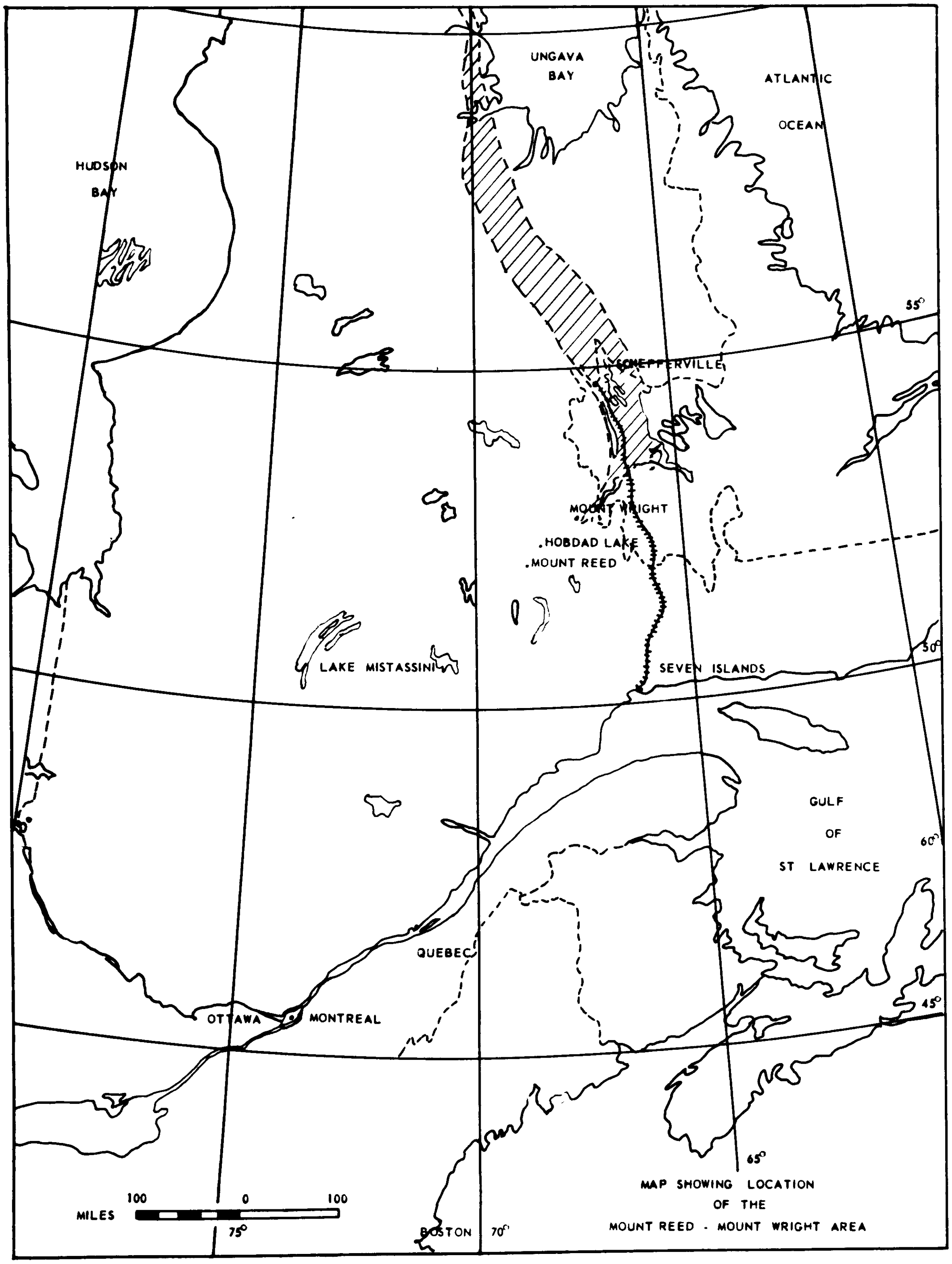
CHAPTER 5

SOME ASPECTS OF THE REGIONAL GEOLOGY

The Mount Wright-Mount Reed area constitutes the southermost part of the Quebec-Labrador iron range. The metamorphic iron formation can be traced northward from the Mount Wright area, through the Wabush Lake area, also the site of an iron ore property under development, to Sawbill Lake where there is a wide belt without any exposure. Iron formation reappears along the west shore of Menihek Lake and from there is continuous all the way up to Ungava Bay. The Sawbill Lake break marks the northern edge of the area affected by high grade metamorphism.

Iron formation of a similar type as at Jeannine Lake also is found at Matonipi Lake about 70 miles west of Mount Reed, indicating that the same iron-bearing rock sequence continues westward and possibly ties in with the iron formations of Lake Mistassini. The trend of the whole belt appears to follow the gravity anomaly discovered by Innes (1957).

The main features of the regional geology now are known thanks to intensive work done by company geologists and geologists of the Geological Survey of Canada and the Quebec Department of Mines. The regional structure is very complicated and if it was not for the excellent horizon markers constituted



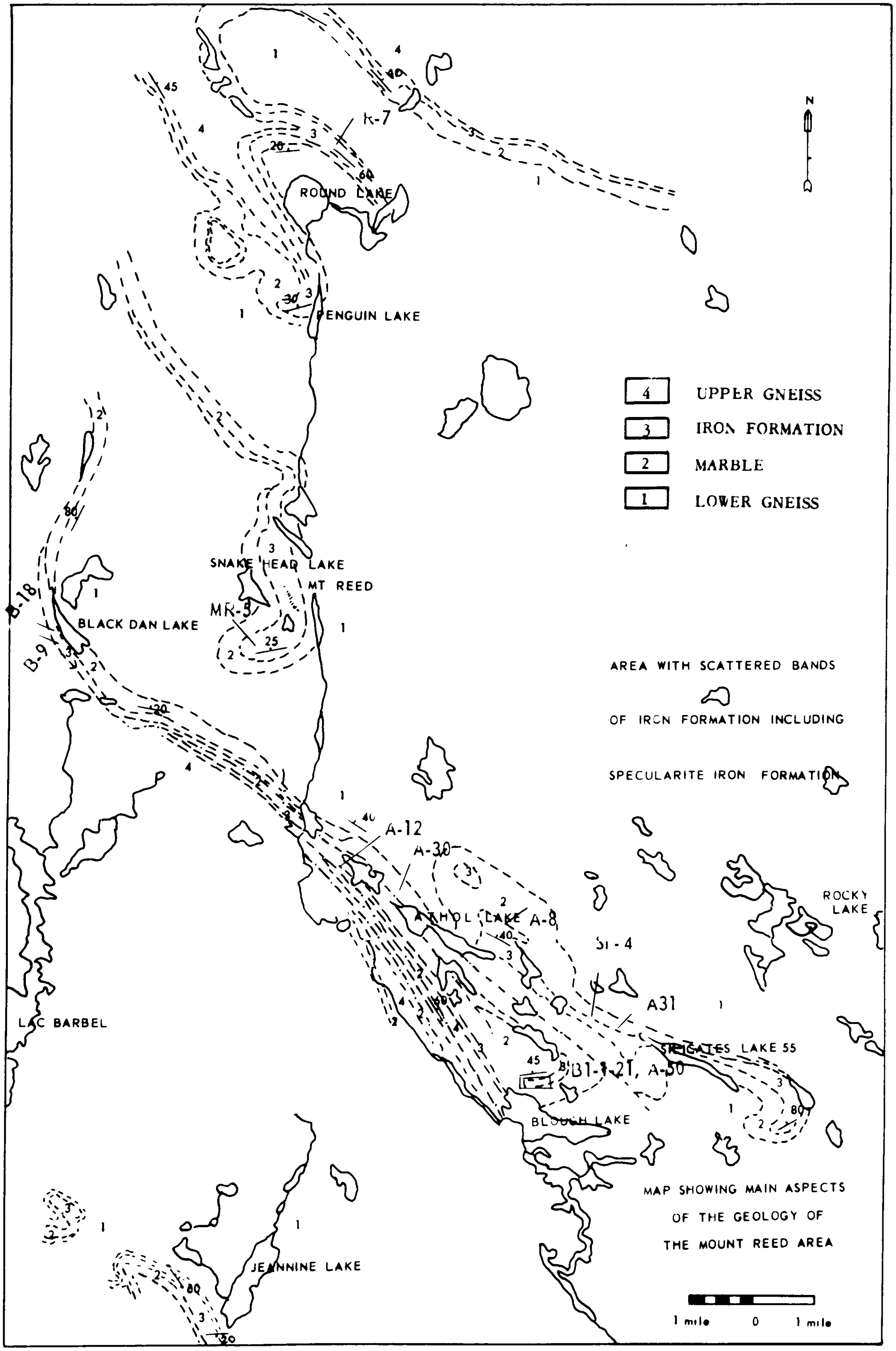
MAP SHOWING LOCATION
OF THE
MOUNT REED - MOUNT WRIGHT AREA

by the iron formation and the marble the structure probably never could be unraveled. Most of the area is covered by overburden, and only on hill crests and along streams are extensive outcrop areas found. Fortunately the iron formation is resistant to erosion and usually follows ridges. Where it does not outcrop it can be traced out with the help of dipneedle.

A map recently published by the Geological Survey (Duffell 1959) shows the main features of the geology of the northern part of the area. The very complicated pattern shown by the iron formation on the map probably is caused by two periods of deformation. Duffell recognizes a dominant northeast trend of the structural features in the area north of Mount Wright and west to southwest trend in the area further south, with some of the larger structures showing effects of two periods of folding. Gastil and Knowles (1957) from a study of the Wabush Lake area conclude that the rocks have been affected by two periods of folding. During one folding the rocks were thrusted west northwest along flat-lying axial planes, and during the other they were deformed by cross folds trending west northwest. It is not certain which of the two periods of folding were the earlier. The writer believes that essentially the same structural pattern is present in the Mount Reed area.

The structural pattern of the Mount Reed area is shown on the accompanying sketchmap. Perhaps the most striking evidence for recurrent folding is the bent synclinal tails such as are found at Silicates Lake and Mount Reed. They may represent second-order folds superimposed on first order isoclinal synclines. The trends of the first-order folds are very difficult to deduce since their trend only would affect the strikes and dips along the noses of the folds. All linear structures apparently are related to the second folding. However, an interpretation which assumes that the earlier folds trended northeast in accordance with the picture present further north seems entirely reasonable. One could for instance speculate that the Silicates Lake, Mount Reed, and Penquin Lake tails are parts of the same first-order syncline now exposed only in synclinal sections of the northwest-trending second-order folds. Daniel F. Bradley presently is making a survey of the structure of the area for Quebec Cartier Mining Company.

The relationship of the two periods of folding with the Grenville orogeny or orogenies on one hand and the orogeny which affected the Labrador through on the other is still not clear. The idea of connecting the Sawbill Lake break with the Grenville front and assuming that at least the second stage of deformation is of Grenville age seems reasonable.



MAP SHOWING MAIN ASPECTS OF THE GEOLOGY OF THE MOUNT REED AREA

CHAPTER 6

STRATIGRAPHY OF THE MOUNT REED AREA

Most rocks in the Mount Reed area probably are of sedimentary origin, although partial anatexis seems to have been widespread in the gneissic rocks and has transformed large parts of them into igneous rocks. Local movements of the juvenile magma no doubt took place, but it is interesting to note that, with the exception of an occasional pegmatite dyke, the granitic rocks have not intruded the iron formation and dolomitic marble. Therefore, if the gneiss and granite complexes overlying and underlying the iron formation-dolomite group are taken as units, all rock types can be grouped into the stratigraphic sequence shown below.

Upper Gneiss	garnet-biotite-gneiss, graphitic gneiss, etc.	5,000 ft.
Metavolcanics ?	garnet-amphibolite metaeclogite	0 - 200 ft.
Iron formation	quartz-silicate I.F. quartz-magnetite I.F. quartz-specularite I.F.	10 - 200 ft.
Quartzite, Quartz rock		0 - 100 ft.
Dolomitic marble		200 - 1,000 ft.
Lower gneiss	migmatite-biotite-gneiss	5,000 ft.

The thicknesses shown are highly arbitrary because a large amount of thickening and thinning during the folding has taken place, so that it is very difficult to estimate the original stratigraphic thicknesses of the separate formations.

The stratigraphic sequence is very similar all along the iron belt. Further north the gneisses are replaced by schist and finally by shales and slates in the Knob Lake area. The lower gneiss presumably corresponds to the Attikamagen shales, the basic rocks to the Nimish volcanics, the iron formation to the Sokoman formation, the dolomitic marble to the Denault dolomite, and the upper gneiss to the Menihek slates of the Kaniapiskau group.

In the Knob Lake area all the formations appear to thin out towards the west (Harrison 1952). In the Howells River area along the west side of the trough (Perrault 1955) the marble commonly is missing and the iron formation is directly underlain by quartzite. In the Mount Wright area the marble formation also commonly is missing. There seems to be a facies change from shallow water sediments in the west to deeper water offshore sediments in the east (Gastil and Knowles, personal communication). Specularite iron formation seems to transgress westward over magnetite iron formation which again transgresses over silicate iron formation further southeast. Concurrently the dolomitic marble appears to thin out and the overlying quartzite thicken. It is possible that the same relationship holds true for the Mount Reed area, but if so, it has to be assumed that thrusting has brought deeper water sediments westward over inshore sediments, because offshore sediments are known to outcrop to the west of inshore sediments (see sketchmap, page 27). In any case, the dolomitic marble generally is much thinner and the quartzite correspondingly exceptionally thick in sections where specularite iron formation is present as compared to silicate iron formation areas.

CHAPTER 7

DESCRIPTION OF ROCK TYPES

The description of rock types is based mainly on observations done in the area around Jeannine Lake, Blough Lake, and Mount Reed on one hand, and in an area around Hobdad Lake and Fire Lake further north on the other hand. The former area will be referred to as the Southern area, the latter as the Northern area. The areas are about 30 miles apart. The descriptions probably are representative for most of the Mount Reed-Mount Wright area as the lithology of the different rock types appears to be very uniform.

The Gneisses

About 85 per cent of the areas studied are underlain by gneissic rocks. Both the upper gneiss and the lower gneiss must exceed 5,000 feet in thickness. It is not safe to name a larger figure as it is impossible to estimate how much the sequence is repeated because of folding and faulting. There are no recognized stratigraphic markers within the gneisses.

There is considerable controversy among geologists who have worked in the area whether the upper gneiss and the lower gneiss can be differentiated lithologically. The writer has mapped upper gneiss only within about 1,000 feet from the iron formation in the Blough Lake area and also in the Round Lake area. In these areas there is a distinct difference between the two groups as shown in the description below. It is possible, however, that over larger areas the upper gneiss has the same character as the lower gneiss.

The lower gneiss is a complex of different kinds of biotite gneisses. Most commonly the rock is a light gray to white rock made up of oligoclase, microcline, and quartz intermixed with varying amounts of biotite. The biotite flakes mostly are concentrated into certain layers which produce a pronounced foliation. In some areas the gneiss has the character of a typical migmatite gneiss with lenses and stringers of coarse-grained quartzofeldspatic material intermixed with finer grained dark-colored biotite-rich bands. Sometimes the boundary of the quartzofeldspatic lenses are sharp and marked by a shelf of biotite. Sometimes the separation of the light and dark parts of the rock is indistinct, with streaks of biotite traversing the white areas and quartzofeldspatic nodules and streaks occurring within the dark material. All gradations exist between this rock type and the more homogeneous foliated biotite-gneiss described above. The foliation commonly is dragged into intricate fold patterns. Where amphibolite lenses and other inhomogeneities are present pegmatitic material has been emplaced along fractures and contacts.

North of Jeannine Lake and also north of Fire Lake the biotite gneiss grades into pink to gray homogeneous biotite granite.

Seven thin sections of the lower gneiss have been studied. They show that the feldspar is of two kinds. In some rocks *microcline* and aligoclase occurs as distinct rounded anhedral grains intermixed with quartz. In other slides *oligoclase* and *antiperthite* are present. In the same slides microcline may occur both in the form of antiperthite and as distinct grains. Untwinned *anorthoclase* without antiperthite structure together with oligoclase also has been noted. The chemical compositions of the feldspars should receive more study, as it may throw some light on the temperature at the time of the regional metamorphism.

Quartz occurs partly as anhedral grains intermixed with the feldspars, partly as fine laths crosscutting the other grains. The quartz content averages about 20 per cent.

The biotite consists of well crystallized flakes pleochroic in green and greenish yellow.

Minor *chlorite* is mixed in with the biotite flakes in some cases.

Muscovite is present in small amounts in most slides.

Hypersthene and *hornblende* are found in one slide of lower gneiss together with biotite, microcline, and andesine.

The genesis of the quartzofeldspatic rocks is a difficult problem and the writer does not pretend to have solved it in this study. A short discussion of the problem is in place, however, to throw some light on the environmental conditions in the rocks at the time of the metamorphism.

Partial anatexis presumably was a major process in the genesis of the migmatite gneiss. It is very difficult, however, to estimate just how large a proportion of the rock was in a molten state. In rocks with sharp boundaries between the quartz-feldspathic fractions and the dark bands the light layers presumably were essentially liquid. In the common biotite gneisses the relationship is not as obvious. The light bands have a quite heterogeneous composition, so if they were liquid they must have contained a large amount of interspersed solid crystals. In some sections the banding even could be assumed to reflect directly the compositional differences in the primary bedding, perhaps somewhat modified by metamorphic differentiation accompanying the recrystallization. However, the presence of true migmatites in the area shows that the temperature in the area at the time of the metamorphism was above the eutectic of granite (at high vapour pressure). Also the intricate folding in the gneisses shows that the whole gneissic complex must have been in a very plastic state. The solid and liquid fractions of the rock may have been blended as a result of continuous tectonic deformation contemporaneous with partial melting, injection of material from outside, cooling, and remelting.

Regional metasomatism, as a process forming granitic rocks of this kind appears improbable to the writer, because of the impossibility of devising a chemical potential that gradually would change the proportions between feldspar and biotite. Such features as the apparent gradual change of biotite-rich layers into quartzofeldspathic rocks along strike and the occurrence of outlines of relict banding in rocks of granitic composition no doubt would be taken as evidence by some geologists for transformation of sedimentary rocks into granite in the solid state. However, perhaps the granite melt was viscous enough so that biotite could remain in the melt to outline the structure of the rock from which the granit melt derived its material.

What diffusion did occur probably was activated by local chemical potential gradients existing between layers of different mineral compositions and between melts and wall rock where the melt has been intruded into rocks not in equilibrium with the melt. The biotite rims noted around quartzofeldspathic lenses indicates that the melt reacted with the wall rock, probably picking up some quartzofeldspathic material from it, leaving biotite behind. Diffusion also may have helped to segregate biotite into certain layers and increase its grain size (Eskola 1932).

A more complete study should be made of the chemical potentials that do exist within the gneiss. This could be done by comparing the compositions of feldspar and biotite in different layers. It would be interesting for instance to know if the pronounced textural disequilibrium between the fine-grained dark segments and the coarser-grained quartzofeldspathic rocks are accompanied by a chemical disequilibrium.

The upper gneiss within the sections studied by the writer has a distinctly different lithology. It is a more typical paragneiss containing garnetiferous and graphitic layers and a lesser amount of light colored quartzofeldspathic bands. It is typically rusty-weathering. In the Blough Lake area there are several impressive gossans containing disseminated pyrite and graphite in the upper gneiss.

In thin sections the upper gneiss looks similar to the lower gneiss except for scattered rounded grains of garnet

Garnet Amphibolite and Related Rocks

Overlying the iron formation one locally finds a layer of mafic igneous rocks with the composition of garnet amphibolite. Such rocks occur in cores of synclines at Fire Lake and at Hobdad Lake and other places in the northern area. Similar rocks are present west of Athol Lake in the southern area associated with dark-colored massive garnetiferous rocks tentatively classified as eclogite. The garnet amphibolites no doubt are metamorphosed mafic igneous rocks. Little is known of their mode of emplacement. They may constitute pre- or syntectonic sills, or they may be volcanic rocks. Their consistent position in the stratigraphic sections seems to favor the latter alternative.

The garnet amphibolite is a fine-grained, dark-colored homogenous, poorly foliated rock. Along the contacts with the overlying gneiss the rock generally is altered to a coarser-grained biotite-garnet gneiss. At Hobdad Lake the rock is in direct contact with silicate iron formation. The contact is marked by a massive garnet-diopside-hypersthene skarn, presumably a reaction product between the magma and the iron formation.

A thin section of the Fire Lake garnet-amphibolite has the following mineral composition:

Green hornblende	30 per cent
Zoned andesine	50 per cent, evenly mixed with the hornblende. The central part of the crystal is higher in sodium.
Garnet	(locally altered to chlorite) 15 per cent
Biotite	3 per cent
Opaques	1 per cent

A thin section of meta-ecologite of Athol Lake shows that the rock consists of 30 per cent garnet and the remainder of a fine-grained mixture of light green clinopyroxene, dark green hornblende and zoned andesine. The garnet grains are surrounded by a ring of fine-grained andesine which gives the rock a very characteristic look in a hand specimen. The symplectitic mass obviously is an alteration product of some earlier mineral component, since the individual granules occur in groups with common optical orientations. The parent mineral is presumed to have been an omphacitic pyroxene. It is hard to think of any other mineral which could form soda feldspar as an alteration product.

A more complete study has been made of a specimen (A-12, page 117) from a nearby locality with a somewhat different mineral composition. It is a dark green coarse-grained rock consisting of 40 per cent hornblende, 20 per cent hypersthene, 30 per cent diopside, and 10 per cent garnet. It also contains a dark brown mineral, presumably rutile. Each one of the four major components have been analysed (Appendix A).

The high magnesium content of the garnet is remarkable. Pyrope garnets generally occur only in eclogite and related rocks. This fact seems to lend support to the idea that the regional metamorphism approached the high pressure and conditions typical for the eclogite facies.

Dolomitic Marble

The dolomitic marble formation is present everywhere in the Mount Reed area between the iron formation and the lower gneiss. Its thickness is very variable partly because of stratigraphic changes, partly because of plastic flow parallel with the bedding in the course of the tectonic deformation. It reaches its greatest thickness in the Blough Lake area where several square miles east of the lake are underlain mainly by marble. Its original stratigraphic thickness is here estimated to about 1,000 feet from the relatively undeformed section north of Athol Lake. Around the fold crests at Silicates Lake and Blough Lake this thickness has been almost doubled. At Jeannine Lake the thickness changes abruptly from about 500 feet to 20 feet across the nose of a second-order anticline. At Fire Lake a thickness of about 20 feet has been measured, at Hobdad Lake about 50 feet.

The marble is a snow-white, coarse-grained, black-weathering thick-bedded rock. The bedding is shown by scattered layers of quartz around which the marble has been altered to tremolite and diopside. The bedding commonly is bent into open drag folds. The mineral composition is dolomite and in the northern area is mixed with some calcite (as shown by slight reaction with acid). Except for the reaction products diopside and tremolite, the only minor components which have been noted are scattered grains of phlogopite.

Quartz Rock, Quartzite, Quartz-Mica Schist

Locally between the iron formation and the marble is a quartzose unit made up of a coarse, almost giant-grained, mass of white to blue quartz. The rock is massive in places; elsewhere is well-bedded. The bedding is indicated by quartz layers of varying colors and by layers of muscovite and specularite. The unit is best developed below the quartz-specularite member of Jeannine Lake and Fire Lake, but similar rocks occur also at Mount Reed and other places below the silicate iron formation. Its origin is somewhat controversial. Some geologists have described it as orthoquartzite; others have used the term quartz-rock to emphasize the possibility that it may be a chemical precipitate of the same origin as the recrystallized chert occurring in the overlying iron formation. A heavy residue analysis made by Gross (1955) of similar rocks from Mount Wright seems to support the idea that they are at least partly of detrital origin. Also an orthoquartzite unit, the Wishart quartzite, occurs in the Labrador trough proper between the Denault dolomite and the Sokoman iron formation. On the other hand, minor bands of specularite occur within the quartz-rock in many places, producing rock types transitional between quartz-rock and specular iron formation. The best guess probably is that the unit is composed of a mixture of detrital and precipitated silica.

The quartz-mica-schist unit as far as the writer knows is found only below the specularite iron formation, and is absent from the silicate iron formation areas. It consists of a relatively homogeneous mixture of medium-grained quartz, muscovite, biotite, and locally some garnet. The muscovite characteristically is greenish. The unit presumably represents a shaly horizon. Micaceous layers also are found within the main body of specularite iron formation at Jeannine Lake, but it is not known whether they are infolded or interbedded with it.

Iron Formation - General Aspects

The iron formation both from an economic and scientific point of view represents the most interesting rock type in the area. It contains all the iron ore deposits in the area. It constitutes one of the finest occurrences of high-grade metamorphic iron formation known. Similar rocks have been described from northern Sweden and Brazil; but they do not show the same variety and areal extent as the Mount Reed-Mount Wright iron formations. A description of their petrology and mineralogy and a discussion of their mode of origin constitutes the main purpose of this paper. Its relatively simple chemical composition makes it an ideal rock type with which to demonstrate the role of volatiles in metamorphism.

For the purpose of field mapping, the Mount Reed iron formations have been classified into three types:

quartz-specularite-iron formation
quartz-magnetite iron formation
quartz-silicate iron formation

Rock types gradational between the specularite and magnetite iron formation on the one hand and magnetite and silicate iron formation on the other hand are known. Specularite and the iron silicates ferrohypersthene and cummingtonite are never found together. The calcium ferromagnesian minerals actinolite-hornblende and diopside-ferroaugite are found in all units, but are as a rule more magnesium-rich in the oxide facies. Sodium-bearing amphiboles and pyroxenes are common in the oxide iron formations of the Blough Lake area. Calcite is a ubiquitous component in the silicate iron formations, and layers of ferrodolomite also are present locally.

The stratigraphic thickness of the iron formation is hard to estimate. In relatively undeformed places it is only about 200 feet thick. Thicker sections found in other places probably are mainly due to repeated folding.

The stratigraphic relationships between the different units of the iron formation still are not completely understood. Two different types of sections are found in the area, one well represented at Jeannine Lake, the other one at Mount Reed and in most of the remaining southern area.

Jeannine Lake type

	feet
silicate iron formation	100
specularite iron formation	200
quartz-mica-schist	50
quartz rock	150
marble	200

Mount Reed type

	feet
silicate iron formation	100
magnetite and magnetite-specularite iron formation	200
silicate iron formation	50
quartz rock	0 - 100
marble	1,000

The thicknesses shown are very arbitrary. The Jeannine Lake is thought to represent an inshore facies, the Mount Reed type a deeper water facies. Unfortunately no well developed transitional types are known to the writer so it is not known for sure how the different sections are related. In offshore facies the oxide iron formation member commonly is completely missing. Sometimes it is present only as discontinous lenses. Sections up to 200 feet wide have been found to pinch out within a few hundred feet. It is not certainly known whether this pinching and swelling is due to stratigraphic changes or represents an incipient boudinage structure. Below are described the general character of the different types of iron formation. In the appendix individual handspecimens whose mineralogy has been studied in detail are described.

Quartz-Specularite-Iron Formation

The quartz-specularite-iron formation, or itaritite as similar rocks in Brazil have been called, is a very spectacular rock type. It consists almost entirely of glistening flakes of specularite and quartz. It is completely fresh on the surface and glows in the sunlight with a brilliant blue luster. It is in part massive and in part foliated. The foliation is caused by differing proportions of quartz and specularite, in places the two minerals being separated completely into different layers. Where the foliation has been distorted into drag folds large segregations of solid coarse-grained specularite has formed along the fold crests. The only minor constituents in the specularite iron formation are magnetite, finely disseminated all through the rock, and in places clusters of actinolite and diopside, together with some calcite.

Quartz-Magnetite-Iron Formation

The quartz-magnetite iron formation is similar to the specularite iron formation except that the oxide is in the form of magnetite. Transitional rock types with specularite intermixed with magnetite also are common. However, very rarely do the layers in the Mount Reed type iron formation attain the same luster as the Jeannine Lake iron formation. The magnetite iron formation as a rule is finer grained. Where no specularite is present, layers of silicates usually are found intermixed with the oxide layers, producing brownish stains on the weathered surface.

A special rock type among the rocks transitional between the oxide iron formation and silicate iron formation is the sodium amphibole and pyroxene-bearing assemblage around Blough Lake and Mount Wright. These rocks are described in Chapter 8.

The Silicate Iron Formation

The silicate iron formation shows a much greater variety in composition and lithology than the oxide iron formations.

The unit locally includes layers of ferrodolomite and then more properly should be described as carbonate-silicate iron formation. However, since there is good evidence that a major amount of the FeMgCa-silicates is derived from carbonates, the silicate and carbonate silicate iron formations are not differentiated in this classification. The main mineral constituents of the silicate iron formation are quartz, hypersthene, cummingtonite, ferroaugite, calcite and locally magnetite.

The rock usually is well banded. The banding is produced by varying proportions of the different mineral constituents and presumably directly reflects the original bedding. The banding is brought out particularly on the weathered surface, where quartz-rich resistant layers stand up over rusty-weathered carbonate-silicate-rich beds. Layers high in carbonate are usually covered by a deep red coating of limonite. Layers in which pyroxene predominates usually are dirty green on the weathered surface. In some places, for instance at Hobdad Lake, the layering may be very colorful with blue magnetite-rich layers, green pyroxene-rich layers, and brown carbonate-rich layers alternating with each other. On lee sides of mountains where the rock has been protected from glacial erosion, the silicate rocks usually are deeply weathered along the surface and joints so that it is hard to find a fresh surface.

The different beds may be very thin and regular and traceable over long distances. More rarely the silicate rock is almost homogeneous over whole outcrops. Where hard quartz-rich layers and soft carbonate-rich layers are interbedded the beds show pinching and swelling. Where the layering has been distorted by folds and faults recrystallization has produced a coarse irregular mass in which primary structures are unrecognizable. In such places big rosettes of cummingtonite are commonly found.

On the fresh surface the color ranges from dark green, brown, to bluish-gray depending on the proportions of mineral constituents present. Ferroaugite has a dark green color, the hypersthene in hand specimens looks dull dark gray; in smaller grains it is brown, contrasting vividly with the green ferroaugite. A massive bluish-gray variety of silicate rock common in the Mount Reed and Blough Lake areas consists mainly of quartz and hypersthene. Cummingtonite ranges in color from gray to light brown, apparently depending on the amount of iron present.

Usually the texture of the silicate rocks is a granular medium-grained xenoblastic mixture of the different mineral constituents with varying proportions of the minerals in different layers. Cummingtonite sometimes appear to be replacing hypersthene. Otherwise no replacement textures are evident that would indicate dissequilibrium in the rock.

CHAPTER 3

THE SPECIMEN LOCALITIES OF THE SOUTHERN AREA

In Appendix B are represented the chemical analyses of silicate minerals occurring in the iron formations of the southern area. Most of the material is from a J-shaped isoclinal syncline just north of Blough Lake. The iron formation is present in the core of the syncline as a 400-foot band thinning out towards the west. The band is bordered by marble on both sides and probably also pinches out in marble towards the west at the presumed nose of the syncline. That the band represents a double sequence of iron formation is shown by the fact that upper gneiss appear in the core of the syncline as the two parallel limbs are traced northward towards Athol Lake. This band of iron formation consists mainly of quartz-silicate-calcite iron formation, but a layer about 200 feet thick consisting of quartz-magnetite iron formation intermixed with sodium and maganese-rich silicates also is present. Twelve thin sections from this place were examined. The specimens described on page 122 are quite typical. Hypersthene, ferroaugite, calcite, quartz, and locally magnetite or graphite are the most common mineral constituents. Ferroaugite appears to be absent in layers with a high FeO/MgO ratio. Cummingtonite has been noted only in one section

A somewhat wider synclinal tail runs from Athol Lake towards Silicates Lake and ends in another J-shaped body just south of Silicates Lake. This belt contains, in addition to silicate iron formation, a large amount of quartz-magnetite iron formation containing alkali amphiboles. An analysis of one such amphibole shows that it is an arfvedsonite. The amphibole in some specimens studied occurs together with hypersthene and a dark green clino-pyroxene, but because of fine-grained magnetite sprinkled all through the coarser-grained silicates it was impossible to separate the minerals for chemical analysis.

In the Athol Lake area three iron formation bands are present. The sequence marble, iron formation, upper gneiss is repeated several times as a result of isoclinal folding and faulting parallel with the axial planes and the bedding. The specimens studied are all from the easternmost and thickest band. It differs from the iron formation of the Blough Lake tail by the presence of a major amount of cummingtonite.

In the Black Dan Lake area along the northern continuation of Athol Lake, iron formation belt cummingtonite is the main iron silicate. Hypersthene has been seen only in a few thin sections partly altered to cummingtonite.

CHAPTER 9

THE SPECIMEN LOCALITIES IN THE NORTHERN AREA

The structural pattern of the Hobdad Lake and Fire Lake areas is not very well known because of the scarcity of outcrops in the area. Very likely the iron formations are situated in similar isoclinal tails as those found in the southern area.

The specimens studied from the Hobdad Lake area are all from an outcrop area about 400 square feet in size located about 2,000 feet southwest of Hobdad Mountain. Both quartz-magnetite and quartz-silicate iron formations are present. The silicate iron formation is exceptionally coarse-grained consisting again of ferrohypersthene, cummingtonite, ferroaugite, quartz and calcite. The hand specimens studied are described in Appendix C.

At Fire Lake typical silicate iron formation is not present. The main part of the iron formation consists of quartz-specularite iron formation which makes up an impressive ore deposit. Above the specularite iron formation is found a horizon containing quartz-magnetite iron formation and dolomite. Along contacts with quartz-bearing rocks the dolomite has been altered to diopside and actinolite. The diopside and amphibole from one such reaction zone has been analysed (F-73). It should be noted that the minerals may not be in equilibrium as they were not taken from specimens in direct contact with each other and activity gradients should be expected in a reaction zone. A large amount of shaly material apparently was present in the contact zone as shown by the high aluminum and alkali content of the hornblende.

The anthophyllite-hornblende assemblage of F-1 was found in an outcrop near the old base camp at Fire Lake. The rock probably is an altered ultrmafic rock rather than an iron formation.

CHAPTER 10

SIGNIFICANCE OF THE CHEMICAL ANALYSES

The analyses were made by photometric methods as first described for use in silicate analyses by Brannock and Shapiro (1956). The results of the analyses are listed in Appendixes A-C. The deviation between duplicate analyses does not exceed 3 per cent and generally is much less. The main sources of error lie either in the preparation of the solutions or in the presence of inhomogeneities in the samples. The reproducibility of measurements in a single solution is extremely good in all the procedures used. A great advantage of the method was that each analysis could be checked over and over again both by making duplicate solutions and by running a single solution several times. Thereby the risk of major analytical errors was eliminated. Several standards including W-1 and 6-1 were used to check the standard solutions. H_2O was not determined, so that the amphibole and chlorite analyses do not add up to 100 per cent. The TiO_2 content was found to be negligible in the silicates of the iron formations.

The analyses generally agree very well with the structural formulas of the minerals.

The main purpose of the chemical analyses is to find out how the different elements distribute themselves between the different phases. The most significant components in the analysed minerals are FeO,MgO, and CaO. From the analyses one can draw some conclusions as to how this system looks at the temperature and pressure conditions present in the Mount Reed area at the time of the metamorphism. Unfortunately all the analyses are not from exactly the same area. It is difficult to find rocks of a significant range in mineral composition within a limited area. However, the degree of metamorphism appears to have been quite uniform in the area, so at least one can assume that the rocks in the southern area and in the northern area respectively were metamorphosed under the same temperatures and pressures.

In Fig. 3 the compositions of the minerals are plotted on a CaO-MgO-FeO diagram together with the tie lines of the different mineral assemblages. Five phases are represented in the diagram, namely hypersthene, cummingtonite, anthophyllite, actinolite-hornblende, and diopside-ferroaugite. Other components also affect the stability relationships of the different minerals, for instance Al_2O_3, Na_2O, and H_2O. Therefore, the stability relationships of the different minerals cannot be completely represented in this diagram. However, some significant features on the phase chemistry of the minerals can be demonstrated with the help of it. The following points shown by the diagram are of interest.

1. The minerals appear to be at least in approximate equilibrium

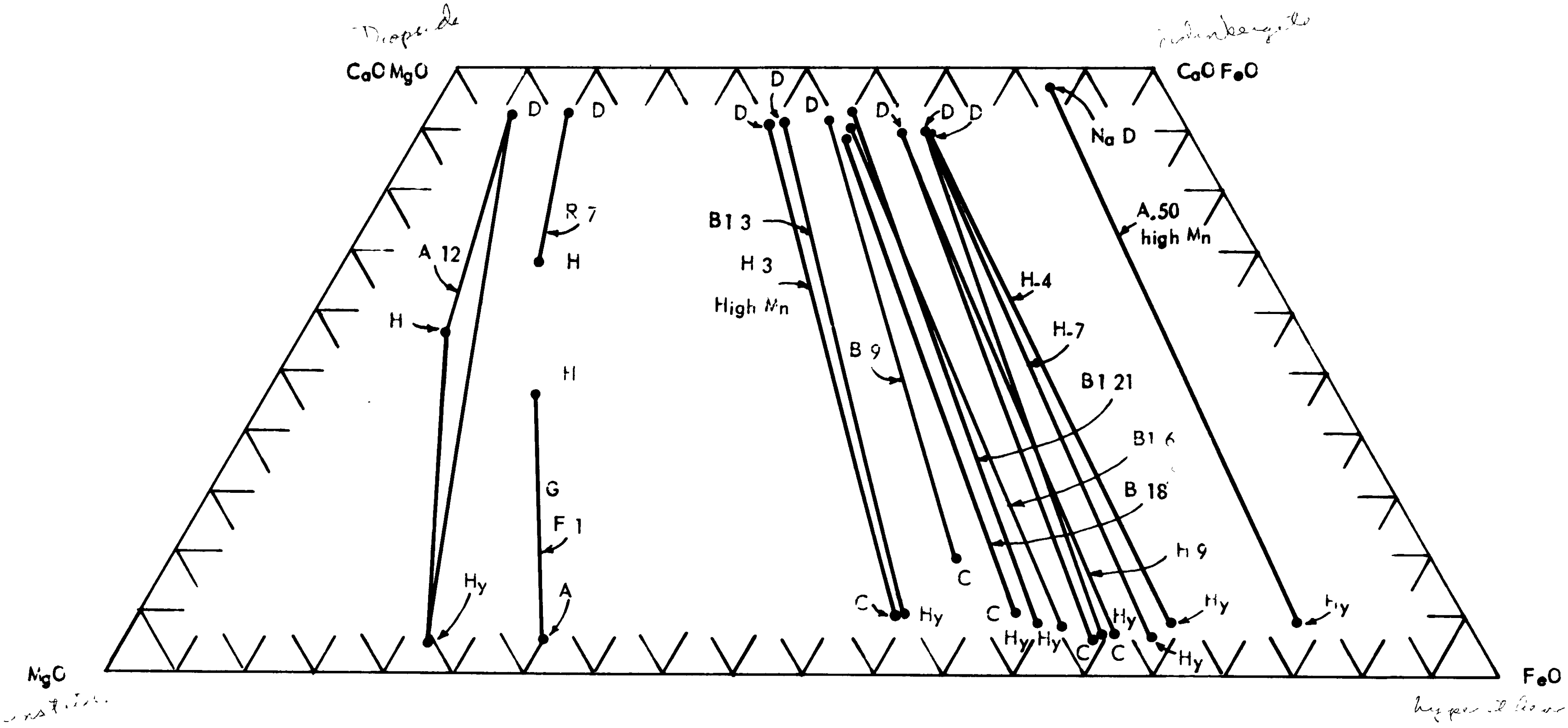


FIGURE 3

DIAGRAM SHOWING FeO-MgO-CaO RATIOS IN
ANALYSED SILICATES OF THE MOUNT REED AREA

A - ANTHOPHYLLITE
B - CUMMINGTONITE
D - DIOPSIDE - FERROAUGITE
H - CA - AMPHIBOLES
Hy - HYPERSTHENE

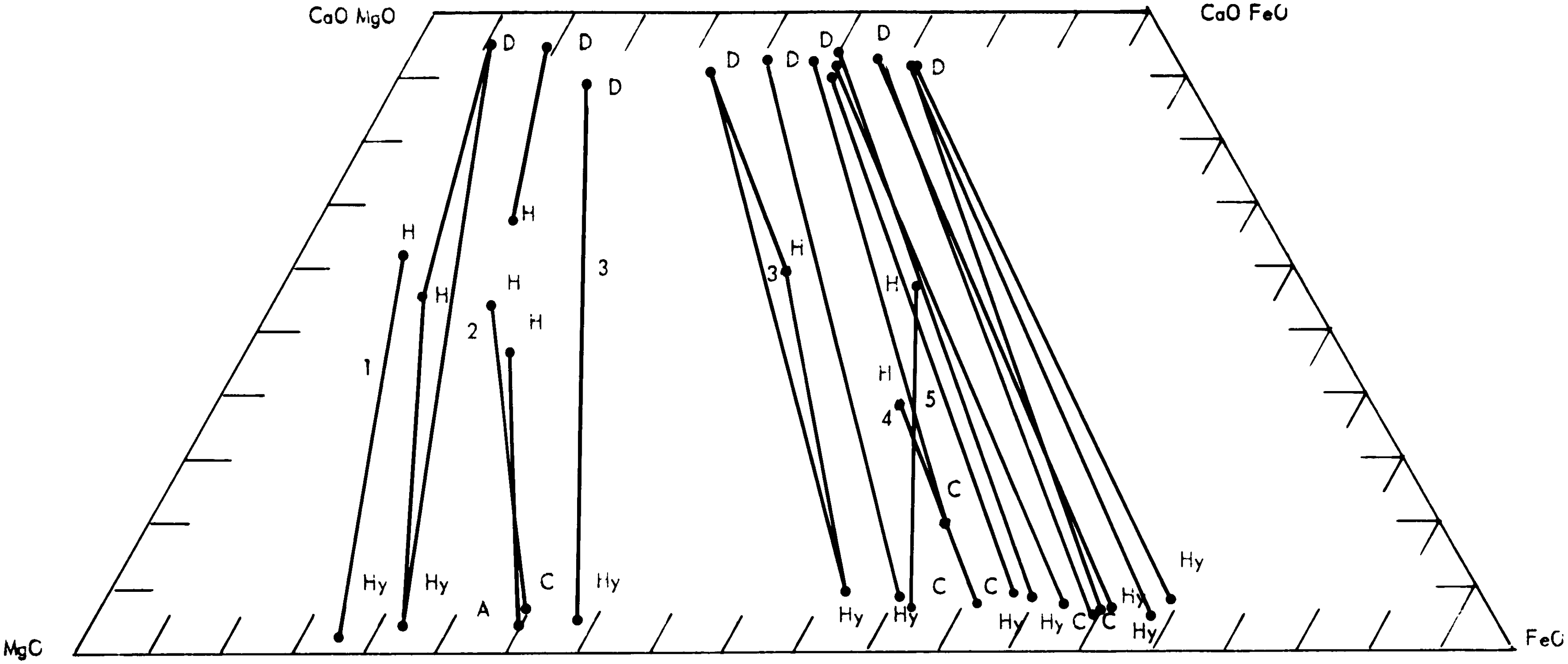


FIGURE 4: FeO - MgO - CaO RATIOS IN COEXISTING AMPHIBOLES AND PYROXENES

A - ANTHOPHYLLITE
C - CUMMINGTONITE
D - DIOPSIDE - FERROAUGITE
H - HORNBLENDE
Hy - HYPERSTHENE

SOURCES OF ANALYSES

1	MIKKOLA, SAHAMA	1936
2	ESKOLA	1950
3	ESKOLA	1952
4	MILES	1943
5	SEITSARI	1952

as shown by the fact that the tie-lines between different mineral pairs are nearly parallel. The only exceptions are the hypersthene-ferroaugite pairs of Bl-6 and Bl-21 which do cross each other. It is possible that in some cases the FeO/MgO ratios still reflect the compositions of the carbonates from which the hypersthene and ferroaugite formed.

2. Cummingtonite is slightly more magnesium-rich than the hypersthene it is in equilibrium with, at least in the more iron-rich assemblages. Towards the magnesium side the hypersthene-**augite** and cummingtonite-**augite** tie lines appear to become almost parallel, indicating that a coexisting cummingtonite and hypersthene in this compositional range may have about the same FeO/MgO ratio.

The higher FeO/MgO ratio in cummingtonites as compared to hypersthenes agrees with the general rule that the low temperature phase is higher in magnesium (Ramberg 1949).

3. The general rule among pyroxenes and amphiboles seems to be that the phase higher in calcium has a lower FeO/MgO ratio than the phase lower in calcium. This relationship has been noted earlier to be valid for igneous pyroxenes (Hess 1941). Also, a compilation of analysed pyroxene pairs made by Muir and Tilley (1958) shows that the same relationship holds for more magnesium-rich metamorphic pyroxenes. In Fig. 4 the writer has compiled a number of analyses of coexisting metamorphic pyroxenes and amphiboles. All the mineral assemblages follow this rule except in the case of a cummingtonite-hornblende pair described by Seitsari (1952).

From theoretical considerations Ramberg (1952) has concluded that the presence of aluminum should favor a more iron-rich amphibole for a given bulk composition. The available analyses seem to show that the direction of the tie lines between pyroxenes and hornblende is independent of the aluminum content of the hornblende. However, the analyses admittedly are too few to make possible any definite conclusions about this matter.

4. The immiscibility gap between calcium pyroxene on one hand and hypersthene and cummingtonite on the other hand is about 42 moles in the iron-rich assemblages, slightly higher in the magnesium-rich phases. The gap probably decreases with temperature, so that this information may be of value for the determination of the temperature of the metamorphic environment. At the present time no experimental data are available for the calibration of a geothermometer based on the immiscibility gap of the pyroxenes. The immiscibility gap between magmatic clinohypersthene and augite is about 28 moles in the compositional range of the ferrohypersthenes (Brown 1957).

5. The mineral pairs of F-1 and R-7 shows that the range of miscibility of CaO and FeO + MgO is about 11 mole per cent in low alkali-amphiboles.

CHAPTER 11

GENERAL ASPECTS OF THE PHASE CHEMISTRY OF PYROXENES AND AMPHIBOLES

Pyroxenes and amphiboles are the main ferro-magnesian minerals in igneous rocks and high-grade metamorphic rocks. Therefore, a better understanding of the stability ranges of these minerals both in the dimensions of composition and temperature and pressure would be very useful in better understanding the petro-chemistry of these rocks. The pyroxenes are common only in the highest grades of metamorphism, mainly in rocks such as charnockite and granulites, found only in deeply eroded Precambrian shield areas. The metamorphic pyroxenes are mainly hypersthene and diopside-augite. The acmite molecule also seems to be able to enter the clinopyroxene in appreciable quantities under metamorphic conditions. Jadeite is characteristic for high pressure conditions.

The amphiboles are far more complex than the pyroxenes because of the many different types of cation substitutions that can take place in the structure. Only after Warren in 1930 deduced the crystal structure of amphibole have we gained some understanding of the ranges of compositions possible in amphibole. Especially valuable contributions to the understanding of hornblendes since have been made by

Kunitz (1930), Sundius (1933), Hallimond (1943), Harry (1950), and Rabbitt (1948). In the case of range of composition, the amphiboles show some similarity with pyroxenes. There are the pure ferromagnesian amphiboles cummingtonite and anthophyllite, which like the corresponding pyroxene hypersthene do not show a continuous solid solution series with the calcium-rich members. Tremolite and actinolite can be compared to the diopside-hedenbergite series of the pyroxenes. Riebeckite has a composition similar to acmite, and glaucophane can be compared with jadeite. From a petro-chemical point of view the most significant difference between pyroxene and amphibole is, besides the different water content, the ability of the amphibole structure to accept a major amount of aluminum at relatively low temperatures and pressures.

CHAPTER 12

CUMMINGTONITE AND ANTHOPHYLLITE

The name cummingtonite in this paper will be used for the monoclinic calcium-poor amphibole which forms a solid solution series from pure $Fe_7Si_8O_{22}(OH)_2$ grunerite to a composition with a Fe/Mg ratio of about three to six. The relationship between cummingtonite and the orthorhombic anthophyllite series has caused considerable controversy in geological literature and their mutual stability ranges are still far from well defined. Cummingtonite generally is high in iron and anthophyllite high in magnesium. However, anthophyllite with as much as 80 per cent FeO and cummingtonite with as much as 80 per cent MgO has been reported. However, Sundius (1933) and Rabbitt (1948) have reviewed the information available about cummingtonite and anthophyllite and both conclude that they do not form complete solid solutions and that iron-rich anthophyllites and magnesium cummingtonites do not exist. Most previously reported so-called iron anthophyllites, except some Al bearing variations (Seki and Yamasaki 1957), have been shown to have been erroneously identified, generally being ferrohypersthene. Similarily reported occurrences of

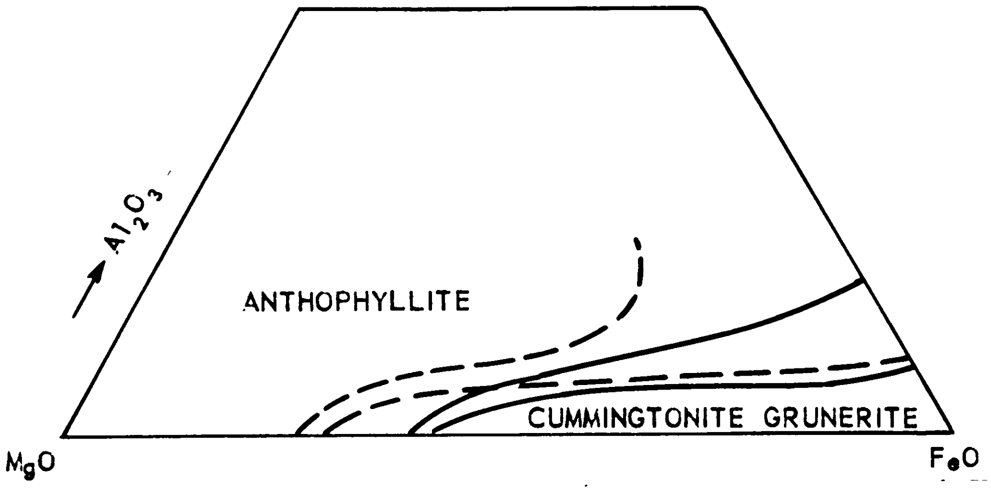


Fig. 5 Diagram showing assumed position of the cummingtonite-anthophyllite two-phase field.
Solid lines - low temperature
Broken lines - high temperature

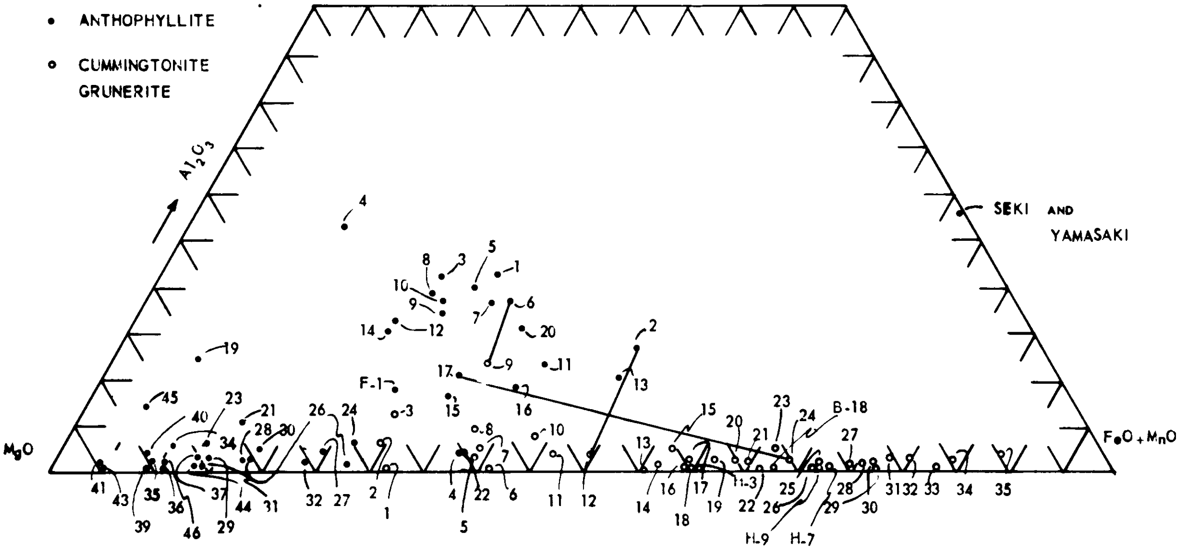


Fig. 6 Diagram showing compositions of analysed anthophyllites and cummingtonite grunerites. The anthophyllite analyses are from compilation by Rabbitt (1948) and Seki and Yamasaki (1957). The cummingtonite-grunerite analyses are from compilation in Appendix 4.

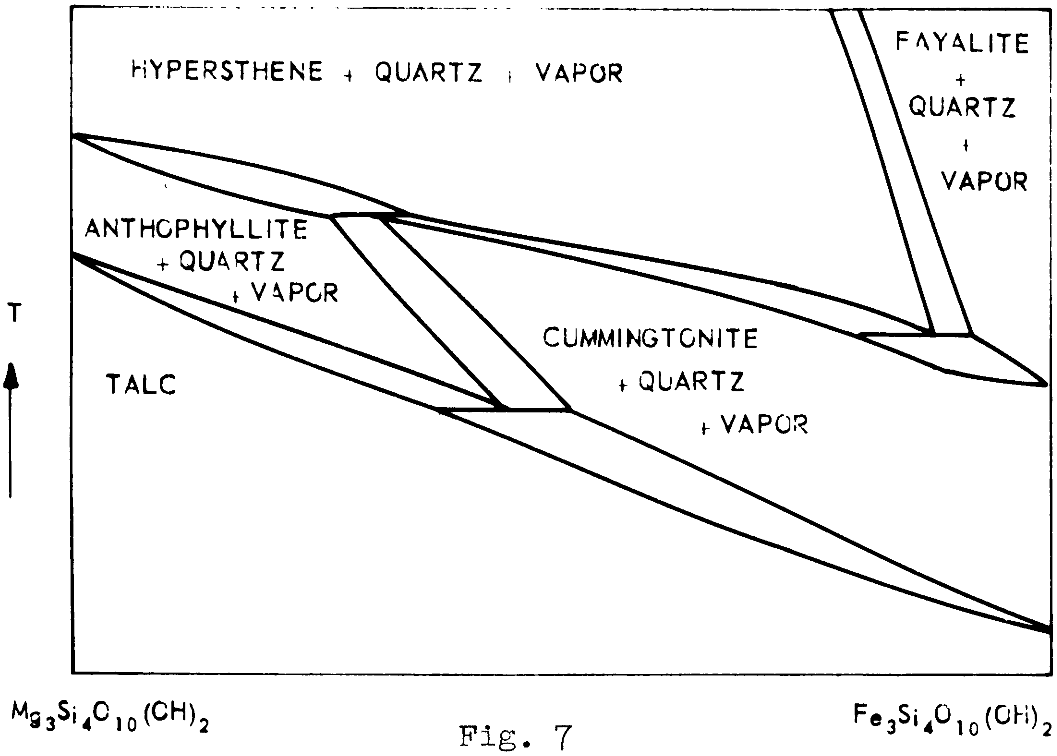


Fig. 7

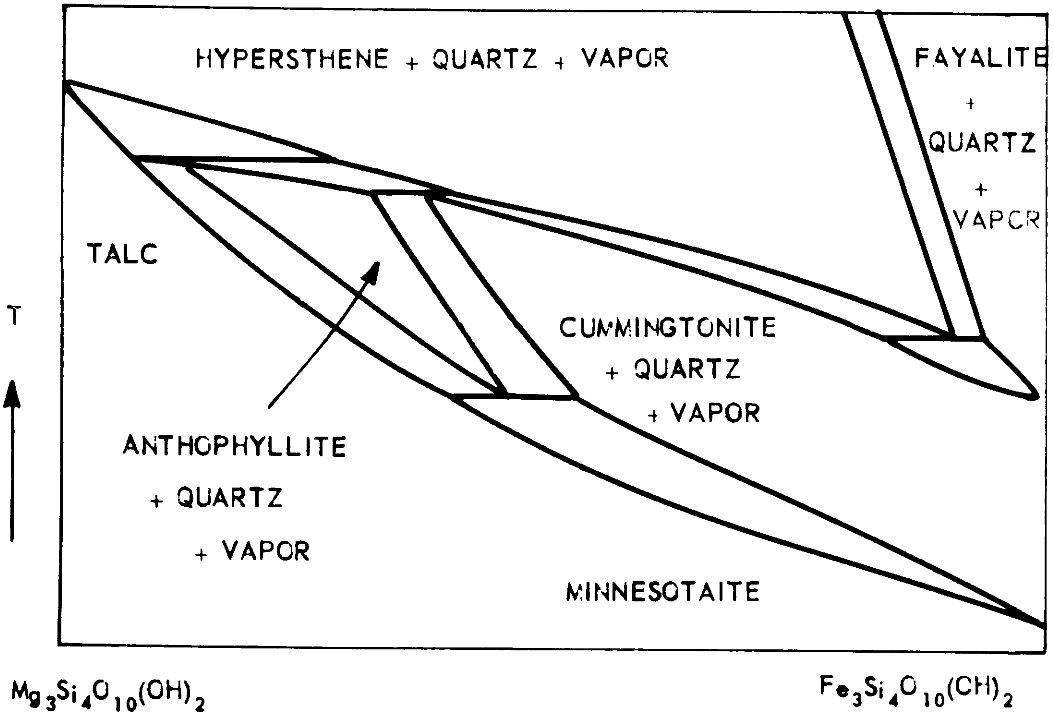


Fig. 8

Hypothetical phase diagrams showing possible stability relationships of cummingtonite and anthophyllite.

kupfferite have been discredited. However, there still is considerable doubt as to the exact extent of the two series, and the problem is complicated by the fact that anthophyllite is able to take up a large amount of aluminum whereas cummingtonite is not. Instead cummingtonite commonly shows a high manganese content. Sundius' study of amphiboles was significant as he presented the first analyses of coexisting anthophyllite and cummingtonite. From the collected analyses he concluded that the cummingtonite and anthophyllite fields generally did not overlap greatly, although scattered analyses disagreed with this point of view. Fig. 5? shows a plot of the anthophyllite analyses collected by Rabbitt (1948) and of a number of cummingtonite analyses collected by the writer. Four examples of analysed cummingtonite and anthophyllite from the same area also are shown. Rabbitt concludes that the two minerals probably were in equilibrium only in the case of the earlier mentioned pair analysed by Sundius. In none of the other cases, cummingtonite and anthophyllite from Orijärvi (Eskola 1936), from Strathy (Collins 1942), and from Idaho (Rabbitt 1948), are the minerals separated from the same rock specimen. The fact that the anthophyllites in most cases are high in aluminum may indicate that the presence of anthophyllite with cummingtonite is due to aluminum rather than to the magnesium. Otherwise, if the pair analysed by Sundius is significant, coexistence of anthophyllite and cummingtonite would be very rare, since they would be stable only within a very small compositional range. The possible stability relationship is shown in Fig. 6.

An overlap in the cummingtonite and anthophyllite stability fields may also be caused by temperature and pressure effects. High temperatures might favor cummingtonite, pusing the field of coexistence towards the magnesium side. As a rule, when two ferromagnesian phases coexist, the one richer in iron generally is the low temperature phase as shown for instance by the pairs clinohypersthene-olivine and olivinemelt.

Fig. 7 shows one way the compositions of cummingtonite and anthophyllite may be related to temperature. The diagram is similar to a hypothetical diagram presented by Boyd (1959). An alternative interpretation is shown in Fig. 8. This interpretation is favored by the following points of evidence.

1. Neither Boyd nor Bowen and Tuttle (1949) have been able to synthesize pure Mg-anthophyllite as a stable phase. It only formed metastably at the breakdown of talc and later changed to enstatite plus quartz. On the other hand Boyd reports that anthophyllite containing iron does not break down. However, since he was not able to synthesize anthophyllite from enstatite and quartz, iron-bearing anthophyllites may also only be metastable. This fact may be taken as evidence that iron-bearing anthophyllites are more stable than the magnesium end member.

2. Enstatite generally alters to talc rather than to anthophyllite.

3. Few pure Mg-anthophyllites are included in the collection of analyses presented by Rabbitt.

Unfortunately, all three points of evidence are subjectto other interpretations, so that a discussion of the stability relationships of the anthophyllite and the cummingtonite series, at the present state of our knowledge, must remain highly speculative, even qualitatively speaking.

It should be noted that the temperatures at which minnesotaite changes to cummingtonite and cummingtonite to hypersthene depends on the H_2O partial pressures in the rocks. In the presence of siderite the cummingtonite and minnesotaite at the temperature of the rection would not be in equilibrium with pure water but with a mixture H_2O and CO_2. Therefore since the partial pressure of water would be less than unity, the reactions would take place at lower temperatures. The reaction taking place at the decomposition of minnesotaite could be expressed as follows:

Minnesotaite + siderite → cummingtonite + carbon dioxide + water (1)

To what extent siderite takes part in this reaction depends on the CO_2/H_2O ratio in the volatile phase in equilibrium with siderite and minnesotaite. Consider Fig. 9a. This diagram assumes that over most siderite/cummingtonite ratios siderite will remain stable after the decomposition of cummingtonite, and the reaction can approximately be expressed as below with only a small amount of siderite taking part.

Minnesotaite → cummingtonite + water (2)

On the other hand, consider Fig. 9b. It assumes that the volatile phase in equilibrium with siderite and minnesotaite is very high in CO_2, so that siderite in the course of the reaction of minnesotaite to form cummingtonite will disappear or decrease greatly in amount. Then the reaction is

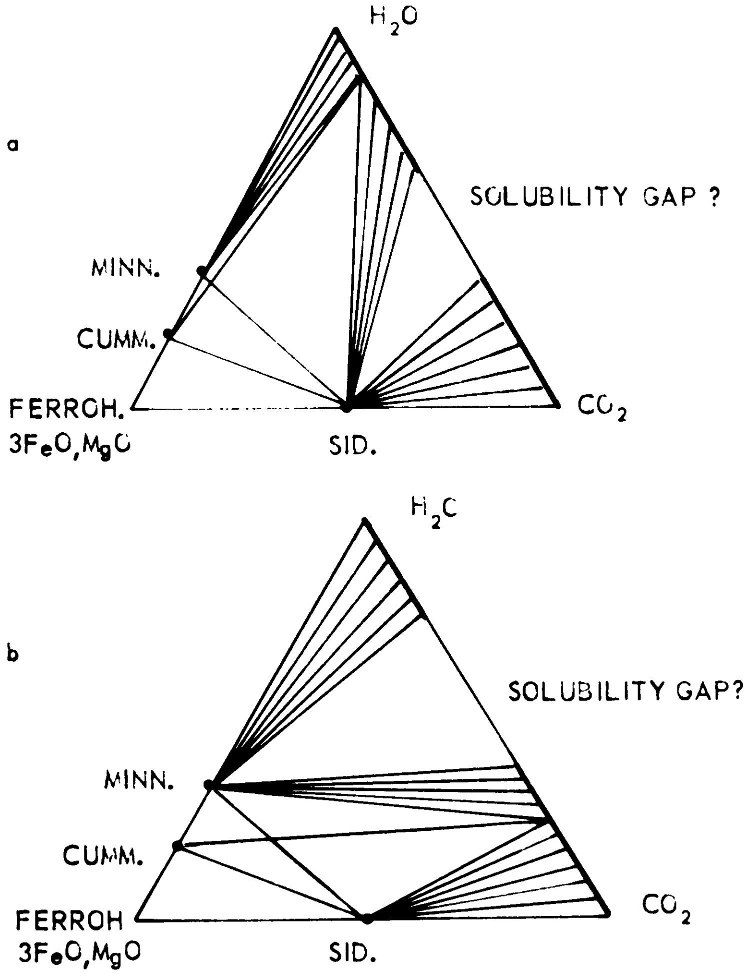


Fig. 9 Hypothetical phase diagrams showing alternative phase relationships in the system 3FeO, MgO-SiO_2-CO_2-H_2O at the point at which minnesotaite becomes unstable in the presence of siderite. The diagrams show phases in equilibrium with quartz.

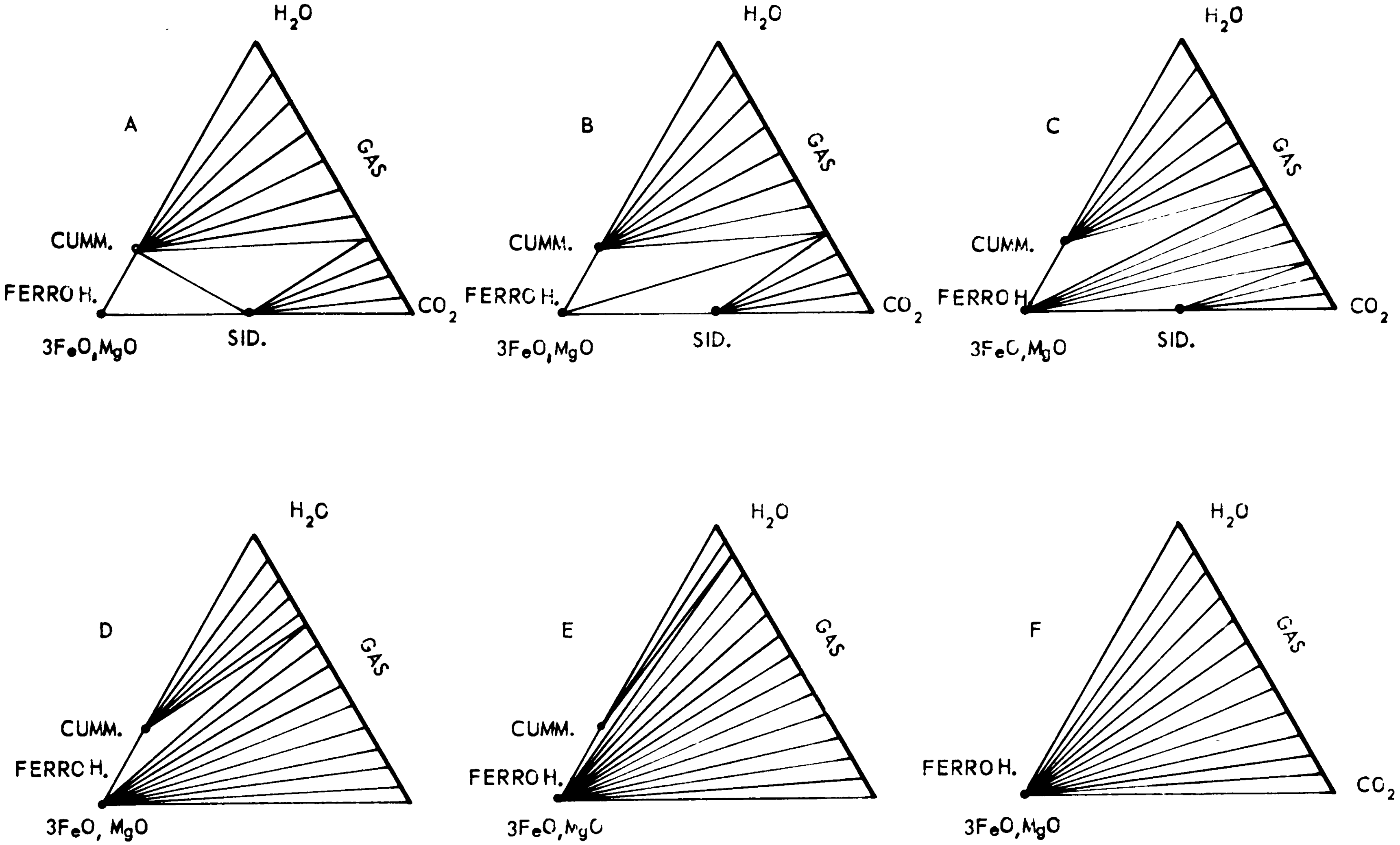


Fig. 10 Hypothetical phase diagrams showing how the system $(Fe,Mg)O-SiO_2-H_2O-CO_2$ may change in the temperature range within which siderite and cummingtonite become unstable. The diagrams show phases in equilibrium with quartz.

best expressed as in reaction 1.

A rock composed only of minnesotaite and quartz can be in equilibrium with varying H_2O partial pressures, so that its temperature of decomposition may vary from place to place in an environment where CO_2 gas is present.

Likewise the decomposition of cummingtonite to form hypersthene, for similar reasons, may take place at very much lower temperatures in the presence of siderite than in the presence of pure water. Here again the extent by which FeO is transferred from cummingtonite to hypersthene through the reaction of cummingtonite with siderite depends on the composition of the volatile phase in equilibrium with siderite and cummingtonite. The facts that the association cummingtonite-hypersthene-quartz is so common in the Mount Reed area and the association hypersthene-siderite-quartz is unknown to the writer indicate that for most bulk compositions cummingtonite does not become unstable through this reaction, i.e. the volatile phase is high in CO_2. The decomposition of siderite therefore can be expressed essentially as the reaction below with little minnesotaite taking part.

Siderite + quartz → hypersthene + carbon dioxide (3)

The probable changes in the stability relationships in the range of temperatures within which siderite and cummingtonite become unstable are shown in Fig. 10.

In the Mount Reed area cummingtonite is thought to have formed partly from minnesotaite as a product of normal progressive metamorphism, partly from hypersthene by reaction with water. To what extent the later reaction has taken place in the area is not quite clear. In some places, particularily at Jeannine Lake and at Hobdad Lake, cummingtonite occurs as large clusters and rosettes of needles. These mineral clusters may be of hydrothermal origin, having formed by addition of water or steam to the rock subsequent to the regional metamorphism and deformation. In the Black Dan area west of Mount Reed, cummingtonite alone is present in most thin sections and hand specimens studied. It is possible that in this area the iron formation has been altered by water diffusing in or being squeezed in from surrounding paragneisses with which the iron formation here is in direct contact.

CHAPTER 13

HYPERSTHENE

Ferrohypersthene is the most abundant ferro-magnesian mineral in the Mount Reed silicate iron formations. Hypersthene generally is thought to represent a high degree of regional metamorphism. However, it may also, as Yoder has pointed out, represent dry conditions. It is most common in norites and charnockites and other rocks metamorphosed in the granulite facies. Such rocks have been described from India, Uganda, Scandinavia, Canada and other places where deeply eroded shield areas are exposed. These rocks commonly are devoid over large areas of hydrous minerals like mica and amphibole, indicating that such minerals are not stable because of high temperatures and pressures.

In the Mount Reed area hypersthene occurs in iron formation which initially contained a large amount of carbonate and thus was characterized by a low water pressure to start with. The surrounding gneisses are muscovite-biotite gneisses and other rocks typical of migmatized areas metamorphosed in the amphibolite facies. The hypersthene probably formed from siderite and ferrodolomite and to a lesser extent from cummingtonite as was described in the previous chapter. It is conceivable that in iron-rich assemblages the temperatures were high enough to invert cummingtonite to hypersthene and steam, but this seems unlikely since cummingtonite appears to be stable over the same range of FeO/MgO ratios as the ferrohypersthenes.

It is possible that hypersthene did not form directly from carbonates, but that siderite first reacted with quartz to form fayalite, and then at higher temperatures fayalite reacted with quartz to form ferrohypersthene. The association fayalite-quartz is common in lower grade metamorphic rocks in Minnesota (Grout 1919) and also in the Swedish eulysites (von Eckermann 1924 p. 274). This assemblage is, of course, also in equilibrium with a melt at normal pressures. However, it is possible that either because of the fairly high magnesium content or because of higher pressures than was present in these areas hypersthene could form directly from carbonates in the Mount Reed area.

CHAPTER 14

DIOPSIDE-FERROAUGITE

We will now move to minerals which include the third major component in the Mount Reed iron formations, namely CaO. The most common calcium-bearing silicate in the area is the diopside-ferroaugite-hedenbergite series. All proportions between FeO and MgO are known in the series in igneous rocks. The calcium pyroxenes probably form a complete solid solution series with the acmite radical at most temperatures and pressures.

The highest iron content found in a ferroaugite in the Mount Reed area is 63 mole per cent of $FeCaSi_2O_6$. Only the sodium and manganese-bearing aegrine-hedenbergite of A-50 has a higher iron content. High iron hedenbergites also are rare in the literature, although Wulfing (1891) reports one containing 84 mole per cent $CaFeSi_2O_6$. In the Mount Reed area the assemblage, ferrohypersthene-calcite appears to take the place for ferroaugite in extreme iron-rich rocks.

The formation of ferroaugite represents a problem which the writer has not quite been able to solve. It almost certainly is formed by reaction between ferrodolomite and quartz.

The problem is that both calcite and hypersthene typically are present together with ferroaugite and one may ask why, at the time of dissociation of dolomite, the calcium in its entirety did not go into calcite and the ferromagnesian components into hypersthene. All three minerals could be expected to form at once from dolomite only within a limited range of FeO/MgO ratios; that is, within the four-component field at which the CO_2 pressure would be just right both for the dolomite at that composition to decompose and for calcite, hypersthene, and augite to coexist. Such a state would be represented by a line on a PT field which may or may not cross the geothermal gradient. However, as hypersthenes and ferroaugite of different compositions coexist with calcite, this cannot be the whole truth. It is conceivable that ferroaugite forms metastably at the time of the reaction and becomes stable only when some of the liberated CO_2 has left the system. It is also possible that two reactions take place. First, dolomite reacts with quartz as shown below.

$$(Fe,Mg)Ca(CO_3)_2 + 2SiO_2 \rightarrow (Fe,Mg)CaSi_2O_6 + 2CO_2$$

Later at higher temperatures ferroaugite becomes unstable in the presence of CO_2 and reacts with any CO_2 that has not left the system, forming calcite and hypersthene.

$$(Fe,Mg)CaSi_2O_6 + CO_2 \rightarrow (Fe,Mg)SiO_3 + CaCO_3 + SiO_2$$

However in any case there appears to be a change in the stable assemblage that forms from dolomite at high FeO/MgO ratios, since no ferroaugite or hedenbergite apparently has formed in the extreme iron-rich rocks and only hypersthene-calcite appears. It is possible that the nonexistance of hedenbergite has something to do with the instability of the compound $FeCa(CO_3)_2$. This compound never has been synthesised and never has been observed in nature (Goldsmith 1959). However, even if siderite and calcite were the parent minerals in this compositional range, hedenbergite should have formed at the time of the decomposition of siderite or later by reaction between ferrohypersthene and calcite if hedenbergite was stable.

It seems as if we have to conclude that hedenbergite and ferroaugite of high iron content are not stable at the temperatures and partial pressures of CO_2 present during the metamorphism. These facts support a phase relationship such as is shown in Fig. 11. The complicating factors of ankerite not being stable and the possible stability of fayalite-quartz have been ignored for sake of simplicity. If the diagram is qualitatively correct the assemblage ferroaugite - ferrohypersthene-calcite forms directly and reversibly within one compositional range, through two reactions or metastably in more magnesium-rich rocks.

The above ideas about the origin of the ferrohypersthene-hedenbergite-calcite assemblage are supported by thermochemical data. The PT curves calculated by Weeks (1956) for the reactions

$$MgCa(CO_3)_2 + 2SiO_2 \rightarrow MgCaSi_2O_3 + 2CO_2 \text{ and}$$

$$MgCa(CO_3)_2 + SiO_2 \rightarrow MgSiO_3 + CaCO_3 + CO_2$$

are very close together and cross each other at 440° and 1,300 atm. pressure of CO_2. Ferrodolomite presumably would decompose to calcite and hypersthene up to much higher temperatures and pressures. FeO favors hypersthene over diopside as shown by the fact that hypersthene has a higher FeO/MgO ratio than the coexisting diopside.

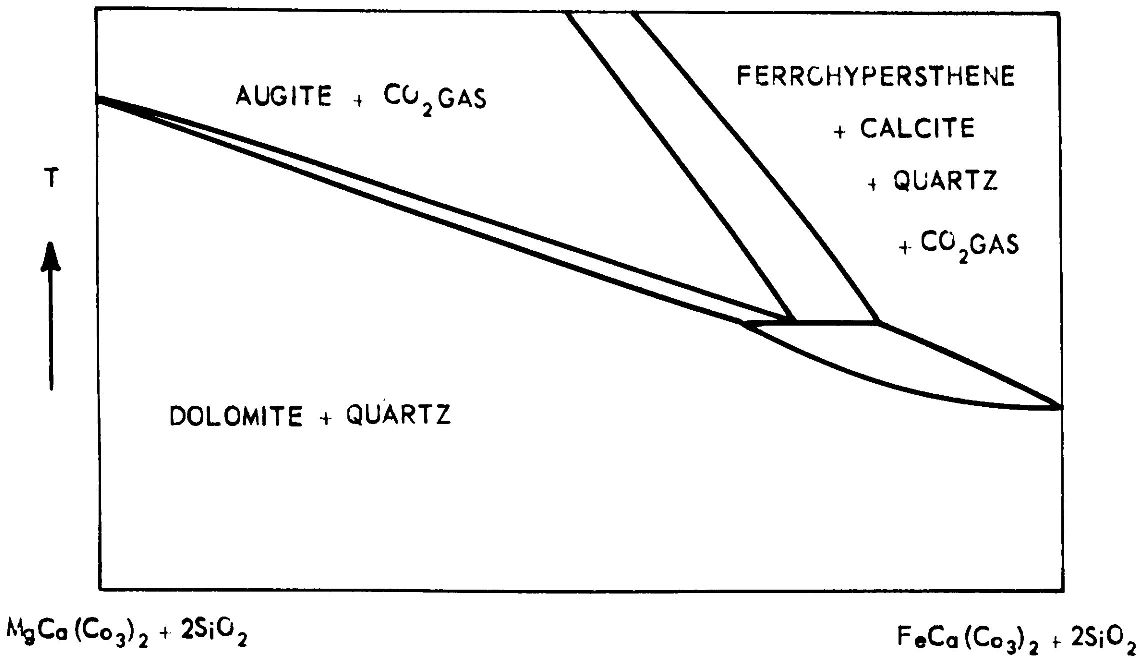


Fig. 11 Hypothetical phase diagram showing the phases that can be expected to form by the reaction of dolomite with quartz at different MgO/FeO ratios.

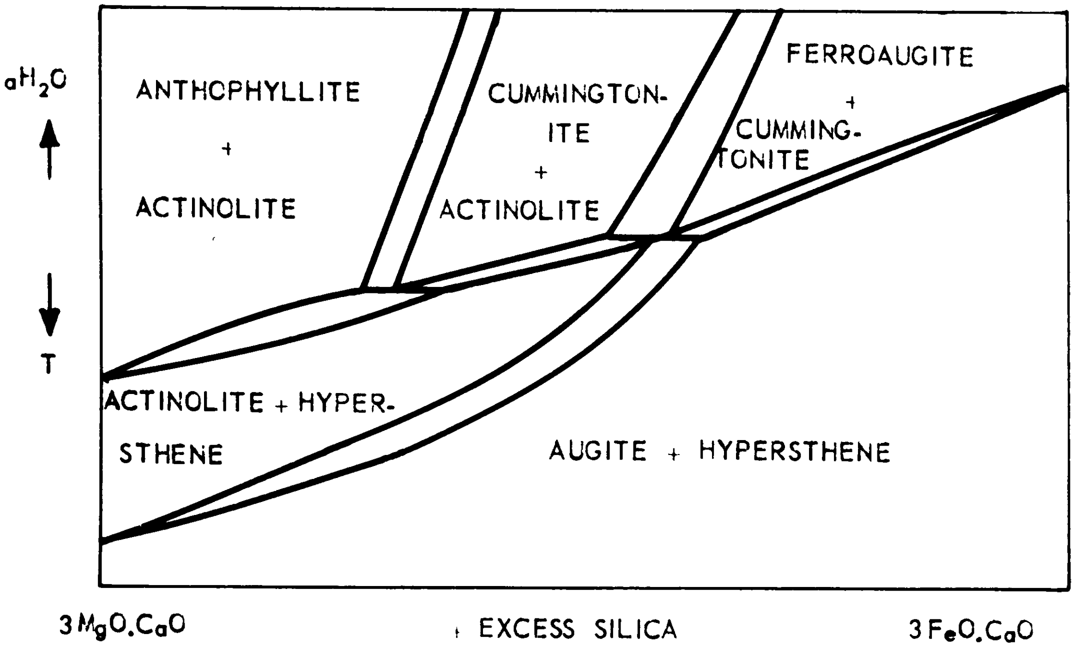


Fig. 12 Hypothetical phase diagram showing how the stability relationships in the system 3MgO, CaO-3FeO, CaO plus excess silica may change with the activity of water.

CHAPTER 15

ACTINOLITE

In the Mount Reed iron formations actinolite occurs principally in the oxide iron formations with or without diopside. Actinolite-diopside rock also is found as an alteration product of dolomite in the dolomite formation underlying the iron formation.

The stability relationships of the actinolite series is complicated by the fact that actinolite is just one end member of the complex hornblende group. The presence of such components as aluminum, ferric iron and sodium may have a large influence on the stability. Three of the four calcium amphiboles analysed contain a major amount of aluminum. It is not the purpose of the present paper to present a complete discussion of the stability of hornblende. It will only be discussed to the extent that it affects the mineral assemblages present in the MgO-FeO-CaO system. However, as an introduction, the following general observations on hornblende should be mentioned. High pressure appears to favor the inclusion of NaAl, the glaucophane molecule into the structure. High temperature favors aluminum particularily in the four coordinated positions (Harry, 1950); the presence of aluminum should stabilize ferrous amphiboles (Ramberg 1952).

The main problem that interests us in this discussion is how the Fe/Mg ratio affects the stability of the actinolite structure. As was mentioned earlier, iron-rich actinolite has not been observed in the Mount Reed area. Apparently, the assemblage cummingtonite-ferroaugite takes its place. Whether ferrous actinolite is stable at some lower temperatures is not quite clear. Ferrous actinolite analyses from the literature are rare. This fact may, however, be due to scarcity of rocks of suitable bulk composition for formation of ferro-actinolite rather than to complete instability of the structure. The association cummingtonite-actinolite is common in lower grade rocks suggesting that the actinolite field extends further to the iron side at lower temperatures. This assumption agrees with the general rule that the iron end members become unstable at lower temperatures than the magnesium-rich varieties. It is also interesting to note that, although the association cummingtonite-ferroaugite is very common, the association anthophyllite-diopside has never been reported. Thus, on the magnesium side the ferromagnesian amphibole dissociates before the calcic amphibole, whereas towards the iron side this relationship is reversed. The associations cummingtonite-actinolite-diopside and cummingtonite-anthophyllite-actinolite are also common, so that qualitatively we can deduce a phase diagram such as is shown in Fig. 12 and Fig. 15 for the amphibolite facies.

Fig. 15 is valid only for a certain temperature, pressure and activity of H_2O. Fig. 12 shown how the mineral assemblages may be affected by the activity of water. If one assumes a system open to water or a system with excess water, the activity is related to temperature, so that the diagram can be turned up side down and be used as a temperature-composition diagram.

The lower temperature boundary of actinolite is probably controlled by the dissociation temperature of dolomite-ankerite, since most actinolite occurs as an alteration product of carbonates. The point where the dissociation curve cuts the field boundary of actinolite-calcite should therefore represent the maximum amount of iron present in naturally occurring actinolite. Kunitz (1930) has reported a few very iron-rich actinolites, but the writer has been unable to find a description of their source. Conceivably ferro-actinolite may form during retrogressive metamorphism as an alteration product of hedenbergite. In any case we cannot at the present say that the ferro-actinolites are unstable as such, as the lack of such minerals in the field may reflect the lack of rocks of a suitable bulk composition for the formation of these minerals.

Iron-rich aluminous calcium-amphibole is more common. A plot compiled by Sundius (1946) of the aluminum content against the FeO/MgO ratio in common hornblendes shows that iron-rich hornblendes usually are high in aluminum. Ramberg (1952) has shown that because of the larger electronegativity of iron as compared with magnesium, it is easier for aluminum to substitute for silicon in high-iron amphiboles.

The low grade metamorphic iron formations of the Lake Superior district commonly contain a blue-green amphibole associated with cummingtonite (Richarz 1930, James 1956). The amphibole has been analysed by Richarz. The analysis is reproduced below together with those of three somewhat similar amphiboles also occurring in iron formation, the last one from Fire Lake. This amphibole, characterized by a high ferric iron content and a low alkali content, apparently is quite typical for iron formations, probably forming in beds containing shaly fractions.

Blue-green amphiboles from iron formation

S	Eastern Mesabi Reicharz 1930	Gillinge Palmgren 1916	Western Australia Miles 1943	Fire Lake
SiO_2	48.76	37.35	n.d.	47.2
Al_2O_3	11.15	12.75	n.d.	8.9
Fe_2O_3	7.92	7.18	8.7	6.0
FeO	21.72	18.73	25.0	9.3
MnO	trace	1.42	n.d.	0.15
MgO	0.38	4.94	n.d.	13.3
CaO	6.16	11.46	n.d.	11.6
Na_2O	1.67	0.96	0.1	1.0
K_2O	0.58	2.87	0.1	0.90
H_2O	1.89	1.22	n.d.	n.d.

CHAPTER 16

THE EFFECT OF MANGANESE, SODIUM, AND ALUMINUM

Manganese, sodium, and aluminum are the main components which may affect the stability relationships of the minerals in the iron formation outside of those already discussed. Aluminum is present in the upper part of the iron formation where it grades into the overlying gneisses, as garnet, aluminous hornblende and biotite. Manganese and sodium show a peculiar sympathetic relationship. Layers enriched in one usually are enriched in the other as well. The elements are abundant in rocks transitional between the oxide and the silicate facies.

Aluminum

Aluminum-bearing assemblages have not been extensively studied in this work partly in order to avoid more complicating factors and partly because of the difficulties encountered in analysing iron-rich minerals for aluminum by rapid silicate analysis methods. The only garnet analysed was from specimen A-12, a diopside-hypersthene-hornblende-garnet skarn from north of Blough Lake. It is an almandite-pyrope with a surprisingly high magnesium content. The rock is from a suite of peculiar mafic rocks occurring commonly in a stratigraphic horizon immediately on top of the iron formation north of Blough Lake. The rocks have from somewhat superficial evidence been classed as meta-eclogite and are described with the other mafic igneous rocks of the area in Chapter 7. The only other aluminous rock, whose mineralogy has been studied in detail, is the peculiar olivine-hypersthene-chlorite-spinel-cordierite rock from Hobdad Lake (page 119). The association hypersthene-chlorite is interesting as it shows that chlorite, generally thought of as an hydrothermal mineral, can exist at a lower water-pressure than anthophyllite. This assemblage and the earlier mentioned garnet-bearing rock seems to delimit the Mg/Fe ratios of hypersthene coexisting with garnet and cordierite, respectively, fairly closely. As was mentioned earlier, the high magnesium content of the garnet is surprising and may indicate a high pressure at the time of the regional metamorphism in the area.

The garnet which occurs locally in the silicate iron formation presumably is common alamandite. More work is needed to establish tie lines between ferroaugite, hypersthene and almandite.

Manganese

The study of the manganese content of the ferro-magnesian minerals was of special interest since it was expected to show whether manganese possibly could have an effect on the mineral assemblages present. Many cummingtonites analysed from the so called eulysites in Sweden, which probably represent meta-iron formations similar to the ones here studied, have a high manganese content. A separate name dannemorite has been applied to these manganese-rich cummingtonites. Therefore, it seemed possible that the cummingtonite content possibly might be dependent on the manganese content. The present study has shown, however, that manganese distributes itself between the different ferromagnesian amphiboles and pyroxenes roughly in the same proportions as iron. The table below illustrates this fact. The relationship does not hold for the magnesium-rich mineral assemblages.

Mn/Fe x 100 in the silicates of the iron formation

	Ferrohypersthene	Ferroaugite	Cummingtonite
B1-3	1.14	1.12	
B1-6	3.06	3.12	
B1-21	0.38	0.33	
A50	7.50	9.18	
B-9		2.00	1.68
B-18		0.85	0.71
H-3		16.9	16.9
H-4	1.28	1.25	
H-7	3.79	3.63	3.62
H-9	4.14	3.71	3.53

It is noteworthy that all the mineral assemblages analysed which show a high manganese content also are high in magnetite. Again the acmite-rhodonite assemblage from Mount Reed is associated with specularite. This shows that manganese is precipitated mainly in the oxide facies of the iron formation. No work has been done on the chemical composition of the opaque minerals so it is not known how much manganese is taken up by them. The acmite-rhodonite association is interesting in that it gives the maximum amount of manganese that can be taken up by acmite at the PT conditions represented. This is a potential geo-thermometer.

The reason for the fact that manganese-rich layers of the iron formation generally also are rich in sodium is not very well understood. It probably has something to do with the fact that the precipitation of both manganese and sodium are favored by an oxidizing environment. Sodium would need ferric iron to be included in the structure of pyroxene.

Sodium

Sodium-iron silicates are common in the Mount Reed-Blough Lake area. Pure acmite is present in a narrow zone at Mount Reed. Aegrine-augite associated with ferro-hypersthene cummingtonite and magnetite has been found in the Blough Lake tail. Arfvedsonite associated with hypersthene magnetite is common in the iron formation zone between Silicates Lake and Athol Lake.

The analyses made of sodium-iron silicates in the area are too meager to make it possible to state anything definite about the Na_2O-FeO-MgO system, but it is likely that this system with an excess of ferric iron behaves very much the same way as the corresponding BaO-MgO-FeO system. At the iron end of the system the association cummingtonite-acmite seems to form preferably. In more magnesium-rich rocks arfvedsonite and magnesio-ribeckite are stable together with hypersthene, in the same way as actinolite in the corresponding CaO system.

In contrast to calcium, sodium probably is derived directly from silicates. Acmite is known to be precipitated out directly (Milton and Eugster 1959) and very likely is stable at least in a dry environment under all metamorphic conditions.

CHAPTER 17

METAMORPHISM OF THE ARGILLACEOUS ROCKS

The mineralogy of the gneisses has not been studied in detail by the writer. For the sake of completeness the main mineral assemblages observed in thin sections from the gneissic rocks will be listed.

1. The association quartz-muscovite-biotite-garnet is characteristic for much of the quartz-mica-schists associated with the specularite iron formation.
2. Muscovite-biotite-orthoclase (-plagioclse-quartz) is the most common association in the lower gneisses.
3. In one thin section a few grains of hypersthene and hornblende are present in biotite-microcline-plagioclase-quartz-gneiss.
4. The association plagioclase-quartz-garnet-biotite-kyanite is present in one thin section of gneiss from the northern area.

The association of garnet with microcline and muscovite on one hand and the association of biotite and kyanite on the other shows that FeO and MgO have to regarded as separate components. Probably biotite is higher in magnesium, almandite in iron.

CHAPTER 18

THE ROLE OF THE VOLATILE COMPONENTS IN METAMORPHISM

The problem about the role played by the volatiles in metamorphism has been much discussed in recent geological literature. The subject is still very controversial.

The classical view has been that water generally is present in excess so that it can be ignored as a factor determining the stability fields of different minerals. (Turner and Verhoogen 1951). This view was challenged by Yoder in 1952. He shows that many variations in the mineral composition of metamorphic rocks which generally are attributed to changes in metamorphic grade can just as well be caused by a variation in the water content in the rocks (Yoder 1952, 1955). Thompson (1955) and later Fyfe, Turner and Verhoogen (1958) maintain that petrological evidence does not support Yoder's assumption that rocks are closed to water. Rather, water seems to be able to move fairly freely within the rock, so that the partial pressure of water at each point in the rock is determined by such external factors as the permeability of the rock towards diffusing material, the amount of water in surrounding areas, temperature and pressure gradients and so on.

Both in the case of the closed system concept and in the case of the classical view that the system contains an excess of water, water can be disregarded as a component in applying Gibb's phase rule since the partial pressure of water is independent of the bulk composition. If the system is open to this component the partial pressure of water has to be dealt with as a degree of freedom in the same way as temperature and pressure. Thus, for a certain isograd defined by a reaction involving water, not only temperature and pressure have to be taken into account but also the partial pressure of water. If the system has an excess of water, the partial pressure of this component always is close to unity provided no other volatile components are present. In any case, water does not have to be included in a graphical representation of such a system if it is assumed that all the phases shown are in equilibrium with the volatile phase. On the other hand, if the system is closed and there may or may not be free water present, the mineral composition depends on the amount of water present in the system, and water cannot be neglected in a graphical representation. The partial pressure in such a system is fixed by the minerals which are in equilibrium at such a bulk composition. The partial pressure in such a system changes abruptly at points in the rock where changes in bulk composition produce changes in mineral composition.

In the following chapter we shall see which of the three concepts best agree with the mineral assemblages in the Mount Reed area.

CHAPTER 19

THE ROLE OF VOLATILES IN THE MOUNT REED IRON FORMATIONS

Gibbs' phase rule states that

$$\text{Variance} = n + 2 - \phi$$

The variance of a system equals the number of independently variable components less the number of phases plus two. By variance is meant the number of intensive variables which can be altered independently without bringing about the disappearance of a phase or the formation of a new one.

If there are five phases present, let us say cummingtonite, ferroaugite, ferrohypersthene, quartz, and calcite composed of six components, FeO, MgO, CaO, SiO_2, CO_2 and H_2O, the variance is 6 + 2 - 5 = 3. Therefore, in order to define the state of the system, we would have to define the temperature, pressure as well as the activity of one component. Now, because of the extensive solid solution between MgO and FeO in ferromagnesian minerals these components in most cases are not independently variable. In such cases the variance is reduced to two, that is the number of components is what would be expected in a rock closed to all phases including the volatile components. The possibility exists, however, that the FeO/MgO ratio of the minerals should be relatively constant within a given area since the activity should not vary over a too great a range if diffusion has been effective.

The mineral assemblages in a rock where the activity gradients of one component have been evened out as a result of diffusion can be represented graphically without considering the mobile component as a component. Thus, we can plot a phase diagram representing a section of the FeO-MgO-CaO-SiO_2-CO_2 system and assume that the diagram is valid for a certain temperature, pressure and activity of H_2O. Alternatively one can assume that the system is open to CO_2 and plot a diagram representing a section of the FeO-MgO-CaO-SiO_2-H_2O system with the activity of CO_2 fixed. Sections of such diagrams are shown on page 89-90 (Fig. 14 and 15) together with a section of the FeO-MgO-CaO-CO_2 system with the activity of O_2 fixed. The possibility of the system being open to H_2O, CO_2 and O_2 will be discussed with the help of these diagrams.

The relationship shown in Fig. 13 definitely is not favored by field evidence. Magnetite is not common in association with the iron-rich silicates, ferrohypersthene and cummingtonite. The silicates associated with quartz-magnetite iron formation are such magnesium-rich minerals as actinolite and diopside and also manganese-rich hypersthene and cummingtonite. The limited mobility of oxygen during the regional metamorphism also is illustrated by the association magnetite-specularite in the oxide iron formations and by the presence of graphite in some of the magnetite-free calcite-bearing

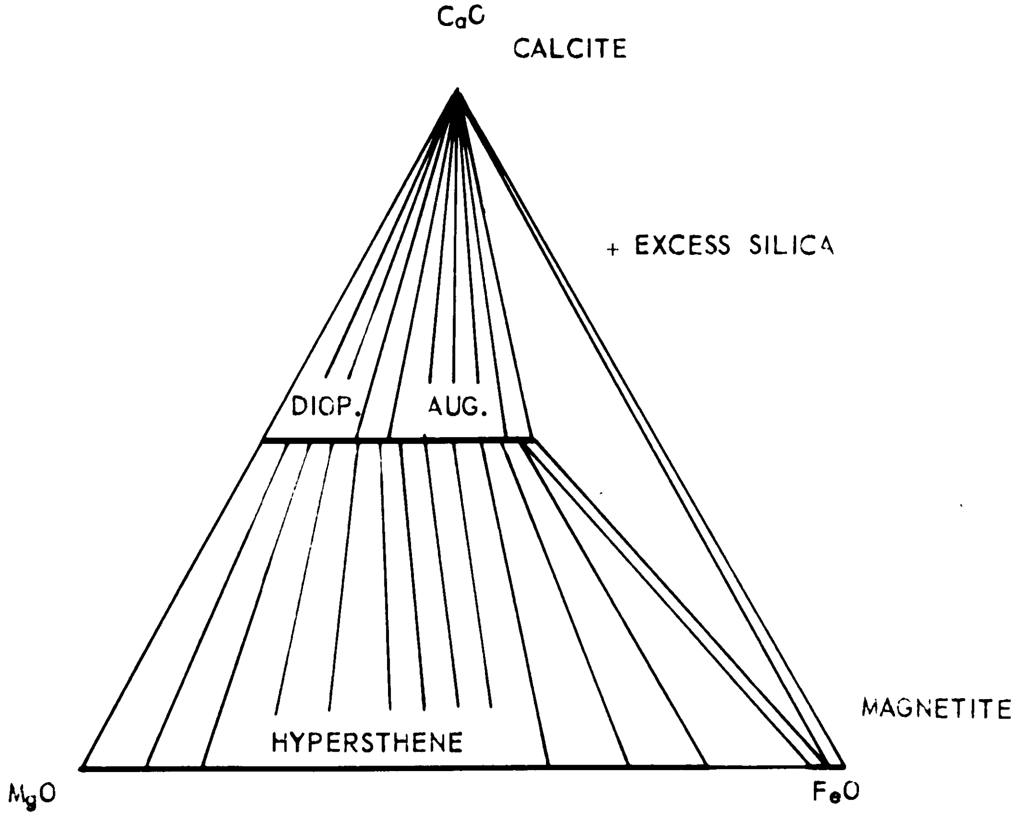


Fig. 13 Hypothetical phase diagram showing a section of the system FeO-MgO-CaO- CO_2-SiO_2 for a fixed temperature, pressure, and activity of oxygen. The diagram shows phases in equilibrium with quartz.

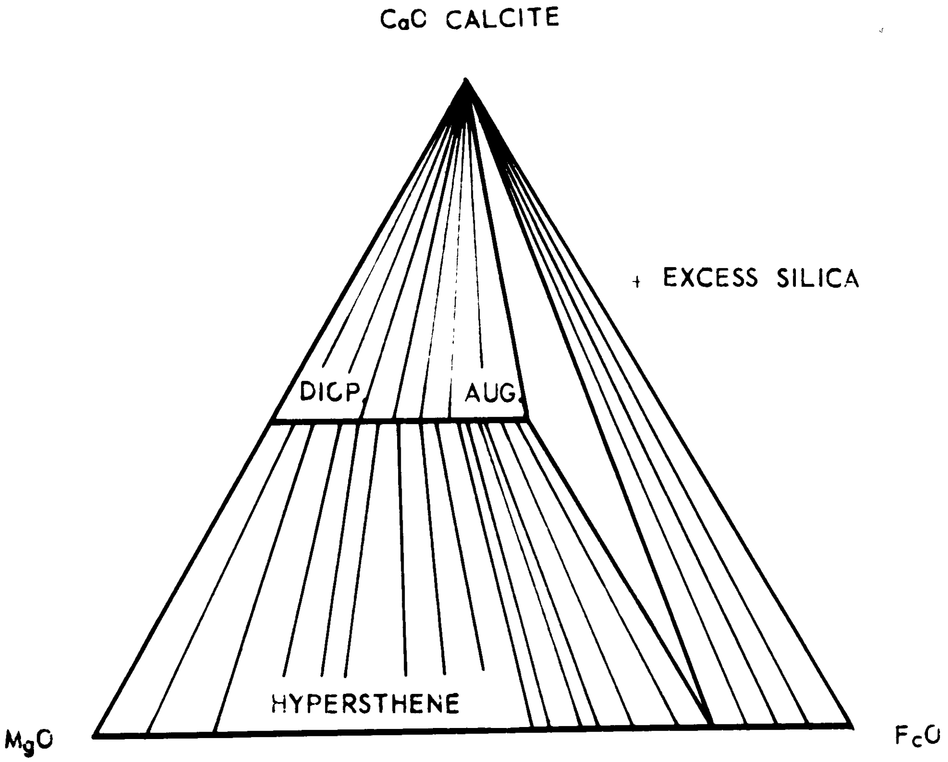


Fig. 14 Hypothetical phase diagram showing a section of the system FeO-MgO-CaO-SiO_2 for a fixed temperature, pressure, and activity of CO_2. The diagram shows phases in equilibrium with quartz. The diagram also shows the assumed stability relationships of the system above the temperature of decomposition of the dolomite series.

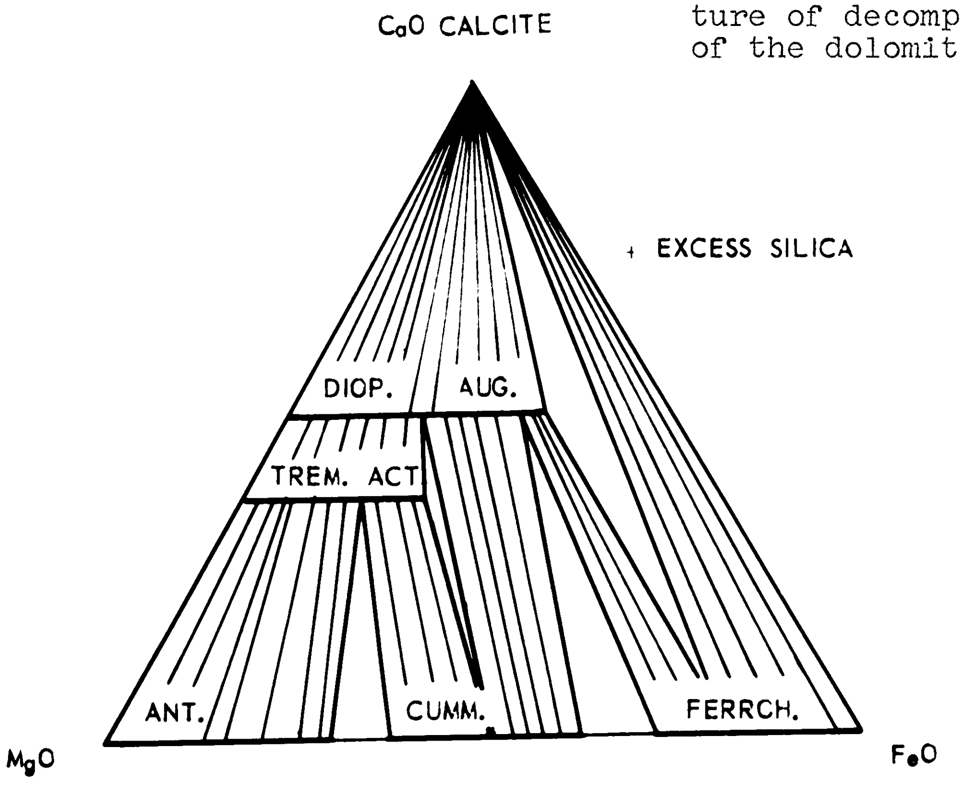


Fig. 15 Hypothetical phase diagram showing a section of the system FeO-MgO-CaO-CO_2-SiO_2 for a fixed temperature, pressure, and activity of H_2O. The diagram shows phases in equilibrium with quartz.

silicate iron formations.

If the system was open to H_2O the composition of cummingtonite should fall within one range of MgO/FeO ratios, the composition of hypersthene within an other, and the hypersthene and cummingtonite should coexist only within a limited range of compositions as shown in Fig. 15.

The two analysed pairs of hypersthene and cummingtonite from Hobdad Lake, H-7 and H-9 show small but significant differences of composition. The samples were taken about 20 feet apart. The analysed hypersthene-ferroaugite assemblage H-4 from the same locality, a specimen without cummingtonite, has a slightly higher iron content and the cummingtonite-ferroaugite assemblage, and a specimen without hypersthene taken about 100 feet away, has a lower magnesium content. All these four mineral assemblages could have been in equilibrium at about the same partial pressure of water in accordance with Fig. 15.

In the southern area there is a definite water pressure gradient between the Athol Lake area and the Blough Lake tail. The hypersthenes in the specimens from Blough Lake, which do not contain cummingtonite, have a lower iron content (mostly about 36 weight per cent) than the two hypersthenes analysed for iron in the Athol Lake area which are associated with cummingtonite. The fact that several other analysed hypersthenes not associated with ferroaugite also contain about 40 per cent FeO indicates that hypersthene coexisting with cummingtonite commonly contains about 40 per cent FeO, not because this is the only composition at which hypersthene and cummingtonite are stable together because of an externally controlled water pressure, but because the bulk composition of the silicate iron formation favors a hypersthene of this composition.

In this connection it should be noted that in the case of multivariant mineral assemblages which include one or more phases capable of extensive substitution of one component for an other, it is very difficult to prove that the rock has been completely closed. In such an assemblage the partial pressure and the bulk composition are variable, so it may be difficult to say whether the bulk composition or an externally controlled water pressure determined the mineral compositions. Also the fact that the assemblages appear to be related to the bulk composition does not preclude diffusion in and out of the system provided the activity gradients driving the diffusion are of local nature. Such activity gradients are influenced by the bulk compositions of the rocks in the immediate neighbourhood and therefore probably are not much different from the partial pressure of the system as determined by the bulk composition any way.

However, we can say with reasonable certainty that long distance diffusion such as would be driven by regional temperature and pressure gradients, the gravity field, etc. has not taken place. In such a case the odds against the partial pressure of water happening to fall within the range in which cummingtonite and hypersthene are stable together would be much larger. Also, it would seem peculiar that the partial pressure of water in the Hobdad Lake area and the Athol Lake area would be quite similar as shown by the similar compositions of the coexisting hypersthene and cummingtonite, whereas the Blough Lake area only 5 miles from Athol Lake would show a quite different partial pressure of water.

The case of CO_2 can be studied in the same way. At a fixed CO_2 pressure coexisting ferroaugite, hypersthene, and calcite should have the same composition in accordance with Fig. 14. Hypersthenes higher in iron should coexist only with calcite and those lower in iron should coexist only with ferroaugite. The clustering of hypersthenes with 36 per cent FeO coexisting with ferroaugite and calcite in the Blough Lake area, and hypersthenes with 40 per cent FeO in the Hobdad Lake area at first hand could be taken as evidence for a system open to CO_2. In order to test this idea hypersthenes from a number of rocks free of ferroaugite were analysed and they all show a higher iron content. However, no specimens have been found which are free of calcite. The hypersthene in Bl-3 containing only 31 per cent FeO coexists with calcite as well as ferroaugite. The large difference in composition between such mineral assemblages as Bl-3 and Bl-6 shows that significant CO_2 activity gradients can exist within such a short distance as 200 feet, the distance between the points from which these specimens were taken. The complete absence of calcite-free assemblages and the great variation in the composition of hypersthenes in equilibrium with ferroaugite and calcite in the Blough Lake area again seems to show that the mineral composition mainly depends on the bulk composition. However, again we are unable to prove that the system has been completely tight.

However, in the above discussion it has been assumed that CO_2 and H_2O may act as independently variable components. It should be pointed out that if a gas phase is present the partial pressure of CO_2 will increase with a decrease of the partial pressure of H_2O provided, of course, that the total pressure of the gas phase is fixed. In such a case if the system is closed to one volatile component, it must be closed to the other as well. In discussing the formation of the ferrohypersthene-ferroaugite calcite assemblage (page 71), it was concluded that ferroaugite reacted with CO_2 gas to form ferrohypersthene and calcite. If this interpretation is correct, a gas phase must have been present at one time together with ferrohypersthene, ferroaugite, and in some cases cummingtonite. The Co_2/H_2O ratio of this volatile phase was fixed in the presence of cummingtonite for each MgO/FeO ratio. Since the variance of the system would not allow the pressure of the volatile phase to vary independently of the lithostatic pressure, the pressure on the volatile phase presumably equaled the pressure on the solid phases. Thus this line of argument favors a system closed to both volatile components.

Summing up the above discussion, we can say that the rock in most places has been closed either to CO_2 or H_2O because of the low variance of the assemblage ferrohypersthene-ferroaugite-cummingtonite-calcite-quartz. If the system was open to one component, material did not diffuse over long distances. Possibly the system was open to water in some places, to CO_2 in some places, to both in other places, and maybe to other components as well in some places, all depending on whether the local activity gradients happened to be steep enough to drive the diffusion. Reaction rims are examples of rocks open to other components than the volatiles. To sum up, there is no evidence that the volatile components acted in any way differently from other components during the metamorphic reactions. The fact that a volatile phase apparently was present at the formation of the present mineral assemblages is difficult to reconcile with an assumption that the rock was open to any component.

The inefficiency of long distance diffusion raises the problem of the fate of the volatiles released in the course of the reactions taking place during progressive metamorphism.

CHAPTER 20

THE METHOD OF ESCAPE OF VOLATILES DURING METAM METAMORPHIC REACTIONS

One of the most powerful arguments that has been put forward in support of open systems is the fact that water and carbon dioxide apparently have been able to escape during the reactions accompanying progressive metamorphism. Yoder (1955) discusses the problem and mentions the alternatives that water may stay on in the rock or diffuse away. The second alternative is not valid for closed systems. If diffusion is fast enough to remove water or carbon dioxide as it is liberated,there is no reason why the diffusion could not start already at a lower temperature since the necessary activity gradients are just as real below the reaction temperatures as above it. This is, of course, the same as an open system.

If the speed of diffusion is too slow to remove the liberated gas phase from the system, it will start accumulating as a new phase. As soon as this happens over a certain area, any new gas added will not change the partial pressure of the volatile component, no partial pressure gradient can be built up, and the diffusion will come to a halt. If the reaction continues, the pressure is built up and the reaction must stop. The only way for the reaction to continue is to increase the volume of the rock or to increase the temperature so that the reaction will continue at the new pressure. However, since temperature and pressure are externally controlled, it is unlikely that the increase in pressure and temperature will follow the univariant reaction curve. The only alternative seems to be that the water finds open pores into which to flow. If the recrystallization is accompanied by tectonic deformation, the regional stress might give energy for such an expansion of the rock. It is questionable whether the observation is valid that we do not find evidence for expansion in metamorphic rocks. On the contrary, the complicated structures found in high grade metamorphic rocks might be a result of increased plasticity due to the presence of water in the rock. Any textural evidence would tend to be obliterated in the course of retrograde metamorphism.

During the deformation, the water vapour and carbon dioxide gas could be squeezed around in the rock and migrate upward towards areas of lower pressure, propelled by mechanical pressure gradients in the same way as a wet sponge is squeezed dry. As the gas phase moved through the rock, it would have reacted with the wall rock in places where the wall rock was not in equilibrium with such a fluid phase. This would be a hydrothermal solution in the classical sense.

In the case of the silicate iron formations there would in most places not be a room problem for water, since in the course of dehydration of the minerals the water would react with the carbonates. The above discussion would apply mainly to carbon dioxide which must have been removed from the rock in large amounts.

Like diffusion, moving gases and solutions also, of course, would tend to even out activity gradients by reaction with rocks they are not in equilibrium with. It is likely, however, that such reactions would be sporadic and incomplete and leave rocks essentially closed in places where solutions and gases did not penetrate.

CHAPTER 21

ORIGIN OF THE IRON FORMATION

Let us now summarize the processes that led to the formation of the Mount Reed iron formations. First we should note what evidence we have about the nature of the iron formations in their unmetamorphosed state.

The geochemistry of sedimentary iron formations has been discussed by Huber and Garrells (1953), by James (1954) and others and will not be presented in detail in this paper. James differentiates between four main facies of iron formation, namely, oxide iron formation, carbonate iron formation, silicate iron formation and sulphide iron formation. Each type is regarded as a primary chemical precipitate. The old view held by Van Hise, Leith (1911) and others, that siderite is the only primary iron mineral, now is only of historical interest. Huber and Garrells have shown that each type of iron formation is precipitated within a certain range of oxidation potential and acidity of water. In sea water the acidity is relatively constant, so that it is mainly the oxidation potential that has controlled the type of sediments precipitated at a given place at a given time. Oxide iron formations presumably are precipitated under shallow water conditions where excess oxygen is present, carbonate iron formations in deeper waters, and sulphide iron formation, mainly in the presence of organic matter, in stagnant basins where the water circulation is slow. The silicate iron formations presumably form in about the same environment as the carbonate iron formation where the carbon dioxide content is too low for siderite to precipitate. Fayalite and greenalite probably are the only primary iron silicates, since they are the only ones that are stable in the presence of water (Yoder 1957).

The iron oxides earlier were regarded as replacement products of siderite. The primary nature of ferric oxide now is generally accepted. The role of magnetite is not as clear. Hematite is known to occur interbedded with siderite (Gruner 1946), so it appears as if it would not be stable at high CO_2 pressures under surface conditions. James suggests that its apparent occurrence as a primary mineral may be interpreted to indicate both low O_2 and low CO_2 atmospheric pressures at the time of its deposition. (James 1954)

Homatite is a major constituent in jaspilite, a common rock type both in the Lake Superior district and in Labrador. The rock types consist of interlayered chert and finely crystalline homatite. Magnetite banded facies also are common. In the Labrador trough the magnetite-bearing facies has been called cherty metallic iron formation (Perrault 1955). It consists of fine metallic oxides, chiefly magnetite, disseminated in a cherty groundmass and also segregated into metallic bands. Minnesotaite, stilpnomelane and siderite commonly are mixed in with the chert and magnetite.

There is hardly any reason to doubt that the specularite iron formation and the magnetite iron formation of the Mount Reed area are direct metamorphic equivalents of the Jaspilite and the cherty metallic iron formation respectively of the Knob Lake area.

The origin of the silicate iron formation is a more difficult problem. Cummingtonite and hypersthene could form both by metamorphism of primary iron silicates and by reaction between quartz and siderite. Both siderite and the silicates greenalite and minnesotaite are common in the Knob Lake area.

Minnesotaite is the main constituent of the so-called minnesotaite iron formation. This rock consists of bands of minnesotaite in the form of radiating aggregates of needles and felted masses interlayered with chert. Greenalite is found as granules within the minnesotaite iron formation and also in the metallic iron formations. It commonly is intermixed with minnesotaite, greenalite being concentrated in certain layers and minnesotaite in others. From field evidence, Perrault concludes that some of the minnesotaite definitely is an alteration product of greenalite but that some may be primary. In some places minnesotaite replaces siderite, indicating that siderite starts breaking down in the presence of water already at this stage of the metamorphism.

Siderite is the main constituent in cherty carbonate iron formation in the Knob Lake area. In this rock type it is mixed in all proportions with chert. It is also found as granules and nodules in the cherty metallic iron formation and in the minnesotaite iron formation.

Ferrodolomite is present in places within the cherty carbonate, apparently secondary after siderite. It also has been found as fine laminae within cherty metallic iron formation. Generally, ferrodolomite does not appear to be as common in the Knob Lake area as it probably was in the Mount Reed iron formation before the metamorphism.

CHAPTER 22

THE METAMORPHIC HISTORY OF THE IRON FORMATION

Unfortunately the information needed to completely reconstruct the metamorphic history of the iron formations is not available. However, from information obtained in the Mount Reed area and from information available in the literature, we can at least suggest a possible model of the phase equilibrium changes in the course of the metamorphism. The sequence of events leading up to the present state of the iron formation can best be represented by a series of phase diagrams. Most minerals in the silicate iron formation are phases in the system $CaO-FmO-SiO_2-CO_2-H_2O$. By assuming an excess of quartz in all assemblages, SiO_2 can be ignored in the graphical representation. The component FmO can be defined as FeO + MgO in the ratio they most commonly occur in the Mount Reed area, let us say 3 to 1. For other FeO/MgO ratios the reactions take place at different temperatures, usually the higher FeO/MgO ratio the lower the temperature of the reaction. Also in magnesium-rich rocks the sequence of events probably will be different as was demonstrated in Chapter 15. In extremely iron-rich, magnesium-poor rocks the sequence of events may also be somewhat different because of the possibilities of fayalite+quartz+being stable (page 69), and high-iron hedenbergite unstable (page 72).

The solubility relationships between CO_2 and H_2O are not very well known (Ellis 1959) and have not been shown on the diagrams. Above the critical point of water these components presumably are completely miscible.

Fig. 16a represents the assumed stability relationships at surface temperatures and pressures.

The primary minerals are assumed to be greenalite, calcite, ferrodolomite and siderite. Greenalite also is assumed to be able to form as a reaction product of siderite and quartz in the presence of water. Ferroactinolite could only form from waters with a very low CO_2 pressure and a high CaO content, probably non-existant in nature. Ferrodolomite may not actually form as a primary mineral but only by ordering or reaction of a mixture of calcite and siderite in the zone of diagenesis analogous with dolomite. Beside each diagram are listed the mineral assemblages which would be expected to form through progressive metamorphism and partial or complete removal of the volatile phases through squeezing or diffusion. As was shown in Chapter 19 it appears likely that the assemblages mostly are in equilibrium with a volatile phase.

It should be pointed out in this connection that the tie lines among low temperature minerals, low in H_2O and CO_2, are purely hypothetical. These bulk compositions are rare in low temperature metamorphic rocks and where they do exist, the mineral assemblages very likely are metastable.

Reactions 1 and 2 are assumed to take place to explain the common coexistence of greenalite and minnesotaite. The minnesotaite in this association hardly could have formed from greenalite since greenalite still is stable. It is also unlikely that it formed by reaction between water and siderite since both greenalite and minnesotaite should not be stable in the presence of excess water at the same time, unless possibly the higher ferric content common in greenalites influences the stability relationships.

Reactions 4 and 5 may take place at nearly the same temperatures in accordance with the experimental results obtained by Flaschen and Osborn (1957). Reactions 4 and 5 were discussed in Chapter 12.

Reaction 6 must take place at a higher temperature than reaction 5 because grunerite and siderite are commonly present in the same rocks (James 1956, Murphy 1959). The diagrams of Figs. 16f and g may be representative of the Mount Wright area where Gross (1955) found ferrohypersthene-ferrodolomite-cummingtonite-quartz to be a common mineral assemblage.

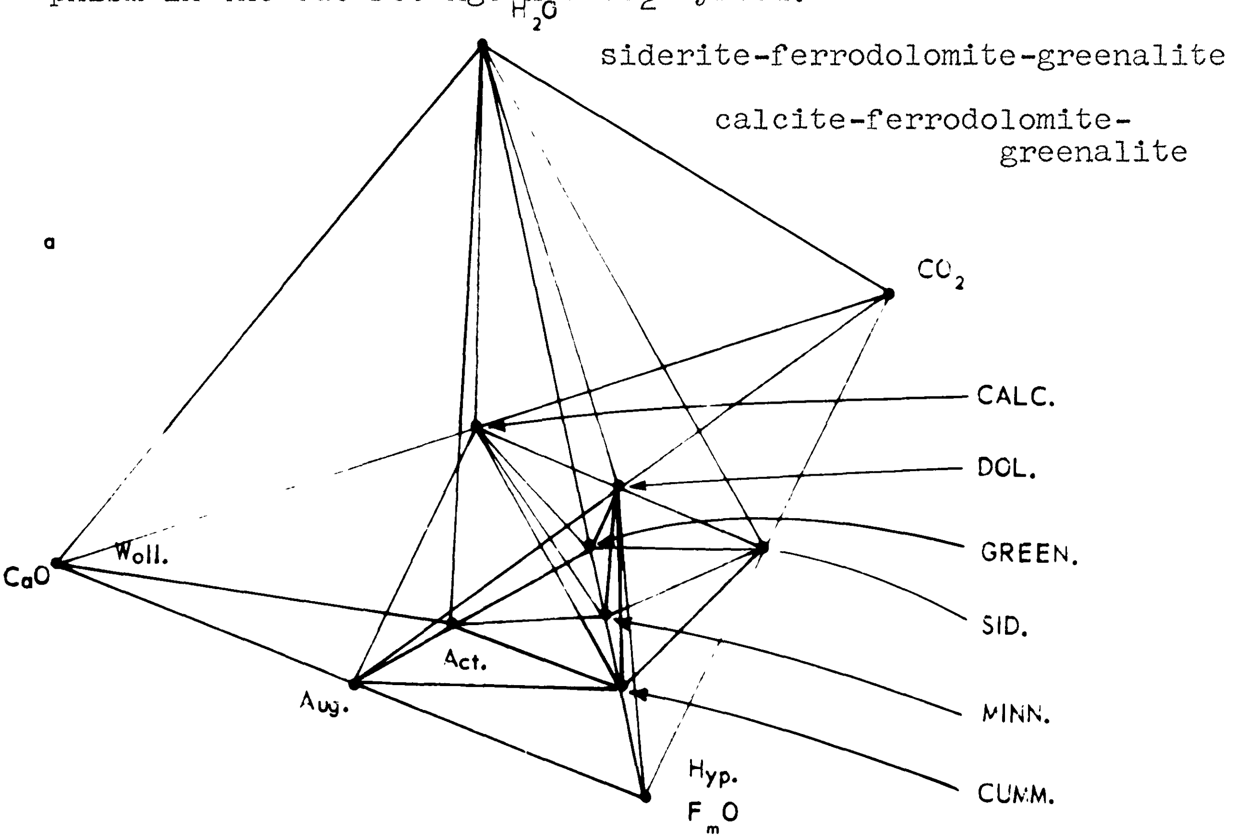
The decomposition of ferroactinolite does not affect the common mineral assemblages in the iron formation. The position of reaction 7 in the sequence is purely arbitrary. Ferrodolomite apparently does not alter to ferroactinolite in the same way as dolomite alters to tremolite. It may alter to calcite-cummingtonite, although in this interpretation ferrodolomite is assumed to be stable in the presence of quartz and water until it decomposes to form Ferroaugite and CO_2 gas.

The association grunerite-calcite-quartz has been reported both from the Lake Superior area (Richarz 1927) and from Labrador (Mueller 1958).

Reactions 8 and 9 have been discussed in Chapter 14, and 10 and 11 can be assumed to take place under high temperatures and pressures characteristic for the granulite facies.

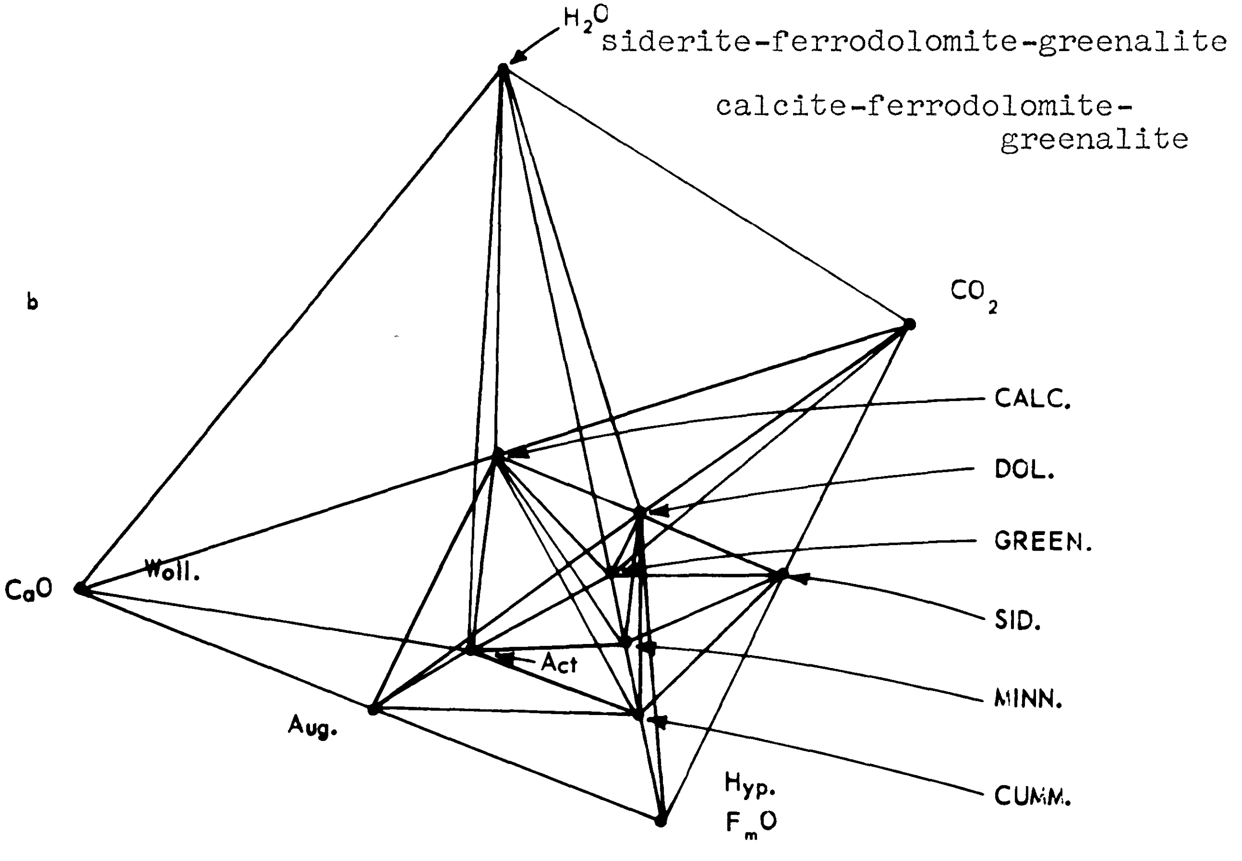
It should be emphasized again that the above sequence of reactions are highly hypothetical. No doubt other phase diagrams could be drawn which would fit available evidence just as well. At the present time it is very frustrating to try to deduce stability relationships from the literature because of the habit of geologists to report the minerals occurring in a rock sequence without specifying the exact mineral assemblages in individual specimens. In the above summary the writer has tried to illustrate how useful it would be to know more about the stable mineral assemblages in studying the metamorphic grade of rocks. It is hoped that the discussion will encourage other geologists to present data which will make it possible to construct a sequence of similar diagrams based more on facts and less on guesswork.

Fig. 16 Hypothetical phase diagrams showing possible changes in mineral stability relationships with increasing metamorphism in the CaO-FeO-MgO-H_2O-CO_2 system.


siderite-ferrodolomite-greenalite

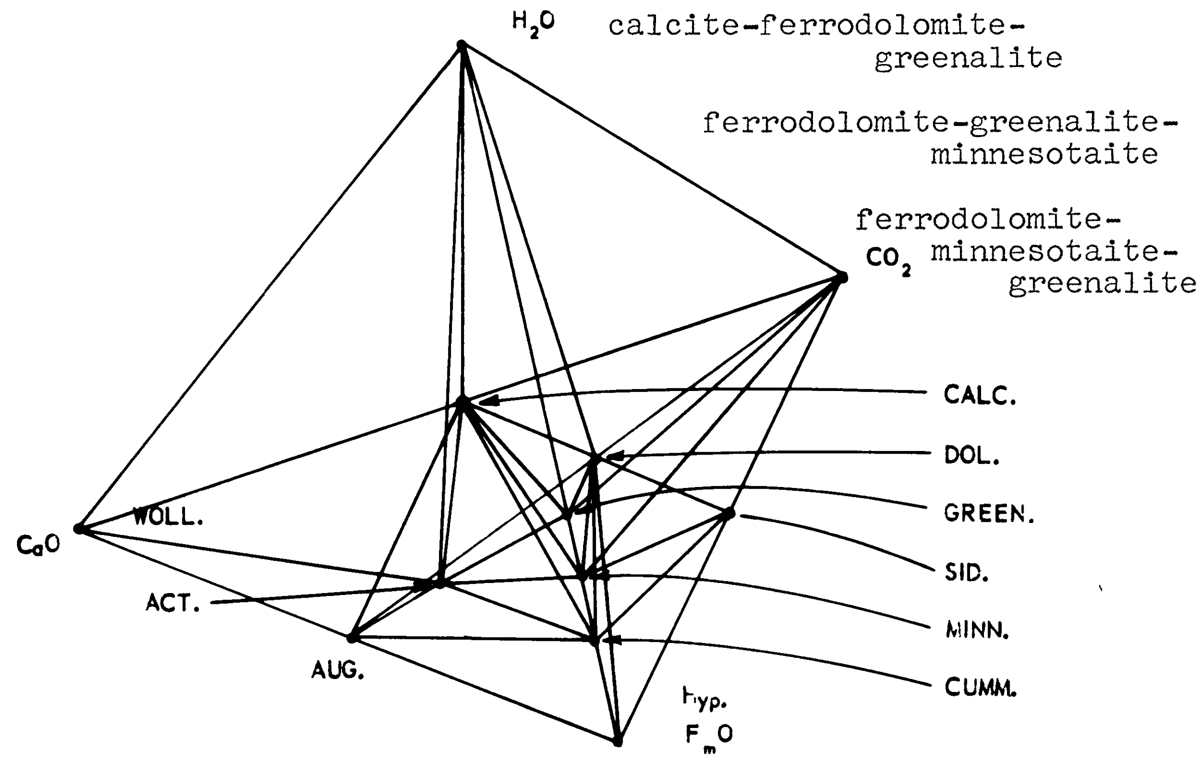
calcite-ferrodolomite-greenalite

siderite + quartz + water → greenalite + CO_2 gas (1)


siderite-ferrodolomite-greenalite

calcite-ferrodolomite-greenalite

greenalite + siderite + quartz → minnesotaite + water-CO_2 gas (2) c



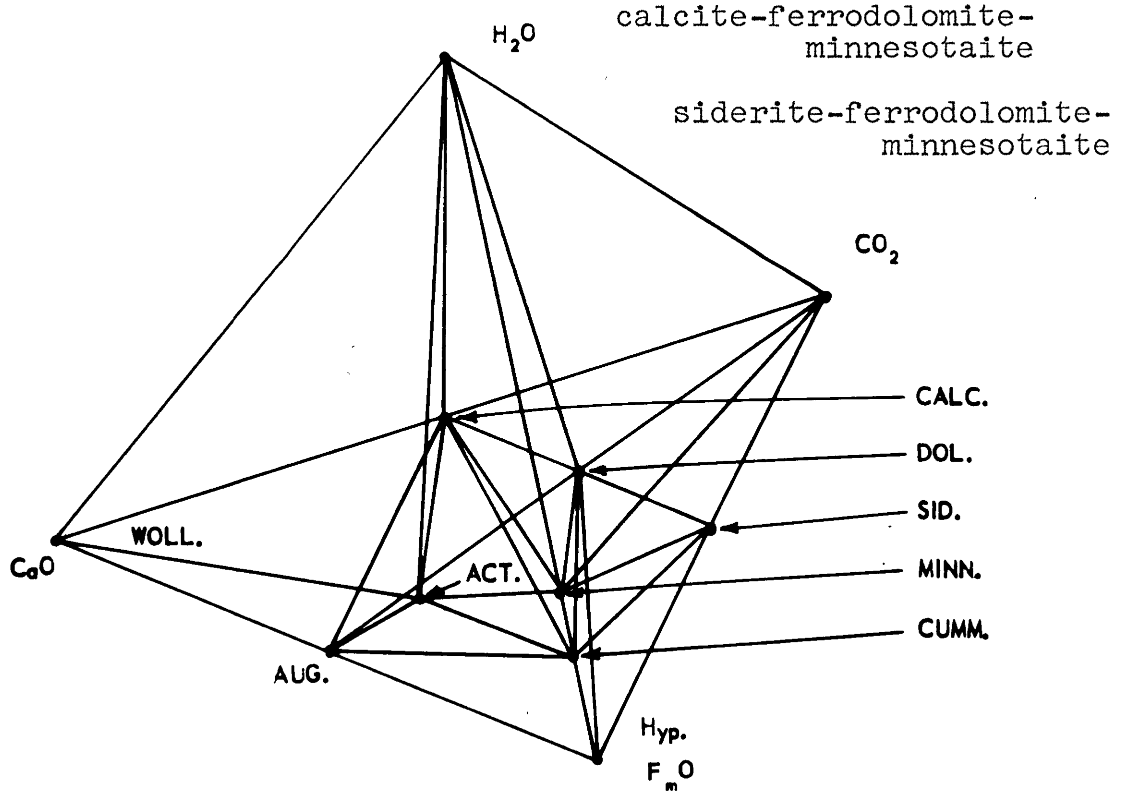
calcite-ferrodolomite-
greenalite

ferrodolomite-greenalite-
minnesotaite

ferrodolomite-
minnesotaite-
greenalite

greenalite + quartz → minnesotaite + water (3)

d

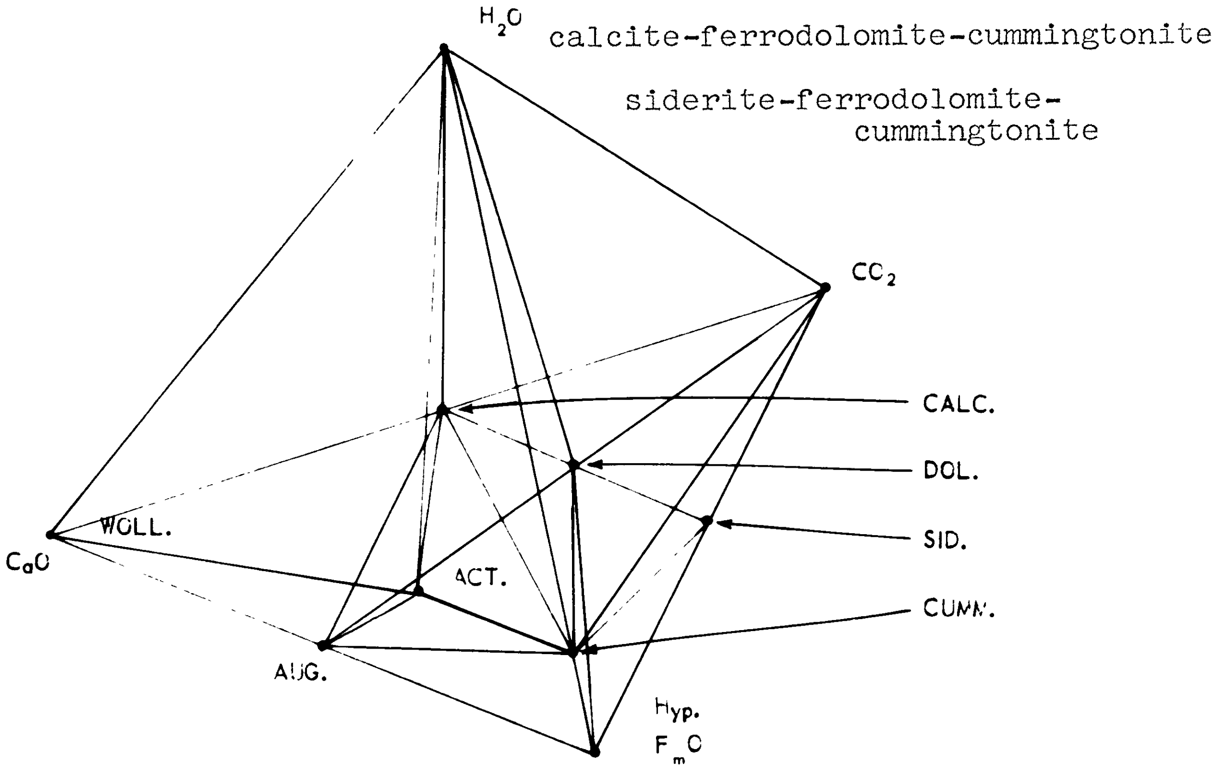


calcite-ferrodolomite-
minnesotaite

siderite-ferrodolomite-
minnesotaite

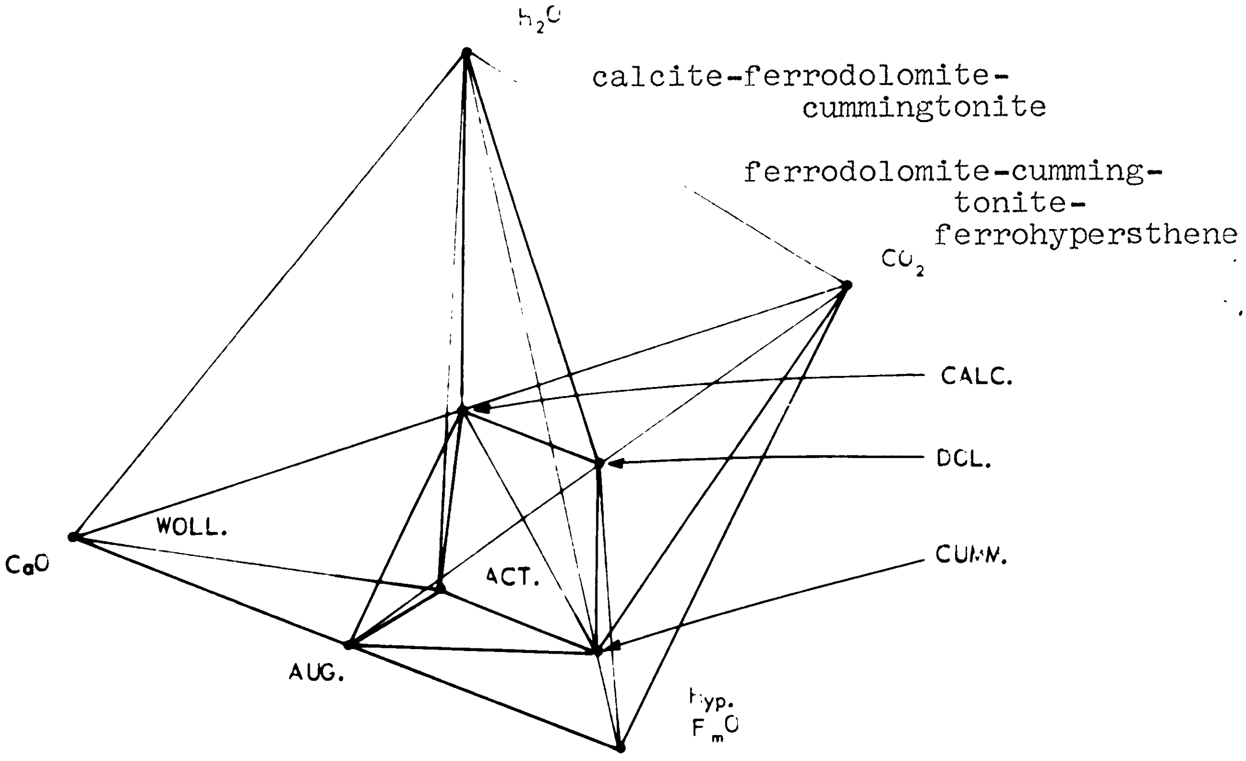
minnesotaite + siderite + quartz → cummingtonite + water-CO_2 gas (4)
minnesotaite + cummingtonite → quartz + water (5)

e

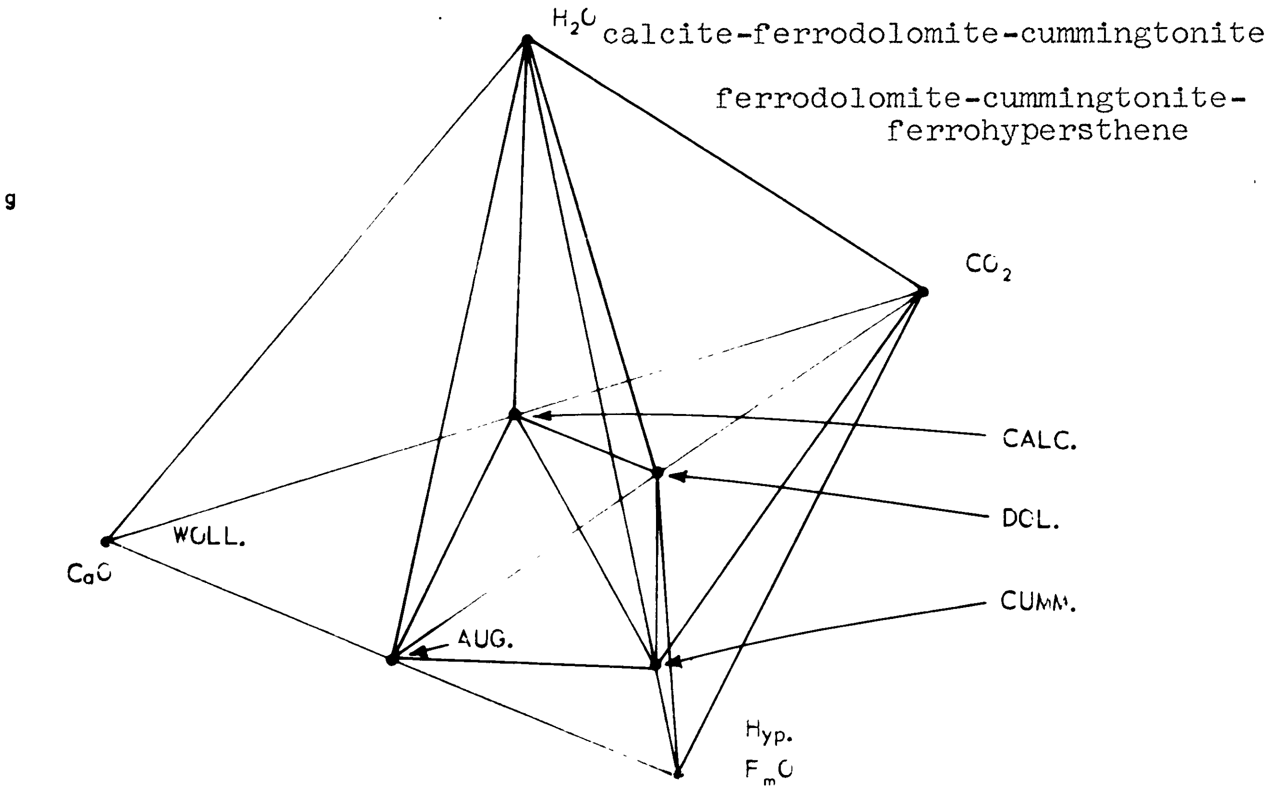


siderite + quartz → ferrohypersthene + CO_2 gas (6)

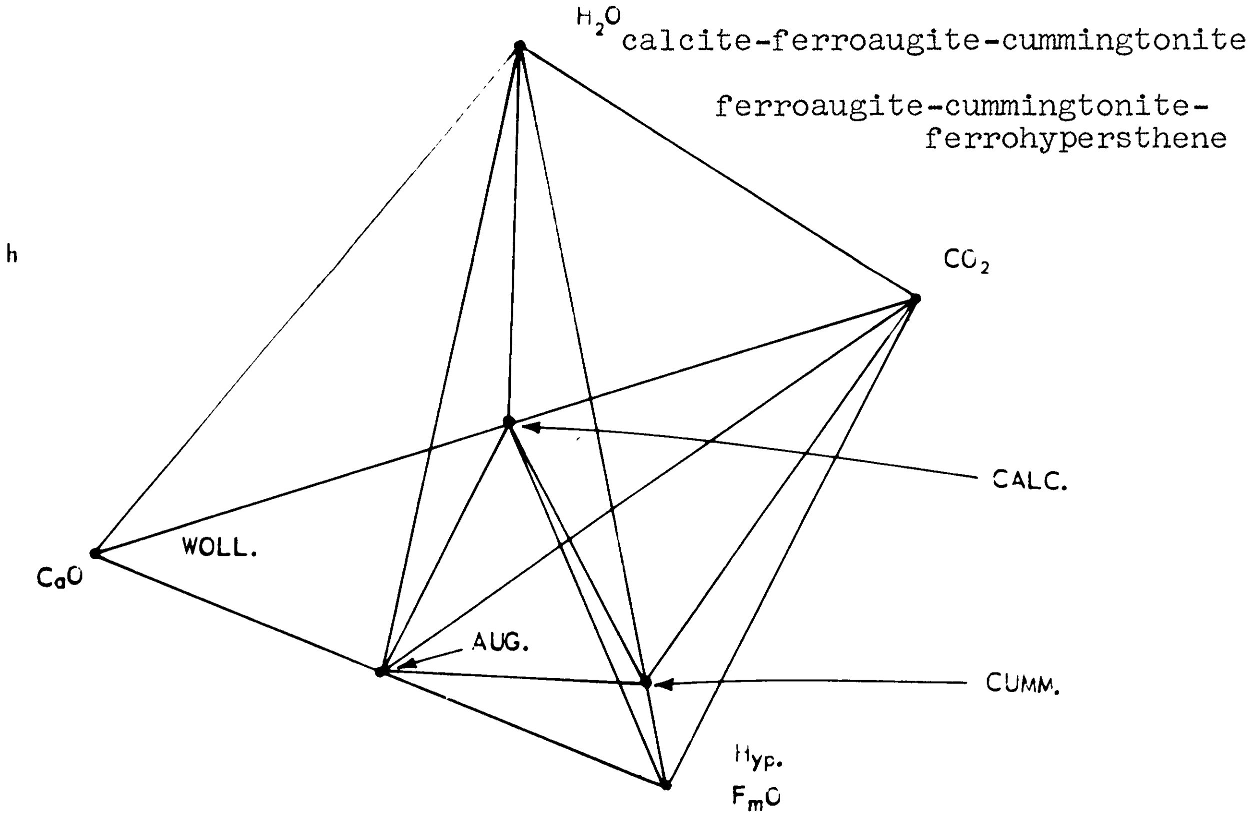
f



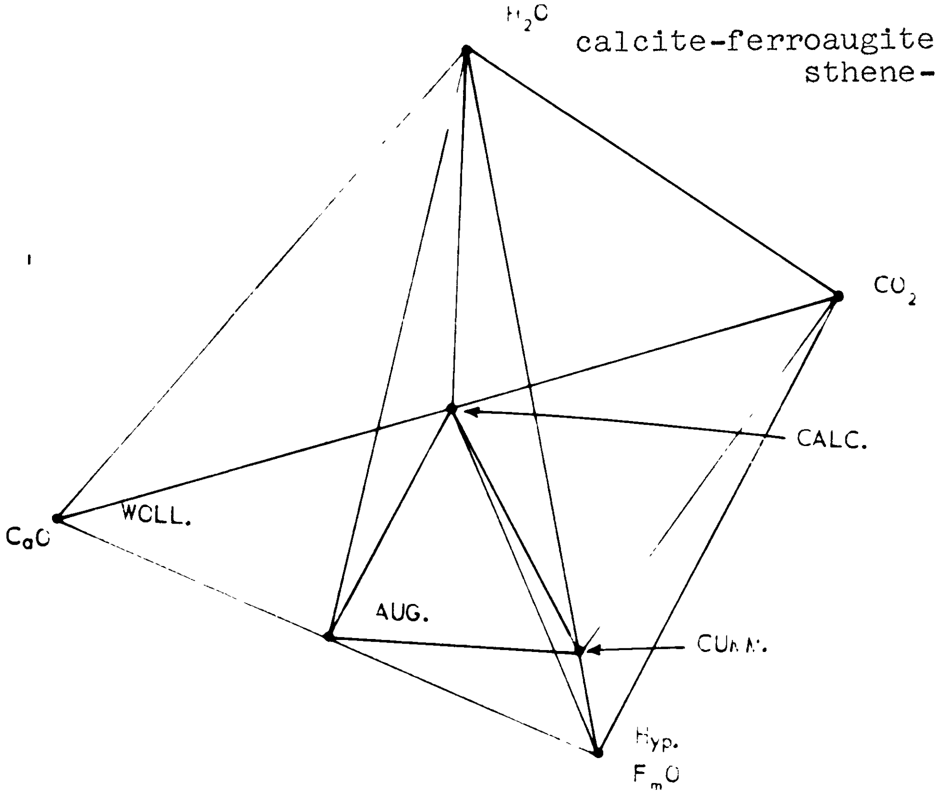
ferroactinolite → ferroaugite + cummingtonite + quartz + water (7)



ferrodolomite + quartz → ferroaugite + CO_2 gas (8)



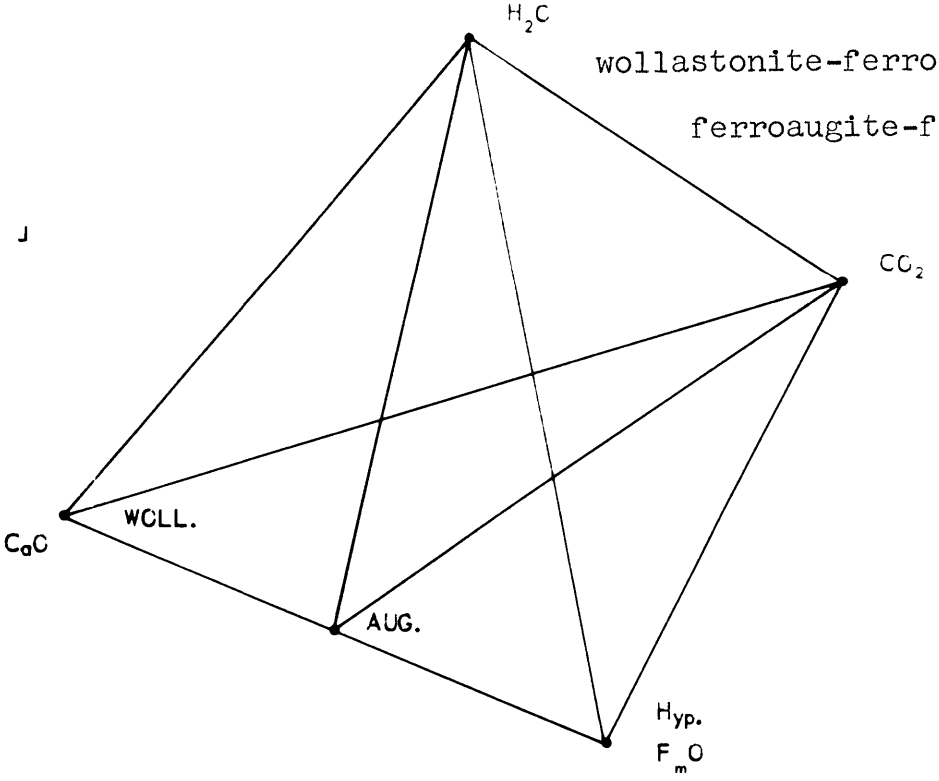
ferroaugite + CO_2 gas → calcite + ferrohypersthene + quartz (9)



calcite-ferroaugite-ferrohypersthene-cummingtonite

calcite + quartz → wollastonite + CO_2 gas (10)

cummingtonite → ferrohypersthene + quartz + water (11)



wollastonite-ferroaugite

ferroaugite-ferrohypersthene

CHAPTER 23

SUMMARY AND CONCLUSIONS

The present study has contributed some new data about the phase chemistry of silicates and carbonates in iron formations.

The chemical analyses of coexisting minerals have shown how the different major elements distribute themselves between the different minerals. The analysis shows that the mineral assemblages of the silicate iron formations are at least in approximate equilibrium. The general rule has been found to hold that the FeO/MgO ratio always is lower in the calcium-bearing pyroxenes and amphiboles than in the pure ferromagnesian minerals. It also was found that cummingtonite generally has a lower FeO/MgO ratio than the coexisting hypersthene.

In light of the new petrological and chemical data, the stability relationships of amphiboles and pyroxenes have been discussed. It is hoped that, as more facts are compiled from the field and from the laboratory, the data will be useful in helping geologists to gain a better quantitative idea about the way temperature, pressure, and bulk composition affects the stability of the ferromagnesian minerals.

Some general conclusions have been arrived at about the factors influencing the mineralogy of metamorphic iron formations.

The study does not support the idea that volatile components can diffuse freely through the rocks. The partial pressure of all components appears to be determined by the bulk composition of the rocks rather than by the physical conditions of the environment. The most important consequence of this idea is that the temperatures at which the different reactions take place is determined by equilibria in a closed system where the pressure of the volatile phase equals the rock pressure. It is, of course, too early to say whether this is a general rule in metamorphic reactions. The possibility, however, should be considered that the reason H_2O commonly can be disregarded in a graphical study of metamorphic grades is the old classical idea that volatiles are ever present in the rocks rather than the more recently advanced idea that the rocks are open to volatile components. If the volatile component is nearly pure water, it would be difficult to determine from a study of the mineral assemblages which of the two concepts are valid, as the type of mineral assemblages in either case would be the same. The iron formations are more favorable for a study of this kind, because the presence of two volatile components in the solid phases makes it possible to demonstrate the non-variance of the partial pressures of the volatile components at constant temperatures and pressures. In the case of the Mount Reed iron formations the volatile phase is believed to have been removed by reaction of ferroaugite with CO_2 gas to form hypersthene and calcite. The mineral assemblages therefore reflect an environment deficient in a volatile phase. Therefore the tightness of the rock to one volatile component can be demonstrated with the help of the phase rule and the tightness of the rock to both H_2O and CO_2, strongly indicated by considerations on the mode of origin of the rock.

The second general conclusion which can be drawn is that $FeO-SiO_2$ systems often behave very differently from their $MgO-SiO_2$ analogues. This was shown in the discussion on the stability of actinolite (Fig. 12). It was also shown that hedenbergite may not be stable at high CO_2 pressures, but is replaced by the association ferrohypersthene-calcite. The opinion has been prevelent that hypersthene and calcite are not compatible (Ramberg 1952b). This does not hold for ferrohypersthene.

To summarize, the study has at least in the mind of the writer pointed out how badly theoretical geologists are in need of more chemical data of minerals from the field. In order that laboratory studies of the stability of minerals will be able to help the field geologist, he must be able to point out what chemical equilibria it would be most significant to study. For this purpose more data are needed on the mineral assemblages occurring in the field as well as a better knowledge on the chemistry of coexisting minerals. The writer hopes that the Rapid Silicate Analysis methods used in this study will become more generally available, so that more geologists will be able to contribute significant data for the study of phase relationships of metamorphic rocks.

CHAPTER 24

ACKNOWLEDGEMENTS

The writer wants to express his great appreciation to Mr. L. J. Severson, president of the Quebec Cartier Mining Company and to Doctor R. W. Marsden, manager of explorations of the Oliver Iron Mining Company for permission to publish information obtained in the Mount Reed area in this thesis. The company generously furnished time and transportation for the collection of the rock specimens. The help and advice of Doctor R. W. Marsden, Doctor D. F. Bradley, Mr. E. C. Ferreira, and Doctor T. H. Moore in the course of the field work is greatly appreciated.

At Massachusetts Institute of Technology, the encouragement and advice given by Professor H. W. Fairbairn, my thesis advisor, in the course of the laboratory wark was of very valuable to the writer. The help of Professor W. H. Pinson, Mr. A. Brownlow and Mr. W. Phinney in straightening out some of the laboratory procedures is also appreciated. The theoretical approach used in the study is a direct application of methods developed by Professor J. E. Thompson in lectures at Harvard University. The writer wishes to thank Professor Thompson for discussions about the problems dealt with in the thesis.

APPENDIX A

CHEMICAL ANALYSES OF MINERALS IN MAFIC ROCKS

A-12 Garnet-hornblende-pyroxenite

A dark green, massive, medium-grained, xenoblastic rock type outcropping in a horizon immediately above iron formation northwest of Athol Lake. The mineral composition is given below:

Slightly pleochroic hypersthene (2V=80°)	20 per cent
Green hornblende (Z∧C 18°, 2V 90°)	40 per cent
Diopside (2V=54°, Z∧C 36°)	30 per cent
Garnet	10 per cent

A-12 Hypersthene

oxide	weight per cent	molecular proportions	metal atoms per six oxygens		
SiO_2	52.6	874	1.887		2.000
Al_2O_3	4.0	39	0.168	0.113	
				0.055	
Fe_2O_3	1.4	9	0.037		
FeO	13.7	191	0.412		
MnO	0.23	3	0.006		
MgO	26.9	669	1.444		2.009
CaO	1.2	21	0.045		
Na_2O	0.09	2	0.009		
K_2O	0.02		0.001		
Sum	100.1				

Diopside

oxide	weight per cent					
	individual analysis	average	molecular proportions	metal atoms per 6 oxygens		
SiO_2		53.5	889	1.961		2.000
Al_2O_3		1.1	11	0.048	0.039 0.009	2.000
Fe_2O_3		1.4	9	0.040		
FeO	3.67 3.85	3.8	53	0.117		
MnO	0.11 0.12	0.11	2	0.004		
MgO	16.58 16.98	16.8	418	0.922		
CaO	22.97 22.66	22.8	407	0.898		
Na_2O	0.08 0.11	0.10	2	0.009		
K_2O	0.03 0.03	0.03		0.001		
Sum	98.2					

Hornblende

oxide	weight per cent					
	individual analysis	average	molecular proportions	metal atoms per 23 oxygens		
SiO_2		48.8	813	6.93		8.00
Al_2O_3		9.5	93	1.58	1.07 0.51	5.32
Fe_2O_3		1.9	12	0.20		
FeO	5.44 5.43	5.4	76	0.69		
MnO	0.12 0.11	0.11	2	0.02		
MgO	18.41 18.72	18.6	463	3.94		
CaO	11.33 11.64	11.4	203	1.73		1.99
Na_2O	0.80 0.82	0.81	13	0.22		
K_2O	0.13 0.16	0.14	2	0.04		
Sum		96.6				

Garnet

oxide	weight per cent	molecular proportions	atoms per 12 oxygens	
SiO_2	40.7	677	3.013	
Al_2O_3	21.8	214	1.905	2.039
Fe_2O_3	4.8	30	0.134	
FeO	15.0	209	0.930	2.710
MnO	0.89	13	0.058	
MgO	10.9	271	1.206	
CaO	6.9	116	0.516	
Na_2O	0.05	1	0.001	
K_2O	0.03			
Sum	100.6			

H-1 Hobdadite

This rock type has been termed hobdadite after Hobdad Lake, the location where it is found. Its mineralogical composition is so unique that a special name is warranted for the rock type. Hobdadite is a massive, dark gray, rusty-weathering, very tough rock which outcrops on the top of Hobdad Mountain just west of Hobdad Lake and holds up the mountain. The rock is xenoblastic, coarse-to medium-grained. A thin section studied is composed of the following minerals.

Light colored hypersthene 30 per cent: small amounts of light green amphibole is intermixed with the hypersthene in small amounts in myrmekite like intergrowths.

Colorless chlorite, 35 per cent: the mineral occurs partly as flaky masses filling up areas between hypersthene granules, partly as euthedral grains sometimes growing parallel with the cleavage of the hypersthene in other places cut across by hypersthene and olivine grains. The mineral appears at least partly to be in textural equilibrium with the other ferromagnesian minerals. Under polarized light the mineral has a very fine striated appearance, the birefringence and relief are low. In thin sections the mineral is colorless; in thicker masses it is light green. The chemical composition given below and the X-ray pattern shows that the mineral is a chlorite.

Olivine-like mineral, 10 per cent: this is a reddish orange mineral with high relief. It is strongly pleochroic within yellow, orange and red. 2V = 69°_{+}. The chemical composition is shown below and indicates that the mineral is related to olivine, possibly it should be classified as iddingsite, although it does not appear to be an alteration product and does not contain a major amount of ferric iron as iddingsite usually is supposed to do.

The thin section also contains small amounts of spinel, magnetite, carbonate and cordierite.

Hypersthene

oxide	Weight per cent	molecular proportions	metal atoms per 6 oxygens		
SiO_2	54.2	901	1.966		2.000
Al_2O_3	5.8	57	0.249	0.034 0.215	2.110
Fe_2O_3	1.7	11	0.020		
FeO	9.1	127	0.277		
MnO	0.2	3	0.007		
MgO	29.1	723	1.578		
CaO	0.1	2	0.004		
Na_2O	0.02	1	0.004		
K_2O	0.05				
Sum	100.3				

Olivine

oxide	weight per cent	molecular proportions	metal atoms per 4 oxygens		
SiO_2	35.9	598	0.905		1.000
Al_2O_3	3.4	39	0.106	0.095 0.011	
Fe_2O_3	2.4	15	0.045		
FeO	11.4	159	0.241		
MnO	0.06	1	0.002		2.021
MgO	45.4	113	1.710		
CaO	0.3	6	0.008		
Na_2O	0.05	1	0.003		
K_2O	0.01		0.000		
Sum	99.0				

Chlorite

oxide	weight per cent	molecular proportions	metal atoms per 10 oxygens			
SiO_2	29.7	494	2.84		3.00	
Al_2O_3	20.5	201	2.42	0.16 2.26	2.33	2.00 0.33
Fe_2O_3	1.0	6	0.07			
FeO	3.8	53	0.31			
MnO	0.01					5.10
MgO	30.8	766	4.41		4.77	
CaO	0.2	4	0.03			
Na_2O	0.09	2	0.02			
K_2O	0.02					
Sum	86.1					

APPENDIX B

SILICATE IRON FORMATION FROM THE SOUTHERN AREA

B1-1

A heavy light-bluish gray homogeneous rock composed of 85 per cent ferrohypersthene, 10 per cent quartz and 5 per cent calcite. A partial analysis of the hypersthene showed it to contain 44.8 per cent FeO.

B1-2

A gray indistinctly banded rock composed of 30 per cent quartz, 30 per cent ferrohypersthene, 20 per cent ferroaugite and 20 per cent calcite. The ferrohypersthene contains 36.0 per cent FeO.

B1-3

A well-bedded rock consisting of alternating rusty-weathering layers rich in calcite and more resistant layers high in quartz and silicates. The mineral composition of a thin section is 15 per cent quartz, 25 per cent calcite, 30 per cent hypersthene and 30 per cent ferroaugite. The chemical compositions of the pyroxenes are given below:

Hypersthene

oxide	weight per cent	molecular proportions	metal atoms per 6 oxygens
SiO_2	50.1	833	2.075

Hypersthene (continued)

Al_2O_3	0.2	2	0.009	2.112
Fe_2O_3	2.4	15	0.075	
FeO	31.8	443	1.103	
MnO	0.37	5	0.810	
MgO	13.1	325	0.012	
CaO	2.2	39	0.097	
Na_2O	0.08	1	0.005	
K_2O	0.03		0.001	
Sum	100.3			

Ferroaugite

oxide	weight per cent individual analysis	weight per cent average	molecular proportions	metal atoms per 6 oxygens	
SiO_2		51.7	859	1.987	2.001
Al_2O_3		0.3	3	0.014	
Fe_2O_3		2.0	12	0.056	1.981
FeO	15.15 15.30	15.2	212	0.491	
MnO	0.18 0.19	0.18	3	0.006	
MgO	9.75 9.55	9.6	239	0.553	
CaO	21.09 20.97	21.0	374	0.865	
Na_2O	0.12 0.13	0.12	2	0.009	
K_2O	0.02 0.06	0.03		0.001	
Sum		100.1			

B1-6

A thin-bedded phase of the silicate iron formation, composed of 35 per cent quartz, 30 per cent ferrohypersthene, 25 per cent ferroaugite and 10 per cent calcite and small amounts of graphite. Some layers consist only of one mineral, others are composed of the different minerals in varying proportions. The chemical composition of the pyroxenes are shown below:

Ferrohypersthene

oxide	weight per cent		molecular proportions	metal atoms per 6 oxygens	
	individual analysis	average			
SiO_2		48.8	813	1.980	1.990
Al_2O_3		0.2	2	0.010	
Fe_2O_3		2.3	14	0.068	2.016
FeO	36.36 36.62	36.6	509	1.240	
MnO		1.14	16	0.039	
MgO	8.94 9.03	9.0	224	0.546	
CaO	1.68 1.81	1.7	30	0.073	
Na_2O	0.59 0.62	0.61	10	0.049	
K_2O	0.03 0.02	0.02		0.001	
Sum		100.3			

Ferroaugite

oxide	weight per cent		molecular proportions	metal atoms per 6 oxygens	
	individual analysis	average			
SiO_2		50.5	839	1.970	1.979
Al_2O_3		0.2	2	0.009	
Fe_2O_3		1.9	12	0.056	2.016
FeO	16.90 17.18	17.1	238	0.559	
MnO	0.56 0.67	0.57	8	0.019	
MgO	7.61 7.90	7.7	191	0.448	
CaO	21.04 21.30	21.2	378	0.887	
Na_2O	0.61 0.68	0.64	10	0.046	
K_2O	0.02 0.05	0.03		0.001	
Sum		99.8			

B1-21

A medium-grained granoblastic rock with indistinct banding composed of about 35 per cent ferrohypersthene, 25 per cent ferroaugite, 30 per cent quartz, and 10 per cent calcite. The compositions of the pyroxenes are given below:

Ferrohypersthene

oxide	weight per cent		molecular proportions	metal atoms per 6 oxygens	
	individual analysis	average			
SiO_2		49.2	818	1.977	1.991
Al_2O_3		0.3	3	0.014	
Fe_2O_3		3.1	19	0.092	
FeO	36.27 35.72	35.9	500	1.211	
MnO	0.14 0.15	0.14	2	0.588	1.974
MgO	9.90 9.78	9.8	243	0.005	
CaO	1.85 1.63	1.7	30	0.073	
Na_2O	0.06 0.08	0.07	1	0.005	
K_2O	0.02 0.02	0.02			
Sum		100.2			

Ferroaugite

oxide	weight per cent		molecular proportions	metal atoms per 6 oxygens		
	individual analysis	average				
SiO_2		50.8	845	1.993		2.000
Al_2O_3		0.3	3	0.014	7 7	
Fe_2O_3		1.9	12	0.056		
FeO	17.41 17.48	17.4	242	0.570		
MnO		0.06	1	0.002		1.973
MgO		7.7	191	0.450		
CaO		21.0	374	0.882		
Na_2O		0.61	1	0.005		
K_2O		0.05		0.001		
Sum		99.9	125			

A-50 Magnetite-silicate-iron formation

A heavy dark-colored homogeneous rock composed of 50 per cent quartz, 25 per cent magnetite, 20 per cent aegirine-hedenbergite and 15 per cent ferrohypersthene. Calcite is not present. Cummingtonite is present in small amounts in another similar thin section studied. The rock is quite coarse-grained and is easily crushed up.

Ferrohypersthene

oxide	weight per cent individual analysis	weight per cent average	molecular proportions	metal atoms per 6 oxygens	
SiO_2		47.1	784	1.987	1.988
Al_2O_3		0.2	2	0.001	
Fe_2O_3		4.1	26	0.131	1.946
FeO	40.21 40.15	40.1	558	1.413	
MnO	3.08 3.12	3.1	44	0.111	
MgO	3.58 3.30	3.4	84	0.213	
CaO	1.62 1.65	1.6	29	0.073	
Na_2O	0.11 0.10	0.10	1	0.005	
K_2O	0.03 0.03	0.03		0.001	
Sum		99.7			

Aegrine-hedenbergite

oxide	weight per cent		molecular proportions	metal atoms per 6 oxygens	
	individual analysis	average			
SiO_2		49.7	827	2.001	
Al_2O_3		0.1	1	0.005	
Fe_2O_3		9.6	60	0.290	
FeO	17.80 18.06	17.9	249	0.603	
MnO		2.03	28	0.068	1.963
MgO	1.75 1.90	1.8	45	0.109	
CaO	15.25 15.46	15.3	273	0.661	
Na_2O	2.95 3.05	3.0	47	0.227	
K_2O		0.03		0.001	
Sum		100.4			

Si-4

A medium-grained massive rock similar to Bl-1 composed of 85 per cent hypersthene, 15 per cent calcite and 10 per cent quartz. The hypersthene contains 40.4 per cent FeO by weight.

A-8

A medium-grained, homogeneous granoblastic rock composed of 55 per cent quartz, 25 per cent ferrohypersthene, 10 per cent ferrohypersthene, 5 per cent cummingtonite, and 5 per cent calcite, and small amounts of magnetite. All the minerals are scattered fairly evenly in the rock. Calcite and cummingtonite generally are separated from each other by hypersthene. The hypersthene contains 39.1 per cent FeO.

A-30

A coarse-grained rock which in hand specimens appear to consist only of large crystals of hypersthene. A thin section shows that ferrohypersthene is intermixed with 10 per cent cummingtonite, 5 per cent calcite and 5 per cent quartz. The ferrohypersthene contains 40.5 per cent FeO.

A-31 Magnetite-arfvedsonite iron formation

The rock is composed of bands of coarse crystals of bluish amphibole in a fine-grained mixture of quartz and magnetite. The amphibole is an arfvedsonite with the following pleochroic formula, X - yellow, Y - green, Z - blue; 2V is 40° and negative. The chemical composition is given below.

Arfvedsonite

oxide	weight per cent	molecular proportions	metal atoms per 6 oxygens	
SiO_2	54.8	910	8.00	
Al_2O_3	3.7	37	0.47	4.92
Fe_2O_3	10.4	65	1.14	
FeO	8.6	120	1.05	
MnO	9.2	30	0.26	
MgO	1.9	228	2.00	
CaO	2.1	34	0.30	1.96
Na_2O	4.7	76	1.34	
K_2O	1.7	18	0.32	
Sum		97.1		

B-9

A light green homogeneous silicate rock composed of granular quartz and ferroaugite mixed with needles of cummingtonite. The mineral composition consists of 35 per cent ferroaugite, 55 per cent quartz, and 10 per cent cummingtonite. An analysis of the ferroaugite and a partial analysis of the cummingtonite is given below.

Cummingtonite

oxide	weight per cent	molecular proportions	metal atoms per 7 oxygens (16 oxygens are assumed to be taken up in SiO_2 and Al_2O_3)	
SiO_2	n.d.			
Al_2O_3	n.d.			
Fe_2O_3	2.5	16	0.30	6.95
FeO	28.6	398	3.69	
MnO	0.23	3	0.03	
MgO	9.9	246	2.28	
CaO	3.8	68	0.63	
Na_2O	0.10	2	0.02	
K_2O	0.03			
Sum	97.9			

Ferroaugite

oxide	weight per cent		molecular proportions	metal atoms per 6 oxygens	
	individual analysis	average			
SiO_2		50.1	835	1.976	1.990
Al_2O_3		0.3	3	0.014	
Fe_2O_3		2.3	14	0.006	2.099
FeO	16.69 16.95	16.8	233	0.552	
MnO	0.34 0.37	0.35	1	0.002	
MgO	8.35 8.17	8.2	204	0.483	
CaO	20.61 20.98	20.8	372	0.881	
Na_2O	0.15	0.17	3	0.114	
K_2O	0.03 0.03	0.03		0.001	
Sum		99.0			

B-18

A rock similar to B-9 and from the same locality. The cummingtonite content is higher (about 30 per cent)

Ferroaugite

oxide	weight per cent individual analysis	 average	molecular proportions	metal atoms per 6 oxygens	
SiO_2		50.7	844	1.980	1.996
Al_2O_3		0.3	3	0.014	
Fe_2O_3		2.8	18	0.084	1.983
FeO	17.06 17.17	17.1	238	0.558	
MnO	0.15 0.16	0.15	2	0.005	
MgO	8.02 8.21	8.1	201	0.472	
CaO	20.30 20.54	20.4	364	0.854	
Na_2O	0.15 0.14	0.15	2	0.009	
K_2O	0.03 0.02	0.03		0.001	
Sum		99.7			

Cummingtonite

oxide	weight per cent	molecular proportions	metal atoms per 23 oxygens	
SiO_2	51.5	857	7.92	7.98
Al_2O_3	0.3	3	0.06	
Fe_2O_3	3.5	22	0.41	6.90
FeO	31.2	434	4.01	
MnO	0.23	3	0.03	
MgO	9.1	226	2.09	
CaO	1.9	34	0.31	
Na_2O	0.16	2	0.04	
K_2O	0.03		0.01	
Sum	97.9			

MR-5

Specimen is from the core of a diamond drill hole at Mount Reed. It consists of alternating layers of specularite-acmite-rhodonite and acmite-rhodonite. The partially analysed minerals comes from a band devoid of specularite. The compositions of the minerals is as shown below:

Rhodonite

oxide	weight per cent	molecular proportions	metal atoms per 6 oxygens
SiO_2	n.d.	-	2 (assumed)
Al_2O_3	n.d.	-	
Fe_2O_3	7.4	46	0.247
FeO	0.9	15	0.040
MnO	48.2	579	1.556
MgO	n.d.	5	
CaO	0.3	5	
Na_2O	0.08	1	
K_2O	0.02		

Acmite

oxide	weight per cent	molecular proportions	metal atoms per 6 oxygens
SiO_2	n.d.		2 (assumed)
Al_2O_3	n.d.		
Fe_2O_3	26.7	167	1.001
FeO	0.4	6	0.18
MnO	6.6	93	0.281
MgO	0.8	20	0.061
CaO	1.5	27	0.103
Na_2O	11.2	181	1.095
K_2O	0.02		

R-7

A green massive medium-grained granoblastic rock composed of 45 per cent diopside, 15 per cent dark green amphibole and 35 per cent quartz.

Diopside

oxide	weight per cent	molecular proportions	metal atoms per 6 oxygens		
SiO_2	54.6	908	1.991		2.000
Al_2O_3	0.7	7	0.031	0.009 0.002	
Fe_2O_3	2.7	17	0.075		
FeO	5.7	79	0.173		
MnO	0.03		0.001		1.958
MgO	14.8	368	0.808		
CaO	22.1	394	0.865		
Na_2O	0.17	3	0.013		
K_2O	0.03		0.001		
Sum	100.8				

Hornblende

oxide	weight per cent	molecular proportions	metal atoms per 23 oxygens		
SiO_2	54.2	900	7.77		8.00
Al_2O_3	5.0	49	0.85	0.23 0.62	
Fe_2O_3	0.3	2	0.03		
FeO	7.7	107	0.92		4.76
MnO	0.03		0.01		
MgO	14.8	368	3.18		
CaO	13.0	232	2.00		
Na_2O	0.14	2	0.03		2.06
K_2O	0.18	2	0.03		
Sum	96.3				

APPENDIX C

SPECIMENS OF SILICATE IRON FORMATIONS OF THE NORTHERN AREA

H-3 Magnetite-silicate iron formation

A medium-grained, banded rock consisting of 55 per cent quartz, 15 per cent magnetite, 15 per cent ferroaugite and 10 per cent cummingtonite.

Cummingtonite

oxide	weight per cent	molecular proportions	metal atoms per 6 oxygens	
SiO_2	53.3	887	7.95	7.99
Al_2O_3	0.2	2	0.04	
Fe_2O_3	2.5	16	0.29	6.90
FeO	26.3	365	3.27	
MnO	4.5	64	0.57	
MgO	11.2	279	2.50	
CaO	1.6	29	0.26	
Na_2O	0.09	1	0.01	
K_2O	0.02			
Sum	99.7			

Ferroaugite

oxide	weight per cent		molecular proportions	metal atoms per 6 oxygens	
	individual analysis	average			
SiO_2		51.1	850	1.984	1.993
Al_2O_3		0.2	2	0.009	
Fe_2O_3		3.7	23	0.107	1.992
FeO		13.5	188	0.439	
MnO		2.54	36	0.084	
MgO		8.9	221	0.516	
CaO		18.9	338	0.789	
Na_2O		0.71	12	0.056	
K_2O		0.03		0.001	
Sum		99.5			

H-4

A coarse-grained, darkgreen, massive rock consisting of 50% ferrohypersthene, 30% ferroaugite, 10% calcite, and 10% quartz.

Ferrohypersthene

oxide	weight individual analyses	per cent average	molecular proportions	metal atoms per 6 oxygens	
SiO_2		47.8	795	1.978	1.988
Al_2O_3		0.2	2	0.010	
Fe_2O_3		2.3	14	0.070	1.981
FeO	40.67 40.30	40.4	562	1.398	
MnO	0.50 0.55	0.52	7	0.017	
MgO	6.68 6.66	6.67	166	0.413	
CaO	1.75 1.73	1.74	31	0.077	
Na_2O	0.09 0.09	0.09	1	0.005	
K_2O		0.02		0.001	

Ferroaugite

oxide	weight individual analyses	per cent average	molecular proportions	metal atoms per 6 oxygens	
SiO_2		51.0	849	2.009	
Al_2O_3		0.2	2	0.008	1.943
Fe_2O_3		2.7	17	0.080	
FeO	20.33 19.72	19.9	277	0.657	

Ferroaugite (cont.)

oxide	weight individual analyses	per cent average	molecular proportions	metal atoms per 6 oxygens
MnO	0.26 0.26	0.26	4	0.009
MgO	5.96 6.00	6.0	148	0.350
CaO	19.21 19.44	19.3	344	0.814
Na_2O		0.28	5	0.024
K_2O		0.03		0.001

H-7

The rock consists of large rosettes of cummingtonite needles mixed with coarse-grained ferroaugite and ferrohypersthene and small amounts of magnetite, calcite, and quartz. Magnetite grains sometimes are concentrated in the centers of cummingtonite rosettes. The hand specimen represents a silicate-rich layer in banded silicate iron formation.

Ferroaugite

oxide		weight per cent	molecular proportions	metal atoms per 6 oxygens	
SiO_2		50.4	838	1.996	
Al_2O_3		0.2	2	0.010	1.978
Fe_2O_3		2.1	13	0.062	
FeO	19.73 19.75	19.4	270	0.643	
MnO		0.75	11	0.026	
MgO		6.6	164	0.391	
CaO		19.6	349	0.831	
Na_2O		0.20	3	0.014	
K_2O		0.03		0.001	
Sum		99.3			

Cummingtonite

oxide		weight per cent	molecular proportions	metal atoms per 23 oxygens	
SiO_2		51.7	859	7.98	8.00
Al_2O_3		0.1	1	0.02	
Fe_2O_3		1.2	8	0.15	6.93
FeO	35.10 35.31	35.2	490	4.56	
MnO		1.25	18	0.17	
MgO		8.0	199	1.85	
CaO	1.	1.1	20	0.19	
Na_2O		0.08	1	0.01	
K_2O		0.03			
Sum		98.7			

Ferrohypersthene

oxide	weight individual analyses	per cent average	molecular proportions	metal atoms per 6 oxygens	
SiO_2		47.8	795	1.987	1.997
Al_2O_3		0.2	2	0.010	
Fe_2O_3		1.9	12	0.060	1.983
FeO	39.43 39.71	39.5	549	1.372	
MnO	1.53 1.50	1.51	21	0.052	
MgO	7.15 7.07	7	176	0.440	
CaO	1.21 1.26	1.2	22	0.055	
Na_2O	0.09 0.10	0.09	1	0.003	
K_2O	0.03 0.03	0.03		0.001	

H-9

A medium-grained, dark, grayish-green rock. In thin sections the rock exhibits a distinct microbanding. In places the bands are monomineralic layers consisting of calcite, hypersthene, quartz, or cummingtonite. In places the different mineral constituents are mixed in varying proportions. Cummingtonite and calcite layers generally are separated from each other by hypersthene. The mineral composition of one thin section consists of 10 per cent ferroaugite, 10 per cent quartz, 20 per cent cummingtonite, 45 per cent ferrohypersthene, and 15 per cent calcite.

Ferrohypersthenes

oxide	weight per cent	molecular proportions	metal atoms per six oxygens	
SiO_2	48.4	807	1.994	
Al_2O_3	0.2	2	0.010	1.981
Fe_2O_3	1.7	11	0.1332	
FeO	38.8	539	1.332	
MnO	1.61	23	0.056	
MgO	7.6	189	0.467	
CaO	1.3	23	0.057	
Na_2O	0.07	1	0.005	
K_2O	0.02			
Sum	99.7			

Ferroaugite

oxide	weight per cent	molecular proportions	metal atoms per 6 oxygens	
SiO_2	50.4	838	1.996	
Al_2O_3	0.2	2	0.010	1.978
Fe_2O_3	2.1	13	0.062	
FeO	19.4	270	0.643	
MnO	0.75	11	0.026	
MgO	6.6	164	0.391	
CaO	19.6	349	0.831	
Na_2O	0.20	3	0.014	
K_2O	0.03		0.001	
Sum	99.3			

Cummingtonite

oxide	weight per cent	molecular proportions	metal atoms per 23 oxygens	
SiO_2	51.7	859	7.98	8.00
Al_2O_3	0.1	1	0.02	
Fe_2O_3	1.2	8	0.15	6.93
FeO	35.2	490	4.56	
MnO	1.25	18	0.17	
MgO	8.0	199	1.85	
CaO	1.1	20	0.19	
Na_2O	0.03			
Sum	98.7			

F-73

Mineral specimens are taken from reaction zones between quartz-magnetite iron formation and dolomite. The reaction zone consists of 6 inches of pure magnetite, 7-9 inches of hornblende and 5 inches of diopside. In a narrow zone hornblende and diopside are intermixed hornblende occurring as unreplaced remnants in a diopside matrix.

Hornblende

oxide	weight per cent		molecular proportions	metal atoms per 23 oxygens		
	individual analysis	average				
SiO_2		47.2	784	6.83		8.00
Al_2O_3		8.9	87	1.52	1.17 0.35	
Fe_2O_3		6.0	38	0.66		5.03
FeO	9.31 9.28	9.3	129	1.12		
MnO	0.16 0.15	0.15	2	0.02		
MgO	13.31 13.31	13.3	330	2.88		
CaO	11.83 11.33	11.6	208	1.81		2.26
Na_2O		1.0	16	0.28		
K_2O		0.90	10	0.17		
Sum		98.1				

Diopside

oxide	weight per cent		molecular proportions	metal atoms per 6 oxygens		
	individual analysis	average				
SiO_2		53.2	884	1.973		2.000
Al_2O_3		0.8	8	0.035	0.27 0.08	
Fe_2O_3		2.5	16	0.071		1.991
FeO	4.57 4.60	4.6	64	0.143		
MnO	0.14 0.14	0.14	2	0.005		
MgO	14.88 15.01	14.9	369	0.824		
CaO	22.47 22.80	22.6	403	0.899		
Na_2O	0.58 0.55	0.57	9	0.40		
K_2O	0.04 0.03	0.04		0.001		
Sum		99.3				

F-1

Anthophyllite-hornblende rock probably representing an altered ultramafic intrusive. The rock consists mainly of a mass of subeuhedral prismatic grains of anthophyllite without any discernable preferred orientation. Clusters of hornblende are present in parts of the hand specimen. The two amphiboles sometimes are intergrown in one grain. Biotite and minor garnet also are present in the hand specimen.

Anthophyllite

oxide	weight per cent	molecular proportions	metal atoms per 23 oxygens		
SiO_2	52.0	866	7.33		8.00
Al_2O_3	7.1	70	1.19	0.67 0.53	
Fe_2O_3	f3.0	15	0.25		
FeO	15.5	216	1.83		
MnO	0.16	2	0.02		6.96
MgO	19.7	489	4.14		
CaO	1.0	18	0.15		
Na_2O	0.06	1	0.02		
K_2O	0.12	1	0.02		
Sum	98.7				

Hornblende

oxide	weight per cent	molecular proportions	metal atoms per 23 oxygens			
SiO_2	48.3	804	6.72		8.00	
Al_2O_3	14.0	137	2.29	1.28 1.01		
Fe_2O_3	3.9	24	0.39			
FeO	8.8	123	1.03		5.61	
MnO	0.14	2	0.02			
MgO	15.2	378	3.16			6.99
CaO	8.4	150	1.25	1.38		
Na_2O	0.30	5	0.08			
K_2O	0.30	3	0.05			
Sum	99.3					

APPENDIX D

LIST OF CUMMINGTONITE ANALYSES USED IN DIAGRAM 5

No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O	Reference	
1	55.24		0.18		17.63	2.00	21.17	1.85			2.41	Hintze	1897
2	54.97		2.38	0.06	17.25	0.02	22.11	1.84	0.30	0.10	0.80	Eskola	1950
3	51.53	0.31	5.02	0.82	16.91	0.22	20.84	1.34	0.65	nil	2.79	Collins	1942
4	53.69		1.65	0.32	5.94	16.10	20.50	1.25			0.02	Rabbitt	1948
5	54.28	0.02	1.26	0.80	21.79	0.26	18.64	0.15	0.14		2.16	Sundius	1933
6	49.20		0.14	0.21	17.23	6.33	18.87	0.29			7.44	Kunitz	1930
7	54.20		2.08		22.09	0.16	19.20	tr	0.20	0.16	2.05	Sundius	1931
8	50.99	0.02	3.78	0.85	21.70	0.18	18.61	nil	0.24	0.31	2.77	Sundius	1931
9	49.60	0.26	8.65	0.48	18.54	1.08	16.78	0.97	0.79		2.52	Collins	1942
10	53.12	0.21	2.78	0.25	22.46	0.27	15.46	2.26			3.33	Tilley	1939
11	51.24	n.d.	1.36		17.50	9.49	17.20	1.62	n.d.	n.d.		Lindroth	1926
12	50.70	0.31	1.72	3.11	26.63	0.19	14.36	0.87	0.60	0.15	1.46	Eskola	1936
13	52.98		0.26	0.60	21.93	8.03	13.58	0.29	tr	tr	2.36	Sundius	1924
14	52.0	0.4	0.4	0.4	22.5	7.7	9.8	5.0				Sundius	1929
15	50.78	0.40	1.77	1.88	29.64	0.14	11.83	1.33	nil	nil	2.01	Seitsari	1952
16	49.60	0.05	0.32	0.32	25.18	4.94	11.62	1.49			6.48	Kunitz	1930
17	56.74		0.91	3.14	24.41	1.58	9.72	0.42			3.81	Simpson	1928

No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O	Reference
18	52.22		0.58	0.42	29.45	3.21	12.04		tr		2.12	Sundius 1931
19	50.74	0.06	0.88	1.80	24.13	7.38	10.57	2.00	0.22	0.08	1.94	Sundius 1931
20	51.09		0.95		32.07	1.50	10.29	tr	0.75		3.04	Hintze 1897
21	50.74		0.89		33.14	1.77	10.31	tr	0.54		3.04	Hintze 1897
22	51.8			0.76	31.9	0.9	9.1	4.6				Saxen 1925
23	49.48		1.92	0.75	31.55		8.63	0.42	0.22		6.98	Kunitz 1930
24	50.32		0.86	1.75	35.36	0.02	8.61	0.88	0.13		1.82	Rabbitt 1948
25	48.83				30.49	8.34	8.39	1.74			0.44	Palmgren 1916
26	50.79	0.07	0.55	0.84	30.64	5.93	7.87	1.42			1.87	Palmgren 1916
27	49.84		0.62	0.44	33.70	0.57	6.23	1.45	1.05	0.12	5.98	Kunitz 1930
28	49.50		0.69		30.69	8.24	8.10	2.02			0.40	Palmgren 1916
29	50.79		0.34	0.89	38.43	1.12	6.50		tr		2.00	Sundius 1931
30	53.11		0.75	1.13	36.81	0.35	6.08	1.59	0.18			Sundius 1931
31	48.63		1.53		33.65	7.32	6.12	1.96			0.60	Palmgren 1916
32	52.00		1.41	1.05	37.93	0.97	5.99	0.66	tr			Sundius 1931
33	50.37	nil	0.54	0.56	40.08	1.07	4.47	0.83	nil	nil	2.40	Miles 1943
34	48.53		1.02	1.14	39.20	0.66	4.06	1.31	1.06	0.19	1.71	Sundius 1931
35	48.89		1.46		38.21	8.46	2.92	0.73				Palmgren 1916

BIBLIOGRAPHY

Bowen, N.L., and Tuttle, O.F.,(1949),The system $MgO-SiO_2-H_2O$: Geol. Soc. America Bull.,60, pp. 439-460.

Boyd, F.R.,(1959), Hydrothermal investigations of amphiboles: Researches in Geochemistry, edited by P.H. Abelson, pp.377-396.

Brown, G.M., Vincent, E.A., and Brown, P.E.,(1957),Pyroxenes from the early and middle stages of fractionation of the Skeargaard intrusion, East Greenland: Min. Mag., vol.31, pp.511-543.

Carstens, C.W.,(1924), Zur Frage der Genesis der Eulysitgesteine: Geol. foren. Stockholm Forh., band 46, pp.248-252.

Collins, R.S. (1942), Cummingtonite and gedrite from Sutherland: Min. Mag., vol. 26, pp.254-259.

Duffell, S., and Roach, R.A. (1959), Mount Wright, Quebec-Newfoundland: Geol. Survey Canada Map 6-1959.

Ellis, A.J. (1959), The solubility of carbon dioxide in water at high temperatures: Am. Jour. Sci., vol. 257, pp.217-234.

Eskola, P. (1932), On the principles of metamorphic differentiation: Comm. geol. Finlande Bull. 97, pp.68-77.

Eskola, P. (1936), A paragenesis of gedrite and cummingtonite from Isopaa in Kalvola, Finland: Geol. Soc. Finlande, Comptes rendus, vol. 9, 475 p.

Eskola, P. (1950), Paragenesis of cummingtonite and hornblende from Muuruvesi, Finland: Am. Mineralogist, vol. 35, pp.728-734.

Flaschen, S.S., and Osborn, E.F., (1957), Studies of the system ironoxide-silica-water at low oxygen partial pressures: Econ. Geology, vol. 52, pp.923-943.

Fyfe, W.S., Turner, F.J., and Verhoogen, J. (1958), Metamorphic reactions and metamorphic facies: Geol. Soc. America Mem. 73, 259 p.

Gastil, G., and Knowles, D. (1957), Regional geology of the Wabush Lake area, Western Labrador (abstract): Geol. Soc. America Bull., vol. 68, p.1733.

Geijer, P. (1925), Eulysitic iron ores in Northern Sweden: Sveriges Geol. undersökning, ser. C, no. 324.

Goldsmith, J.R. (1949), Some aspects of the geochemistry of carbonates: Researches in Geochemistry, edited by P.H. Abelson, pp.336-358.

Grout, F.F. (1919), The nature and origin of the Biwabik iron bearing formation of the Mesabi range, Minnesota: Econ. Geology, vol. 14, pp.452-464.

Grout, F.F., and Broderick, T.M. (1919), The magnetite deposits of the eastern Mesabi range, Minnesota: Minnesota Geol. Survey Bull. 17,

Gross, G.A. (1955), The metamorphic rocks of the Mount Wright and Matonipi Lake areas of Quebec: Ph.D. thesis, Univ. of Wisconsin.

Gruner, J.W. (1946), The mineralogy and geology of the taconites and iron ores of the Mesabi Range, Minnesota: Iron Range Resources and Rehabilitation, St. Paul, Minn., 127 p.

Gruner, J.W. (1944), The composition and structure of minnesotaite, a common iron silicate in iron formations: Am. Mineralogist, vol. 29, pp.363-372.

Hallimond, A.F. (1943), On the graphical representation of the calciferous amphiboles: Am. Mineralogist, vol. 28, pp.65-89.

Harrison, J.M. (1952), Iron formations of Ungava Peninsula, Canada: Mineteenth Geol. Congress, Alger, section X, pp.19-33.

Harry, W.T. (1950), Aluminum replacing silicon in some silicate lattices: Min. Mag., vol. 29, pp.142-149.

Hess, H.H. (1941), Pyroxenes of common mafic magmas; Part 2, Am. Mineralogist, vol. 26, pp.573-594.

Hintze, C. (1897), Handbuch der Mineraloggie, BandII, 1841 p.

Huber, N.K., and Garrels, R.M. (1953), Relation of pH and oxidation potential to sedimentary iron mineral formation: Econ. Geology, vol. 48, pp.337-357.

Innes, M.J.S. (1957), Gravity and isostasy in Central Quebec: Am. Geophys. Union Trans., vol. 38, pp.156-165.

James, H.L. (1954), Sedimentary facies of iron formation: Econ. Geology, vol. 49, pp.235-285.

James, H.L. (1956), Zones of regional metamorphism in the Precambrian of Northern Michigan: Geol. Soc. America Bull., vol. 66, pp.1455-1488.

Kunitz, W. (1930), Die Isomorphieverhaltnisse in der Hornblende Gruppe: Neuses Jahrb., Beilage-Band 60, Abt.A., pp.171-250.

Lindroth, G.T. (1926), Bidrag till fragan om kalk-skarnjärnmalmernas genesis: Geol. fören. Stockholm Förh., band 48, pp.357-410.

Miles, K.R. (1943), Grunerite in Western Australia: Am. Mineralogist, vol. 28, pp.25-38.

Mikkola, E., and Sahama, T.G. (1936), The region to the southwest of the "granulite series" in Lapland and its ultrabasics: Comm. geol. Finlande Bull. 115, vol. 19, pp.357-386.

Milton, C., and Eugster, H.P. (1959), Mineral assemblages of the Green River Formation: Researches in Geochemistry, edited by P.H. Abelson, pp.118-150.

Mueller, R.F. (1958), Chemical petrology of a metamorphosed iron formation (abstract): Geol. Soc. America Bull. 69.

Muir, I.D. (1952), The clinopyroxenes of the Skeargaard intrusion, Eastern Greenland: Min. Mag., vol. 29, pp.690-714.

Muir, I.D., and Tilley, C.E. (1958), The compositions of coexisting pyroxenes in metamorphic assemblages: Geol. Mag., vol. 14, pp.336-358.

Murphy, D.L. (1959), Preliminary report on Mount Wright area: Department of Mines, Quebec, 7.p.

Palmgren, J. (1916), Die Eulysite von Södermanland: Geol. Inst. Uppsala Bull., vol. 14, pp.108-225.

Perrault, G. (1955), Geology of the western margin of the Labrador trough: Ph.D. thesis, Univ. of Toronto.

Rabbitt, J.C. (1948), A new study of the anthophyllite series: Am. Mineralogist, vol. 33, pp.263-323.

Ramberg, H. (1949), The facies classification of rocks: Jour. Geology, vol. 60, pp. 331-356.

Ramberg, H. (1952a), Chemical bonds and the distribution of cations in silicates: Jour. Geology, vol. 60, pp. 331-356.

Ramberg, H. (1952b), The origin of metamorphic and metasomatic rocks: Univ. of Chicago Press, 317 p.

Richarz, S. (1927), Grunerite rocks of the Lake Superior region and their origin: Jour. Geology, vol. 35, pp.690-708.

Richarz, S. (1930), A peculiar blue-green amphibole from the metamorphosed iron formation of the eastern Mesabi Range, Minnesota: Am. Mineralogist, vol. 15, pp.65-69.

Saxen, M. (1925), Om mangan järnmalm fyndigheten i Vittinki: Fennia, vol. 45, no. 11, p. 18.

Seitsari, J. (1952), On association of cummingtonite and hornblende: Annales Academie Scientiarum Fennicae, Series A, III, Geologica-Geographica 30.

Seki, Y., and Yamasaki, M. (1957), Aluminian ferroanthophyllite from the Kitakami Mountainland, Northeastern Japan: Am. Mineralogist, vol. 42, pp.506-520.

Shapiro, L., and Brannock, W.W. (1956), Rapid analysis of silicate rocks: U.S. Geol. Survey Bull. 1036C, 56 p.

Simpson, E.S. (1928), Contributions to the mineralogy of western Australia: Series iii, Royal Soc. Western Australia Jour., vol. 14, pp. 45-56.

Sundius, N. (1924), Till discussionen on de svenska jarn och mangan malmernas genesis: Geol. fören. Stockholm Förh. band 46.

Sundius, N. (1929), Zur Kenntnis der monoclinen Ca-armen Amphibole: Geol. foren. Stockholm Förh., band 46, pp.154-167.

Sundius, N. (1931), The optical properties of manganese poor grunerites and cummingtonites compared with those of manganiferous members: Am. Jour. Sci., vol. 21, pp.330-340.

Sundius, N. (1933), Uber die Mischungslucken zwischen Anthophyllite-Gedrit, Cummingtonit-Grunerit, und Tremolit-Actinolith: Min. pet. Mitt., Band 43, pp.422-440.

Sundius, N. (1946), The classification of the hornblendes and the solid solution relations in the amphibole group: Sveriges geol. undersökning, Arsbok 40, no. 4, pp.1-36.

Thompson, J.B. (1959), Local Equilibrium in metasomatic processes: Researches in Geochemistry, edited by Ph.H. Abelson, pp.427-457.

Thompson, J.B. (1955), The thermodynamic basis for the mineral facies concept: Am. Jour. Sci., vol. 253, pp.65-103.

Tillgy, C.E. (1936), Eulysites from Ross-shire: Min. Mag., vol. 24, pp.331-342.

Tilley, C.E. (1935), Metasomatism associated with the greenstone hornfelses of Kenidjack and Botallack, Cornwall: Min. Mag., vol. 24, pp.181-202.

Turner, F.J., and Verhoogen, J. (1951), Igneous and metamorphic petrology, 602 p.

Van Hise, C.R., and Leith, C.K. (1911), The geology of the Lake Superior region: U.S. Geol. Survey Mono. 52, 641 p.

von Eckermann, H. (1922), The rocks and contact minerals of the Mansjo Mountain: Geol. fören. Stockholm Förh. band 44, pp.203-410.

Warren, B.E. (1930), The crystal structure and chemical composition of the monoclinic amphiboles: Zeitschr. Kristallographie, Band 72, pp.493-517.

Weeks, W.F. (1956), A thermochemical study of equilibrium relations during metamorphism of siliceous carbonate rocks: Jour, Geology, vol. 64, pp.245-270.

Winchell, A.N. (1938), The anthophyllite and cummingtonite-grunerite series: Am. Mineralogist, vol. 23, pp.229-333.

Wulfing, E.A. (1891), Beitrage zur Kenntnis der Pyroxenefamilie in der chemischer und optischer Beziehung, Heidelberg.

Yoder, H.S. (1955), The role of water in metamorphism: Crust ofthe Earth, Geol. Soc. America special paper 62, pp.505-524.

Yoder, H.S. (1957), Isograd problems in metamorphosed iron-rich sediments: Annual report of the director of the Geophysical Laboratory 1956-1957, pp.232-237.

BIOGRAPHY

The writer was born in Helsingfors, Finland on August 25, 1931. He attended Swedish Normallyceum in Helsingfors from where he graduated in 1949. He also attended high schools in Sweden and Switzerland for shorter periods. In 1949 he moved with his parents to Canada and enrolled the same year at McGill University in Montreal. From this university he obtained a Bachelor of Science degree in 1953 and a Master of Science degree in 1955. The title of the M.Sc. thesis was "The petrology of the Stony Rapids norite area in northern Saskatchewan." Since 1955 the writer has attended Massachusetts Institute of Technology. The studies were financed by Quebec Department of Mines scholarships in 1955-56 and 1956-57, and by a research assistantship in the fall of 1957.

Since 1950 the writer has worked during the summers for various mining companies and government surveys in Canada. In 1950 he was employed by the Iron Ore Company of Canada in Labrador, in 1951, by Quebec Department of Mines in the Mistassini area in Quebec, in 1952, by the Geological Survey of Canada in western Newfoundland, in 1953 and 1954 by the Canadian Nickel Company in northern Saskatchewan, in 1955, 1956, and 1957, by the Quebec Cartier Mining Company in northern Quebec, and in 1958 by the Geological Survey of Canada on Baffin Island.