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A STUDY OF PRECAMBRIAN BANDED  
IRON FORMATION

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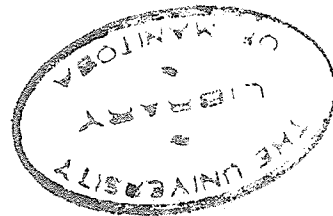
A Thesis  
Presented to  
the Faculty of the Department of Geology  
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In Partial Fulfillment  
of the Requirements for the Degree  
Master of Science

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by  
Rade Calich  
March, 1954



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## ABSTRACT

### A STUDY OF PRECAMBRIAN BANDED IRON FORMATIONS

by Rade Calich

A review of the literature shows that most writers agree that the Precambrian banded iron formations are of sedimentary origin.

Separate hypotheses are not necessary to explain differences in iron formations from different localities. All iron formations were alike in their early history, having begun to be formed by the same agencies. The earliest stage of recognizable iron formation was a precipitate consisting of iron oxide and silica. Present-day differences in iron formations resulted from various "accidents" which added new components or changed the compositions of the existing ones, namely, mixing of clastic sediments with the iron and silica components during deposition, addition of material from igneous sources, and metamorphism of the iron formation, including alteration.

A qualitative spectrographic study of magnetite grains from various iron-formation specimens proved non-diagnostic, but showed that a quantitative study would be in order.

A study of mounted and polished grains of the same magnetite showed no intergrowths of ilmenite or any other mineral with the magnetite. This might be taken as one evidence that the magnetite crystals did not grow from an igneous melt..

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## CHAPTER I

### INTRODUCTION

#### Nature of the Problem

The problem involves examination of specimens of iron formation by the use of various techniques, and a rather thorough inspection of the literature on iron formations, in order that the data so obtained may afford the development of a theory on their origin, or at least favor one of the existing theories. If it can be shown that the iron formations of Southeastern Manitoba are similar to the iron formations of the great iron ranges of the world, then any theory which has been proposed for the large iron deposits should apply to the small bands of Manitoba, and conversely, any new ideas revealed in a study of the Manitoba iron rocks should apply to their large-scale counterparts elsewhere.

#### Importance of the Investigation

There is yet no satisfactory hypothesis to account for the origin of Precambrian banded iron formations. Indeed, opinions differ so widely that even until a few years ago authorities did not agree on whether the iron formations were formed by sedimentation or by the intrusion of a liquid magma.

Many students of the problem have said that probably no one hypothesis can be applicable to Precambrian banded iron formations in general; that there is enough difference between

the iron rocks of various localities to demand a particular hypothesis for each one. However, it would probably be more correct to say that, for each particular type of iron formation, there is required not a particular hypothesis, but rather a particular minor variation of the same general hypothesis; for in spite of the specific differences between the iron formations of various localities, so many properties are common to all of them that the operation of some major factor must be admitted. All of them are strikingly banded; all of them contain iron and silica dominantly; and all of them occur only in wall-rock of Precambrian age. Surely there must be something in common among the conditions which favored the formation of them all.

The writer cannot hope to uncover this great truth; that task will require a profound insight into the principles of geology such as can be developed only through years of experience coupled with deliberate unprejudiced reasoning. This problem might even be one whose solution must await the time when the science of geology is more mature. But in the meantime, if this dissertation contributes in any way, however small, to a later solution of the problem, its presentation will be considered to have been fully justified.

#### Definitions

The term "Precambrian banded iron formation" is descriptive though cumbersome, and in this thesis it is replaced by the shorter term "iron formation". In the literature, however,

one encounters a variety of names. In the Mesabi district, the iron rock is called taconite; in the rest of the Lake Superior region it goes by the name of jaspilite, ferruginous chert, and siliceous ironstone; in Brazil it is known as itabrite; and in India and Australia it has the lithologic names hematite quartzite, hematite jasper, magnetite quartzite, jasper bars, and others. In Finland they are called jasper-quartzites. The term ironstone is sometimes used (Pettijohn, 1948, pp. 334 and 337) in connection with certain iron formations. Occasionally jasper has been used synonymously with jaspilite; this is erroneous in modern terminology. Most of these names are but local terms, and are confusing to readers not familiar with them; it is here suggested, therefore, that all Precambrian banded iron formations be grouped together as iron formation, as this term is becoming more widely accepted year by year. Further, the term could be incorporated into the development of descriptive conventional rock-names, for example magnetite-grunerite-quartz iron formation, hematite-siderite iron formation, and so on.

One distinction, which is not always fully expressed in the literature, but which must be recognized, is that iron formation, no matter under what other name it is known, is not necessarily iron ore; with a few exceptions, the iron formations of the world are too lean in iron to be classed as ore. The actual ore was derived by concentration of the iron from the iron formation which served as the protore; the processes of concentration are different from those which produced the iron

formation, and accordingly they are not discussed here.

Australia is one place where the iron formation itself is rich enough without secondary concentration to be regarded as ore (Miles, 1946, p. 119).

#### Previous Work on the Manitoba Iron Formation

Manitoba iron formations have not been studied hitherto because of their insignificant size and commercial unimportance.

#### Sources of Specimens

Seventy-four specimens of iron formation and associated wall rock were collected in Southeastern Manitoba during the summer of 1950. Localities of these are shown on the index map in the back cover of the thesis. In addition, eleven specimens were received from Australia; seven from Finland; two from the Marquette range of Michigan; one from the Cuyuna range of Minnesota; one from Great Bear Lake in the Northwest Territories; and one from the Black Hills of South Dakota.

Ninety-two thin sections were made of these specimens. In addition, fifty-nine polished sections and twelve grain mounts in bakelite were made of certain representative specimens of Manitoba iron formation.

## CHAPTER II

### REVIEW OF THE LITERATURE

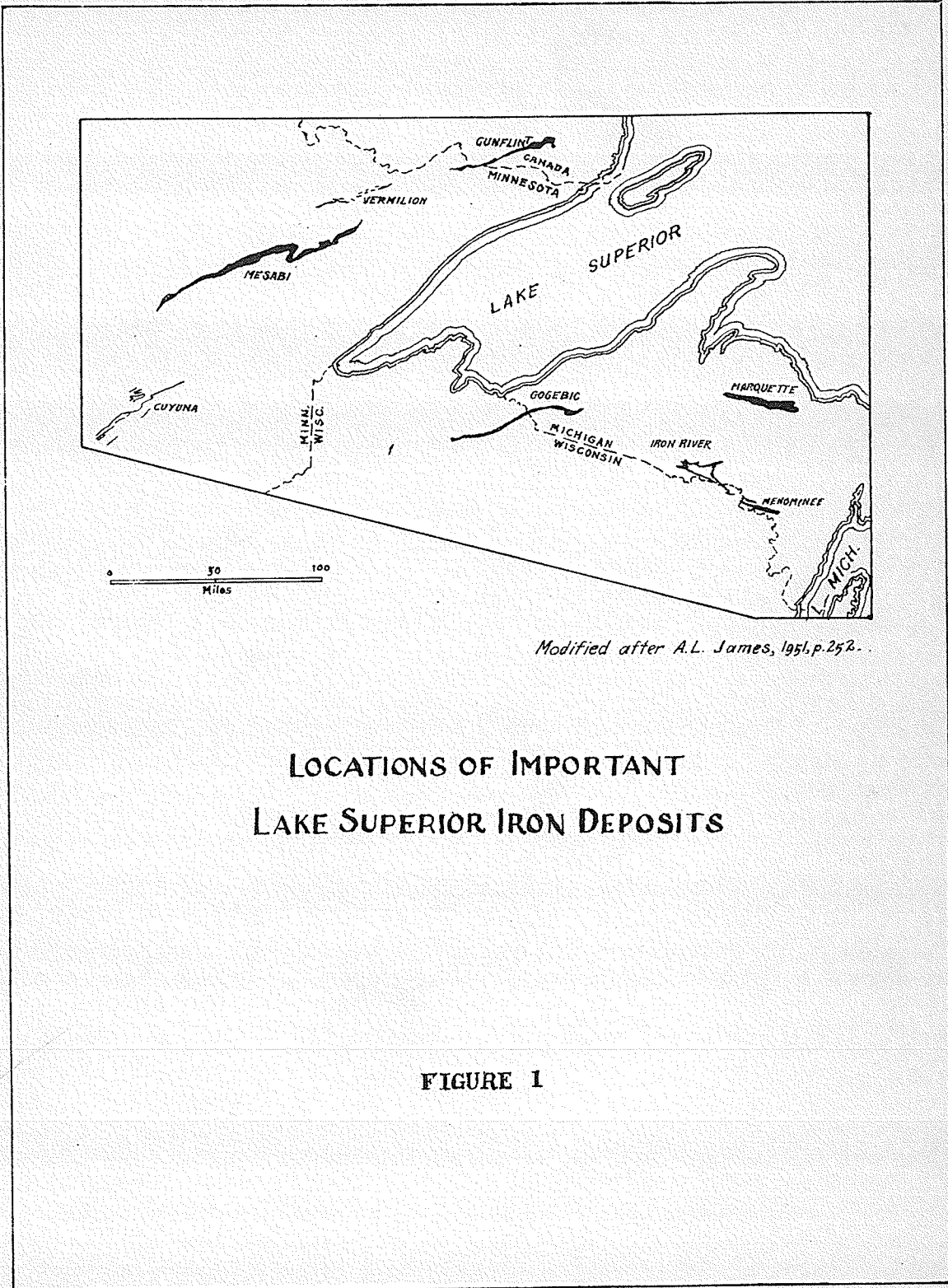
#### INTRODUCTION

The volume of literature on the origin of iron formation is prodigious. The Winchells (1891) list nearly a thousand references to literature directly or indirectly connected with the origin of iron ores, published before 1891; this is regarded by them to be an incomplete bibliography.

In this thesis, various theories are presented, much condensed, in two divisions. The first division includes the eighteen early theories which are synopsized by A. A. Julien (1882) and listed by the Winchells.<sup>1</sup> Some of the comments made by the Winchells on many of these theories are included. The second division consists of the most important theories proposed since that time, on which literature was available. The early theories are listed according to the kind of theory, for this is the way in which they are listed by Professor Julien; the modern theories are enumerated in approximately chronological order, to show the growth of modern concepts of origin of iron formation. Figure 1 shows the main localities to which reference is made in the literature.

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<sup>1</sup>References are not given here, but are quoted by N. H. Winchell and H. V. Winchell (1891).



*Modified after A.L. James, 1951, p.252.*

### LOCATIONS OF IMPORTANT LAKE SUPERIOR IRON DEPOSITS

**FIGURE 1**



## EARLIER THEORIES

### Theories of Extraneous Origin

Meteoric fall. Certain iron formations were thought to be of celestial origin, having dropped to earth as meteorites. Later, however, these have come to be considered to be of terrestrial origin.

Eruption as dikes, or in masses accompanying basaltic flows. Cracks in the earth have been filled and overflowed by molten iron from a large body of iron situated at a great depth below the surface.

W. W. Mather, in 1839, spoke of "injected veins" of iron ore penetrating the gneiss of New York; these, he said, have melted the gneiss but maintained a sharp contact with it instead of flowing together.

Sir R. Murchison said that certain magnetites in the Ural mountains had flowed out of the adjacent hillside into the depressions they now occupy.

Foster and Whitney proposed in 1851 that the iron ore deposits of Lake Superior had been erupted in the metallic state, then rearranged by oceanic action and covered by succeeding sediments.

Dr. E. Emmons advocated an igneous origin for the iron ores, as well as for quartz and calcite veins and beds of limestone.

In 1858, H. D. Rogers recognized other modes of origin

for some iron ores, but said that magnetic iron ore occurs as true injection veins.

B. Von Cotta, in 1864, accepted the eruptive hypothesis for magnetite, hematite, and even carbonate iron ores.

In 1878, J. W. Dawson described a vein of iron ore associated with carbonates of calcium and magnesium; he said that the vein was injected as molten or sublimed carbonate of iron, calcium and magnesium, and later roasted by heat, whereupon some of the siderite was oxidized to form red oxide of iron. He neglected to explain how, if the original melting did not oxidize the carbonate, the subsequent roasting would.

Dr. M. E. Wadsworth also believed in an eruptive origin for the Lake Superior iron deposits. The main argument against this is that in the ores, both granular quartz and magnetite exist in a state of high purity; in a magma they would have combined to produce silicates, by the same process as is used by the iron welders, who sprinkle sand on the ends of the iron to be welded in order that the silica may form an iron silicate slag with the magnetic iron oxide, which slag can then be knocked off. Winchell and Winchell (1891) state many excellent arguments, too numerous to mention here, against an igneous origin for the Lake Superior deposits. Magnetic iron ore and even metallic iron ore of magmatic origin, they say, do occur in Europe and Greenland, but these are not of the same type as the Lake Superior iron ores.

Sublimation into fissures and porous rocks. Ever since small deposits of hematite and magnetite were seen subliming from

hot volcanic vapors, there have been advocates of the formation of large deposits of iron ore in fissures connected with reservoirs of molten matter in the interior of the earth. This theory cannot be applied to regions without volcanic action, and even if volcanic action is present, the amount of iron deposited from large volcanoes in great periods of time is negligible.

### Theories of Indigenous Origin

Concentration from ferriferous rocks or lean ores, by solution and removal of the other predominant constituents. This theory was first put forth by G. Bischof in 1847. It accounts for subaerial concentration of iron ores, but not for the formation of subaqueous ores, nor the lean protores, which contain too many soluble minerals.

Saturation of porous strata by infiltrating solutions. First proposed by L. Vanuxem in 1838, this theory might account for some lean ores, but not for the pure hematite and magnetite ores.

Infiltration into subterranean chambers and channels. Small recent irregular deposits of limonite may have formed in this way, but cavities a mile or two long and from fifty to a hundred feet wide probably did not exist in rocks such as now contain the iron ores. This theory was advanced as early as 1847 and perhaps much earlier.

Decomposition of pyrite. The pyrite and other iron min-

erals of decaying schists were decomposed, and the iron was transferred as ferrous sulphate in solution, to be precipitated as carbonate or oxide. C. U. Shepard, the first advocate of this theory as early as 1837, was far ahead of his time, as he recognized that the ironstones of Connecticut were not veins but beds. He applied the theory only to limonite deposits.

Deposition in the sea. Ferric oxide and ferrous carbonate were laid down in a deep sea, either by mechanical or chemical deposition, and later dehydrated to form hematite, or reduced by further heating to form magnetite. E. Hitchcock, in 1833, seems to have been the first to advance this view.

C. U. Shepard, in 1837, and J. W. Foster, in 1849, suggested that the iron ores had an origin similar to that of their enclosing strata.

J. D. Whitney, in 1855, presented the hypothesis that the ores of Pilot Knob, Missouri, may have been introduced "by a precipitation from a ferriferous solution, in which the stratified rocks were in process of formation". This is very close to some of the most widely accepted modern theories.

Van Cotta likewise believed that "there can be no doubt that all true ore-beds were originally formed by mechanical or chemical precipitation from water".

J. P. Lesley and B. S. Lyman both believed that the iron ores found in sedimentary strata were precipitated as iron carbonate. R. D. Irving applied this method of formation to the Lake Superior iron ores, and Van Hise did likewise for the Penokee-

Gogebic ores of Michigan and Wisconsin.

M. E. Wadsworth claimed that the iron ores of Lake Superior are "chiefly eruptive, partly intrusive, partly in overflows; also formed in part by decomposition of the jaspilite and ore in situ, and in part by mechanical and chemical deposition".

Winchell and Winchell present their theory under this same heading. They say that molten material came in contact with ocean water, which dissolved out the iron; currents formed by the volcanic ejections and by the same causes as produce currents today, and carried the warm saturated solutions to cooler parts of the sea, where precipitates of silica and iron oxide formed. The iron formations are limited to Precambrian time because the earth's crust was thinner then, and more molten magma came to surface. The lenticular form and laminated structure of all iron formations are typically marine.

Deposit from springs. Bischof suggested that spring-deposited iron oxide might aid in the formation of iron beds. The amount of iron disgorged by springs, however, is negligible.

Alteration of diffused ferric oxide into ferrous carbonate. Iron oxide is reduced to carbonate by organic matter in place in the iron rock itself. W. B. Rogers was the only geologist who advocated this theory; if there was no organic life at the time of formation of the iron ores, Rogers' hypothesis could not apply.

Metamorphism of ancient bog ores. Robert Bakewell in 1833 suggested that ironstone may have been "the produce of decomposed vegetation as bog or peat-iron is supposed to have been".

A number of eminent authorities supported this bog-metamorphism hypothesis, among them being T. S. Hunt, J. S. Newberry, J. D. Dana, Jos. le Conte, and A. Geikie. Such a theory would require the presence of life on the earth early in the Precambrian -- a conclusion apparently justified by the presence of a little graphite in some of the Archaean ores; but graphite is not necessarily an evidence of life; it is found also in meteorites, and may also have been a primary constituent of the earth. Some writers, believing that iron ore can form only with the help of organic life, accepted it as axiomatic that the presence of iron ore indicates life.

Metamorphism of ancient lake deposits. Limonite of the lake ores might be metamorphosed to hematite ore resembling the fossiliferous oolitic ore of the Clinton. However, true lake ores contain phosphorus and sulphur, and are formed by the action of organic matter; these things are not true for the Keewatin and Huronian iron formations.

Violent abrasion and transport. J. D. Whitney in about 1855 proposed that in Precambrian time there was without doubt long-continued and violent action while the deposition of stratified sediments was going on, "volcanic agencies combined with

powerful currents may have abraded and swept away portions of the erupted, ferriferous masses, re-arranging their particles and depositing them again in the depressions of the strata". This theory of Whitney's is merely supplementary to his main eruptive theory; the objection to it is that such deposits would contain native iron and would be conglomeratic, which is not so.

Concentration and metamorphism of iron sands.

B. J. Harrington in 1873 was the first to propose this mode of origin. Crystalline rocks, on disintegration, yield magnetite and ilmenite which are concentrated in the same manner as in the Gulf of St. Lawrence at present; only some iron ores are formed in this way, the majority having originated as bog or lake ores. Julien elaborated this view, saying that both magnetite and quartz were deposited in alternating bands.

Julien further observed that no titanitic acid is found in bog ores; therefore the presence or absence of titanitic acid can be used in diagnosing whether an iron formation originated from the metamorphism of a black sand or a bog ore.

The Winchells object to the black-sand theory on the grounds that it does not account for the origin of the iron-rich rock from which the black sand was derived.

True veins formed by chemical segregation or secretion.

Probably no profitable deposit of iron originated in this way. Though veinlets of iron ore do occur in the form of limonite, siderite, or hematite, the theory is mainly a relic of the early days when all ore deposits were supposed to be in veins connected with the centre of the earth.

Electro-telluric action. Iron ores formed as a result of the reactions and decompositions produced by electro-magnetic currents in the earth. R. W. Fox spent many years maintaining the validity of this theory, but at that time (1822) the workings of electrical forces were not too well understood.

Substitution of ferrous oxide and change to peroxide.

Lime of the original rock was replaced by ferrous oxide, and this was then converted to ferric oxide. This may apply to more recent ores whose environments indicate the former presence of carbonate in the rock; but limestones are not found or believed to have existed abundantly in the Laurentian and Keewatin rocks themselves, and such limestones as are present show no transition to iron ores.

Decomposition of basic rocks. Eruptive or metamorphic basic rocks are decomposed, and the resulting iron is concentrated in drainage basins as oxide. J. P. Kimball in 1884 gave the clearest statement of this; he described the exact chemical processes by which he believes iron is removed from basic rocks. The Winchells disagree; the theory does not apply, they say, to the ores of Michigan, Wisconsin and Minnesota. The Keewatin rocks do not decay rapidly enough, and the iron ore bodies are so related to their enclosing sedimentary rocks as to appear definitely contemporaneous. The Winchells conclude that, though Kimball's description of the processes of removal of iron is good, the deposition was not in epicontinental drainage basins, but in the ocean; and the ore is not a separate product, as described



by Kimball, but is one of the contemporaneous constituents of the rock in which it occurs.

#### MODERN THEORIES

Even before Van Hise and Leith (1911) published their monograph on the Lake Superior region, most geologists accepted a sedimentary hypothesis for the origin of iron formation. To this day few have disagreed with such a theory, though many variations of it have been proposed.

Any sedimentary hypothesis for the origin of iron formation must answer a number of questions: (1) What was the source of the iron and silica ? (2) How were these transported ? (3) How were they deposited ? (4) Where were they deposited ? (5) Why are they so regularly and strikingly banded ? (6) Why were banded iron formations formed all over the world only in Precambrian time ? (7) What were the original minerals when they were deposited, before metamorphism converted them to what they are now ?

No hypothesis can be considered acceptable unless all of these problems are resolved; But a satisfactory resolution of them all is no simple task. As a result, some modern writers have been forced to revert to an igneous theory, with the hope that it can answer the questions more satisfactorily.

Spurr (1894): Fine detrital silt from subaerial erosion was reconstructed in moderately deep seas by marine organisms to a sediment consisting of glauconite grains and some calcareous and siliceous matter. The beds were elevated to the atmosphere; surface water

removed the calcareous material and decomposed the glauconite into silica and iron oxide. Finally the silica and iron were separated into bands or bodies -- the iron was concentrated in regions of greatest oxidation, the silica in regions of least oxidation. The areas of great oxidation were formed by regional disturbance of the strata.

N. H. Winchell (1899) accepts Spurr's hypothesis that the iron formation was originally a glauconite-like formation, but later (1900) proposes that the greenalite resulted from a volcanic sand.

Van Hise and Leith (1911): All the Lake Superior ores are similar in origin. Iron and silica came from the weathering of hot or cold basic igneous rocks, from direct contributions of magmatic waters from the magmas, and from direct reactions of the sea water on the hot lavas. The iron was precipitated from these solutions on contact with cold sea waters as oxide, carbonate and silicate.

Leith and Harder (1911): The Precambrian ores of the Minas Geraes district of Brazil are very similar to the Lake Superior ores. They were formed by normal processes of sedimentation; iron was deposited as ferric hydrate. Silica occurs as sand grains, not as chert.

Harder and Chamberlin (1915, pp. 399-401): The iron formation, or itabrite, of Minas Geraes is an iron-oxide-bearing sandstone or quartzite. The quartz grains are the result of ordinary clastic disintegration of crystalline rocks. The origin of the iron could not have been clastic because the iron

oxides occur almost pure in great masses, and a clastic origin does not account for this segregation of iron and silica. Probably the iron was deposited from solutions in which it was in the form of carbonate, becoming oxidized on deposition. The precipitation may have been purely chemical, but was more likely due to bacterial action. Iron was deposited whenever the conditions were favorable for precipitation rather than for clastic deposition.

Grout (1919): Silica is best dissolved by alkaline solutions, iron by acids. The best solvent for both iron and silica together would therefore be an alkaline bicarbonate solution. The iron may have come from the weathering of basic rocks, or as magmatic emanations. Deposition occurred on the broad bottom of a shallow sea. Organisms were responsible for the precipitation. The banding resulted from the recurrent dying off of the organisms whenever too much iron accumulated. The original minerals were chert and ferric oxide. Metamorphism produced magnetite and recrystallized coarse grained chert.

Grout and Broderick (1919) maintain the same theory as the above, but say that the original rock was chert containing siderite, ferric oxide and greenalite.

Gruner (1922,1924): The Biwabik formation originated during Upper Huronian time, when large areas of North America were covered by greenstones and basalts. Iron and silica were dissolved by ordinary surface waters, and carried to the sea by rivers rich in organic matter, which kept them from being precipitated prematurely. This may have been a large inland sea or the ocean.

The precipitation of silica and iron was caused chiefly by algae and bacteria, but also partly by inorganic reactions. A small part of these colloids partly united to form indefinite amorphous iron silicates, but most of the freshly-precipitated material was in the form of silica, and carbonates and oxides of iron. Hot submarine lava flows or springs may have contributed a small part of the silica, but little or no iron. Metamorphism produced taconite, or ferruginous chert.

Leith (1924) admits that the source of the iron is still not certainly known. Today, iron is being removed by ordinary weathering to a lesser extent than any other element except aluminum; thus iron formations cannot be the result of normal weathering as we know it today. For some iron formations, volcanism may have supplied the iron, but in most of the iron formations of the world no such agency can be noted.

Macgregor (1925) replies to Leith by stating the essence of his theory, which he published in full two years later, on the Precambrian atmosphere. He indicates that if the Precambrian atmosphere consisted almost entirely of carbon dioxide and nitrogen, the difficulties in explaining the source of iron would become negligible; Water rich in carbon dioxide very easily dissolves the ferrous carbonate of basic rocks, and also enhances the removal of silica from silicate minerals.

Quirke (1925) condemns Macgregor's hypothesis on the grounds that it "transgresses the law of uniformitarianism".

Collins, Quirke, and Thomson (1926): The Michipicoten iron formations were formed by ascending hot solutions contain-

ing  $\text{CO}_2$ , Fe,  $\text{SiO}_2$  and S compounds at least. The solutions converted the volcanic tuffs, through which they were ascending, to carbonates and sulphides of iron. When they reached the surface, they spread out in depressions and by evaporation and cooling precipitated their content of silica and any remaining carbonate.

Gill (1927) : The iron and silica of the Gunflint iron formation came from the normal weathering of country of low relief during temperate or tropical climate. The iron and silica were transported to sea by rivers in which they were stabilized by organic colloids. Precipitation was affected not by organisms, but probably by mixing of solutions. The final product was hydrated ferrous silicate, hydrated ferric oxide, and silica. Locally calcium carbonate was precipitated, reacted with the ferrous compounds, and formed ferrous carbonate. Thick banded iron formations were produced only in Precambrian time because only then were low relief and a temperate climate maintained for the proper length of time.

Macgregor (1927): The Precambrian atmosphere was nearly devoid of oxygen, and rich in carbon dioxide. Ferrous carbonate, abundant as a decomposition product in early lavas and sediments, was readily dissolved out by water rich in carbon dioxide. The presence of carbon dioxide also increased the solubility of silica from silicate minerals. The iron was transported in solution and deposited by bacteria; Iron-depositing bacteria can precipitate iron in the ferric state in the absence of oxygen; moreover, if algae with chlorophyll were present in middle Precambrian time,

the oxygen which they produced would serve to precipitate ferric iron from ferrous salts in solution. By this hypothesis, the world-wide distribution of iron formation and its limitation to the Precambrian eon is self-explanatory.

Aldrich (1929): The iron and silica of the ironwood range of Wisconsin are of magmatic origin; they were transferred from depth to surface in one of two ways: Either they were emitted from magmas at depth and brought up in aqueous solution; or the molten lavas themselves came up to surface and gave up iron and silica solutions to sea waters or meteoric waters. Deposition was by repetition of the same process: Immediate gel deposition of the silica, then more leisurely precipitation of ferrous carbonate. The carbonate remained unoxidized because it was deep under water, away from free air.

Stark (1929): The Agawa iron formation of northeastern Minnesota is an impure clastic sediment. There is no evidence that iron and silica were ever precipitated chemically, nor is there any replacement by carbonate, as there is in the Michipicoten range. In Huronian time, the sea was agitated by intermittent volcanic ejections, as shown by the series of tuffaceous sediments; but during the quiescent periods between explosive ejections, finely-sorted iron-rich quartzose bands were laid down by floating and leaching away of the lighter and more readily soluble feldspar and hornblende, by wave action, leaving behind an iron-rich quartzose residue. With renewals of rapid additions of volcanic material to the sea, the iron-rich rocks were soon covered by coarser tuffs.

Moore and Maynard (1929): Iron is dissolved by cold water from rocks, and carried as ferric oxide hydrosol; silica is carried as colloidal silica; and both are stabilized by organic matter. When carried into the sea, silica and ferric oxide are precipitated by the electrolytes there present. Banding is due to differential rates of precipitation of these substances, combined with the influence of seasonal changes on the type of material brought in at different periods throughout the year. If abundant organic matter was present, iron carbonate could form instead of iron oxide. Hot waters (from thermal springs) may have played a more important part than is commonly thought.

Dunn (1935): The iron formations of India were originally fine-bedded ferruginous tuffs; as these were deposited under sub-aerial conditions, the chlorite and magnetite of the tuffs were oxidized to hematite both by the atmosphere and by magmatic solutions produced during contemporaneous volcanic activity. The same solutions silicified the tuffs at the surface during deposition. The banding of the iron formations is therefore a retention of the fine bedding of the tuffs.

Dunn (1941) again states the same theory for the origin of the iron formations of India.

Gruner (1941, pp.1616-17): Some of the Agawa formation was definitely formed by replacement. A shear zone cuts across beds of a syncline and replaces them with iron carbonate. In other places, greywackes and slates grade into chert; these in turn become replaced by iron oxide and jasper bands as a greenstone contact is approached. Even the greenstone is replaced by

iron carbonate along definite shear zones.

Woolnough (1941): It has been recognized that there are three types of sedimentary iron deposits: The older Precambrian iron formations, which are highly siliceous and markedly banded; the later Precambrian, obviously sedimentary iron formations which are less strongly banded and less siliceous; and the Paleozoic and Mesozoic formations, which are of marine origin, only slightly siliceous, and not banded.

The reason for this difference is that the early Precambrian formations were deposited on land, whereas the later ones were deposited in the sea.

When a colloidal solution of iron and silica enters the sea, the iron is precipitated immediately, but the silica is carried away by tidal and river currents, and laid down elsewhere; the resulting ferruginous sediments are therefore not banded.

The well-banded Precambrian formations, on the other hand, were formed as follows: The continent was very well peneplained, and rainfall was seasonal. Streams were sluggish. During the dry season, saline deposits formed in the depressions; at the same time, hydrosols of iron oxide, alumina and silica, stabilized by organic colloids, rose from the sub-soil to the surface by capillarity, and were precipitated by evaporation. During the next rainy season, the iron and silica were redissolved by the extremely slow-moving streams, and carried down to the basins, where they were precipitated by contact with the electrolytes; the iron was precipitated immediately, the silica next; thus a band of silica formed above a band of iron oxide. The soluble



salts were eventually redissolved during the same rainy season, and carried away from the site of deposition and down into the subsoil. Alternation of dry and rainy seasons thus produced a strongly-banded iron formation. The special conditions required, then, are widespread peneplanation combined with seasonal rainfall.

Taliaferro (1943, p.152): Hot-springs supplied the iron, silica and manganese for the Jurassic Franciscan formation of California.

Bruce (1945): Both the Huronian and Keewatin iron formations seem to have been subaqueous in origin, because their overlying rocks were deposited under water. It is not necessary to assume widespread operation of a single type of process, since iron formations differ in the details of their composition, and have evidently been formed under different conditions. Moreover, Precambrian iron formations are so similar to sediments of later epochs that it seems impossible that the processes under which they formed were unique and occurred only in Precambrian time. It is more likely that accumulation and precipitation took place under some specially favorable combination of circumstances that occurs seldom, but that is not restricted to any age.

Miles (1946): The iron and silica were derived from the chemical weathering and erosion of an originally probably basic terrain. These were transported as ferric oxides and silica hydrosol stabilized by carbonaceous matter. They were brought to the continental shelf by rivers, and there precipitated, by inorganic chemical processes, as carbonate, or hydroxide, or both;

in the presumably carbon dioxide-rich atmosphere, the hydroxide would be rapidly converted to carbonate. Precipitation was brought about by the electrolytes already present in the sea water.

This iron hydroxide and carbonate later became dehydrated and oxidized to magnetite. Some siderite still remains where metamorphism was not too intense.

In areas of higher temperature and pressure, some of the iron of the original hydroxide or carbonate has reacted with silica to form grunerite, hedenbergite, and fayalite.

Various impurities present in the original rock gave rise to several other types of metamorphic minerals.

Miles also states the older theory which was held in Australia by many workers, but with which he disagrees; namely, that the "jasper bars" are silicified shear zones.

Tyler (1948) found it hard to agree with the statements of Leith and Harder (1911) and of Harder and Chamberlin (1915) that quartzose components of the Minas Geraes iron formation were, because of their sandy appearance, necessarily of clastic origin. He did a laboratory study of a number of specimens from that locality and found that the Brazilian itabirite does not contain clastic heavy accessory minerals, such as should be found in most truly clastic rocks. Moreover, he found the quartz of the itabirite to have a mosaic texture. He concludes that the quartzose phase of the itabirite is a recrystallized chert, and not a clastic quartzite. No heavy accessory minerals occur in the Lake Superior iron formations either; thus the Minas Geraes iron

formation is very similar to the metamorphosed recrystallized phase of the Lake Superior iron formation, and probably has the same origin.

Kaitaro (1949): The jasper-quartzites of Finnish Lapland are very similar to the iron formations of the Lake Superior region. They were considered by V. Hackman in 1925 to be normal sediments, older than the surrounding greenstones. In 1941, E. Mikkola proposed that they are sinter deposits on the continent, related to movements of basic magmas.

According to the trace-element researches of Th. G. Sahama in 1945, the elements zirconium and titanium, typical of residual quartzites, are rare or absent in the jasper-quartzites, indicating that the jasper-quartzites are not residual material. Germanium and gallium, abundant in recent hot-spring deposits, are absent in the jasper-quartzites; this signifies that if the jasper-quartzites owe their origin to magmatic exhalations, these exhalations must have taken place under the ocean, inasmuch as germanium and gallium, according to their geochemical behavior, tend to remain in sea water instead of being precipitated along with the rest of the hot-spring material. Iron-rich solutions alternating with silicic acid exhalations passed into the sea, and iron in the form of hydroxide or perhaps carbonate was precipitated. Whether the precipitation was accomplished by organic or inorganic agencies cannot be determined. The solutions of iron and silica were a by-product of the extrusion of spilitic flows which are abundant in the area.

Tanton (1950): Iron range rocks are formed by liquid

immiscibility in ore-forming magmas. They are not of sedimentary origin. The banding is due to flowage of molten immiscible iron-bearing and siliceous material. Tanton agrees with Wadsworth (v. page 9), and holds that the igneous interpretation accounts for all the Lake Superior iron ores.

James (1951): The iron-rich rocks of the Iron River district of Michigan and Wisconsin were formed during humid-tropical or humid sub-tropical conditions, whenever these conditions arose, regardless of extensive changes in physical environment. Deposition was in closed basins, as described by Woolnough. The rocks are products of an era of iron-rich sedimentation during which the type of iron mineral formed depended on the immediate depositional environment.

## CHAPTER III

### PETROGRAPHIC STUDY

#### INTRODUCTION

The purposes of a petrographic study were (1) to learn the constitution of the various iron formations; (2) to show whether there are enough direct or indirect similarities among them; if iron formations from various localities are similar or identical mineralogically and texturally, it should be reasonable to suppose that they all had a similar origin; (3) to see whether the data so obtained contribute any evidence in support of one or another hypothesis on the origin of iron formation.

Although most of the information was obtained from the examination of thin sections of iron formations and their enclosing wall rock, such an examination would not show the exact nature of the opaque minerals, such as magnetite, hematite and others which might be present but which could be missed in a thin-section study. Therefore the thin-section study was supplemented with a study of polished sections, enough of which were made for each locality to afford a fair representation of the opaque minerals. The polished-section evidence is too meagre to warrant a separate description, and for this reason it is presented in conjunction with the thin-section data.

#### PETROGRAPHIC DESCRIPTION OF IRON FORMATIONS

##### Lake Superior Region

The only specimens of Lake Superior iron formation

studied in thin section were the three from the Marquette and Cuyuna ranges; these specimens are described at the end of this chapter. A general description of the Lake Superior rocks is necessary in addition, in order that the rocks which were actually studied during the present investigation might be compared with them, especially as, due to their large size, and to the amount of work already done on them, the Lake Superior rocks have become standards of comparison for other iron formations of the world.

E. L. Bruce (1945, p.595) has adequately summarized the important characteristics of banded iron formations of the Lake Superior region. The iron formations of the Vermilion, Gunflint and Michipicoten ranges are of Keewatin age; those of the Mesabi, Cuyuna, Penokee-Gogebic, Marquette, Iron River, Menominee and Baraboo ranges are Huronian. The iron formations are finely banded, composed of alternate bands of quartz and some variety of iron oxide and often amphibole. Most of them do not contain clastic minerals, though some contain layers of chlorite and actinolite schists, which represent fine-grained muddy sediments. In many iron formations carbonates are present in the form of siderite, sometimes as ferro-dolomite or calcite; if carbonate is absent now, there is often evidence testifying to its former existence. In the iron formations of Huronian age, greenalite -- a granular "amorphous" ferrous silicate -- is an important constituent of certain beds. Most of the iron formations occur in sedimentary rocks, but others occur in tuffs; some occur with chlorite schists which may be volcanic rocks, or iron-rich sediments. Keewatin

iron formations lie usually but not always directly on basic lavas.

The mineralogic constitution of the Lake Superior iron formations is described in more or less detail by Bruce (1945, pp.590-591). Below is a summary of his descriptions.

Soudan formation of the Vermilion range: Five types have been recognized:

- (1) Slightly ferruginous well-banded chert.
- (2) Dark grey or black cherty bands interlaminated with bands of magnetite and some amphibole.
- (3) Red layers of quartz with minute hematite flakes interbanded with layers rich in hematite, with magnetite in places.
- (4) White quartzose bands alternating with iron-rich layers of brown hematite with limonite in places.
- (5) Grey banded rock, the light-colored bands of which are mainly siderite.

Biwabik formation of the Mesabi range: Yellow, brown or green ferruginous cherts with some amphibole and siderite. Some beds are largely greenalite in a cherty matrix.

Negaunee formation of the Marquette range: Cherty iron carbonates, sideritic slates and jaspilites; the jaspilites consist of bright red quartz layers alternating with dark red bands rich in iron oxides. Ferruginous cherts associated with the jaspilite are less brightly colored and contain some earthy oxides.

Penokee and Gogebic ranges: Slaty and cherty iron carbonates as in the Marquette formations and ferruginous cherts as in the Mesabi; the carbonates are ferro-dolomite as well as siderite.

## Southeastern Manitoba<sup>1</sup>

In the field, the iron formation bands are easily recognized by their striking banding, dark color, and resistance to erosion which makes them stand out in relief above their wall-rocks. The thickness of the bands of iron formation seen in southeastern Manitoba ranged from about an inch to a hundred feet or perhaps more -- the thicker bands were not usually exposed across their whole outcrop width. The appearance of a typical folded band of iron formation is shown in Figure 2.

Long Lake and Bidou Lake. A series of parallel iron formation bands, each no more than two inches wide, is interbedded with tuff. In the tuff, parallel to the iron bands on either side, is a basic sill consisting essentially of greenish-blue amphibole.

Two varieties of tuff were seen, grading into each other. One is a coarse-grained arkosic tuff, composed of crystals of plagioclase (andesine), fragments of rhyolite, and grains of chloritic material, possibly pseudomorphic after some mafic material. The matrix is made up chiefly of euhedral crystals of epidote and some chlorite. The other tuff is a fine-grained, fine-bedded cherty variety, consisting of a fine-grained quartz matrix, in which are minute flakes of chlorite and small lenticular epidote aggregates aligned parallel to the bedding. Figure 3 shows coarse-grained tuff overlying fine-grained tuff. Cross-bedding and grain gradation are seen here on a microscopic scale.

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<sup>1</sup>.For localities of Manitoba specimens see the index map in back.





FIGURE 2

Appearance of two parallel thin bands of  
iron formation (dark grey) in the field,  
near Gunnar mine.

Photo by Derek Featherstonhaugh



X 7.5

FIGURE 3

Grain gradation in tuff  
Specimen 73

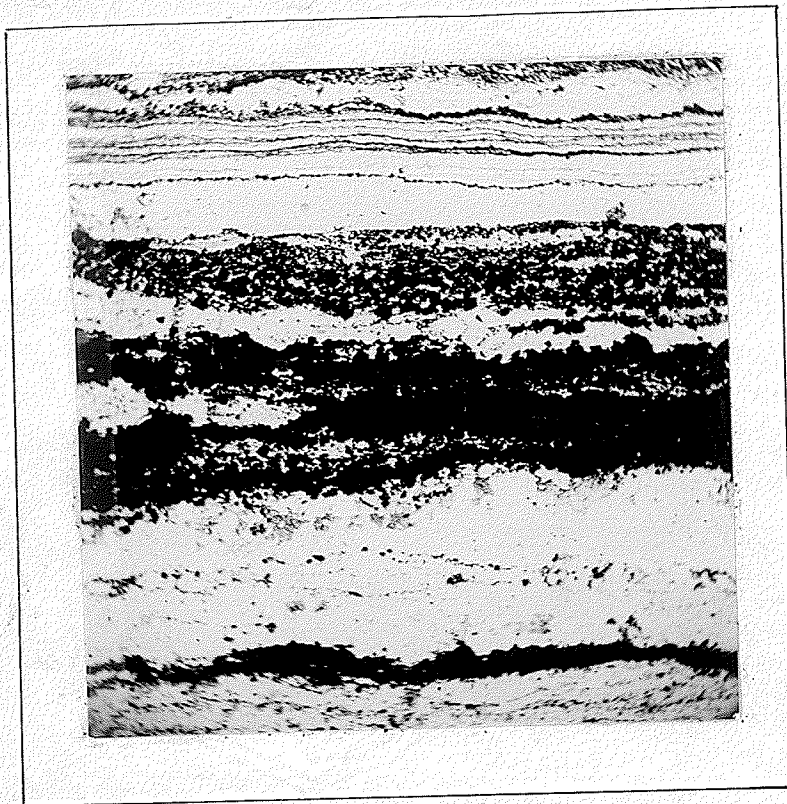
Nearer the sill the cherty tuff is richer in epidote and chlorite (though these may be part of the original tuff), and is cut by veinlets of blue amphibole; near the veinlets in the tuff are a few minute dark blue tourmaline crystals.

The iron formation bands farther from the intrusive consist simply of a fine-grained mosaic quartz matrix in which small magnetite crystals are concentrated in bands (Figures 4 and 5). Radiating clusters of minute needles and flakes of stilpnomelane are regularly disseminated throughout.

Closer to the intrusive, cracks in the iron formation are filled with coarse-grained mosaic quartz and occasional needles or even large, irregular grains of blue amphibole (Figure 6). Stilpnomelane occurs in these veinlets in larger grains than in the matrix of the iron formation band. The veins also contain large euhedral pyrite crystals, and some chalcopyrite.

In places the blue amphibole veins are dominant; the rock resembles a breccia in which the fragments are magnetite-chert, and the matrix is blue amphibole. The fragments are no longer merely magnetite and quartz, but consist of magnetite, stilpnomelane, limonite, and some quartz; the magnetite grains are not euhedral as in the fresh iron formation, but rounded. Displacement of the fragments is very small.

Gunnar Mine. Two bands were examined from the Gunnar mine. The band west of the shaft appears to be an offset continuation of the band north of Bidou Lake; it is likewise enclosed in tuff, and consists of quartz and magnetite; however, it contains chlorite to the extent of about fifteen percent, and no stilpnom-

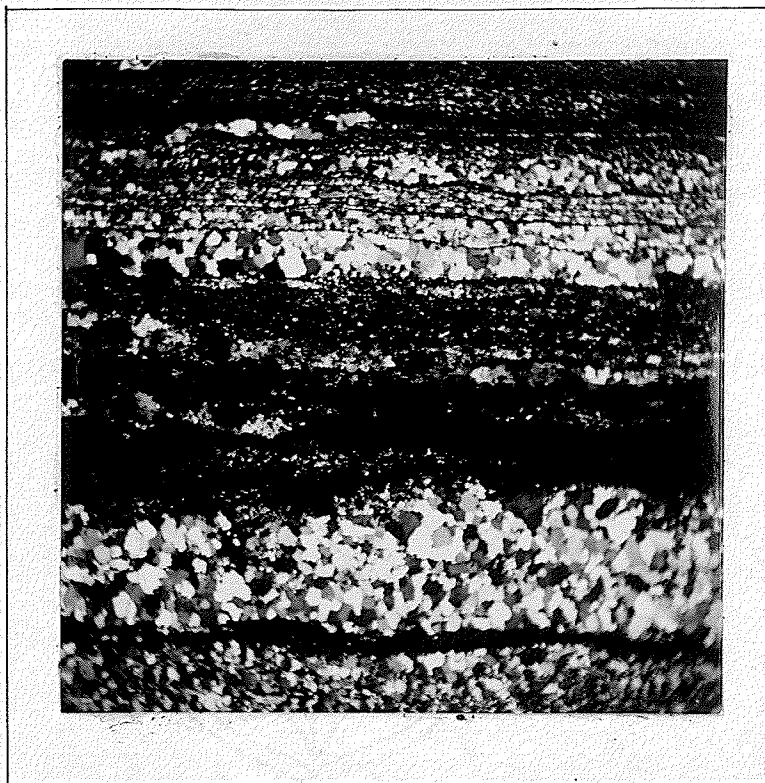


X 17.5

FIGURE 4

Pure quartz-magnetite iron formation with  
small patches of carbonate  
Specimen 52



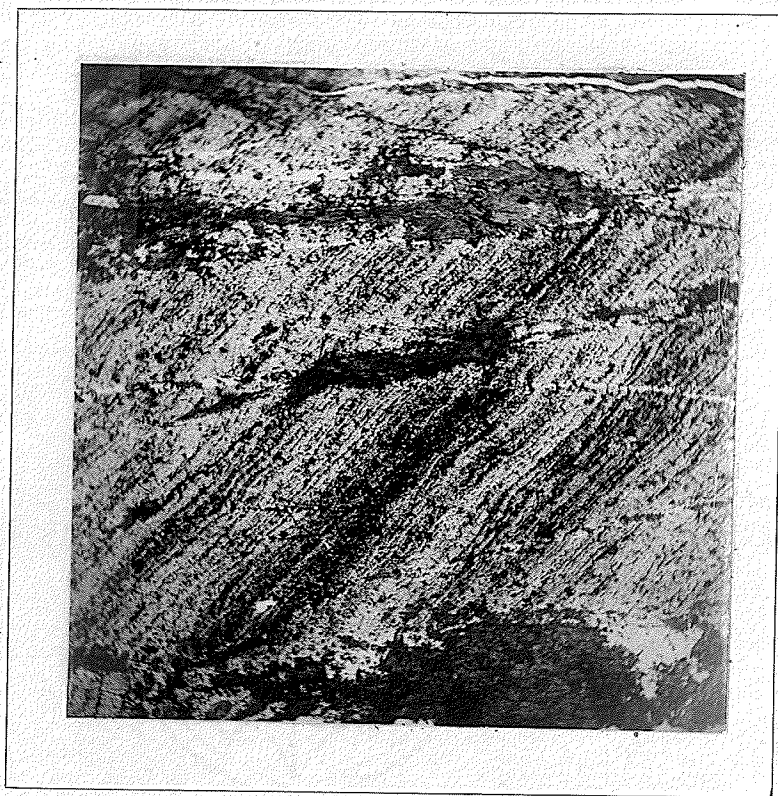


X 17.5

Crossed nicols

FIGURE 5

Same field as Figure 4 but with crossed  
nicols  
Specimen 52



X 16

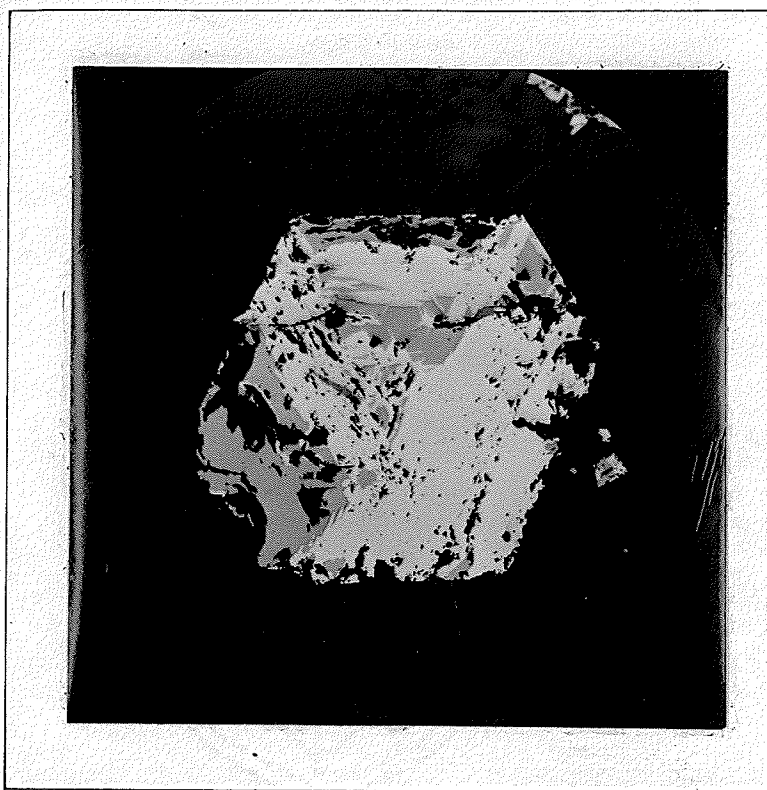
FIGURE 6

Veinlets of blue amphibole in quartz-  
magnetite iron formation  
Specimen 66

elane. The grain size of all minerals is greater than at the Bidou Lake locality. The iron band is traversed by calcite veinlets. About half of the magnetite has been replaced by hematite along definite planes. Some of the grains are composed entirely of hematite but retain the magnetite outline; therefore they may be designated as martite (Figure 7).

The band east of the shaft is intimately associated with bedded tuff. The tuff consists of fragmental plagioclase, quartz and carbonate, in a matrix of these same minerals together with small chlorite flakes; the chlorite flakes are parallel to the bedding unless the tuff is drag-folded, where they are parallel to the axial planes of the folds. Beds of tuff alternate with bands of mosaic quartz; some of these quartz bands contain calcite patches and rhombs; others have euhedral magnetite crystals, with or without calcite; these latter are therefore the iron members. In some of the non-ferruginous quartzose layers, and in the magnetite-bearing layers, minute flakes of chlorite are scattered, apparently more concentrated nearer magnetite-rich areas.

An altered diorite, consisting of large crystals of mottled pale green and blue amphibole in a dominantly epidote groundmass, lies very close to the iron band, which follows the contact between the tuff and the diorite, but no metamorphic or hydrothermal effects appear to be present in the tuff or iron bands. However, in the diorite itself there are small, indefinitely bounded streaks and twisted lenses of cherty-looking material, which resembles inclusions of tuff in the process of assimilation.



X 175

FIGURE 7

Polished section showing replacement of magnetite (dark grey) by hematite (light grey) along crystallographic directions  
Specimen 43

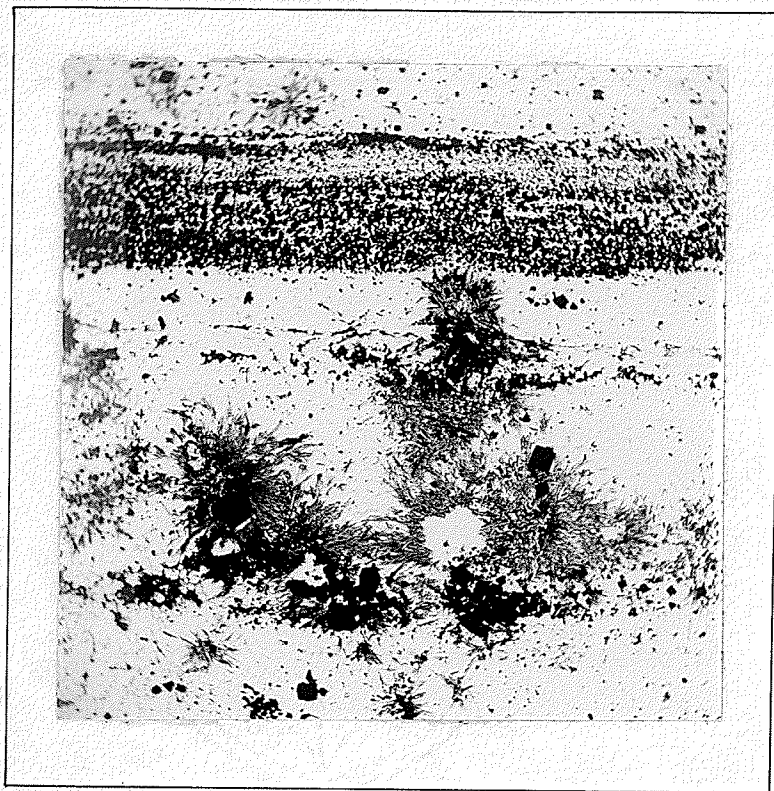


Garner Lake, Beresford Lake, Moore Lake. A long, fairly wide zone consisting of numerous iron formation bands interlaminated with beds of tuff and sediments stretches from Garner Lake past Beresford Lake to Moore Lake.

At Garner Lake the iron formation consists of a matrix of medium-grained mosaic quartz containing euhedral magnetite grains and radiating clusters of grunerite (Figure 8). Stilpnomelane is present among the grunerite needles and especially in the cracks and about the margins of the larger magnetite grains. The grain size of the magnetite varies with that of the quartz -- when quartz appears as large grains, the magnetite granules are also large. A few small irregular grains of blue amphibole are present.

The wall rock is a quartz-bearing chlorite schist in which the quartz occurs as angular grains between chlorite flakes. Longitudinal and diagonal fractures and shears in the chloritic mass are filled with calcite and some stilpnomelane laths.

In another place north of Garner Lake, calcite has replaced nearly all the quartz of the iron formation, bands of which here occur in "limestone" -- probably a well-carbonatized shear zone parallel to the trend of the iron formation and sediments. The iron formation from this locality has a marble-like groundmass of calcite ( $\omega = 1.659$ ) in which appear a few grains of quartz, some grunerite, magnetite and chlorite. The chlorite and magnetite are associated together in bands, and are deformed considerably. This deformation and perhaps the presence of chlorite are evid-



X 17.5

FIGURE 8

Quartz-magnetite iron formation with  
radiating grunerite needles  
Specimen 32

ently results of the shearing.

East of Beresford Lake, the "fresh" iron formation is the same as the unreplaced variety from Garner Lake, and is made up of magnetite, grunerite, and stilpnomelane; quartz, though not lacking, is subordinate in quantity. In polished section, the magnetite grains are seen to be altering along cracks to hematite. Some phases, however, are slightly different; in one, the quartz matrix contains small carbonate rhombs, of the same size as the quartz grains of the matrix, disseminated throughout, and stained brown wherever they are near a magnetite grain. Calcite veinlets cut across the structure in all directions. Another phase of the iron formation has plagioclase grains along with the quartz of the matrix; these interlock with the quartz grains in a typical mosaic structure. Small patches of calcite, not abundant, are present. Two specimens contain many small needles of blue amphibole.

The foot-wall rock is the same chloritic tuff that was seen at Garner Lake. The hanging-wall rock is a greywacke consisting of fragments of quartz and plagioclase, ragged patches of calcite, flakes of chlorite and abundant small clusters of epidote.

Between Moore Lake and Little Bulldog Lake, several bands of iron formation run parallel to a contact between greywacke and diorite. Some of the bands are in greywacke, others are in diorite. In some places the iron rock is tightly folded, and the folds are truncated by the diorite.

The diorite is very much like that found at the Gunnar mine and consists of mottled pale blue and green amphibole in a



matrix dominantly of epidote and fine-grained mosaic quartz, or perhaps feldspar.

The bands from the greywacke are the same grunerite-magnetite-quartz-stilpnomelane rocks seen east of Beresford Lake and north of Garner Lake, without calcite. One specimen (Figure 9) is almost completely grunerite, quartz and stilpnomelane. Traces of magnetite remain as black dust in streaks parallel to the banding. The quartz here forms bands which alternate with bands of grunerite and stilpnomelane; it is coarse-grained, so that in hand-specimen these bands resemble sandstone.

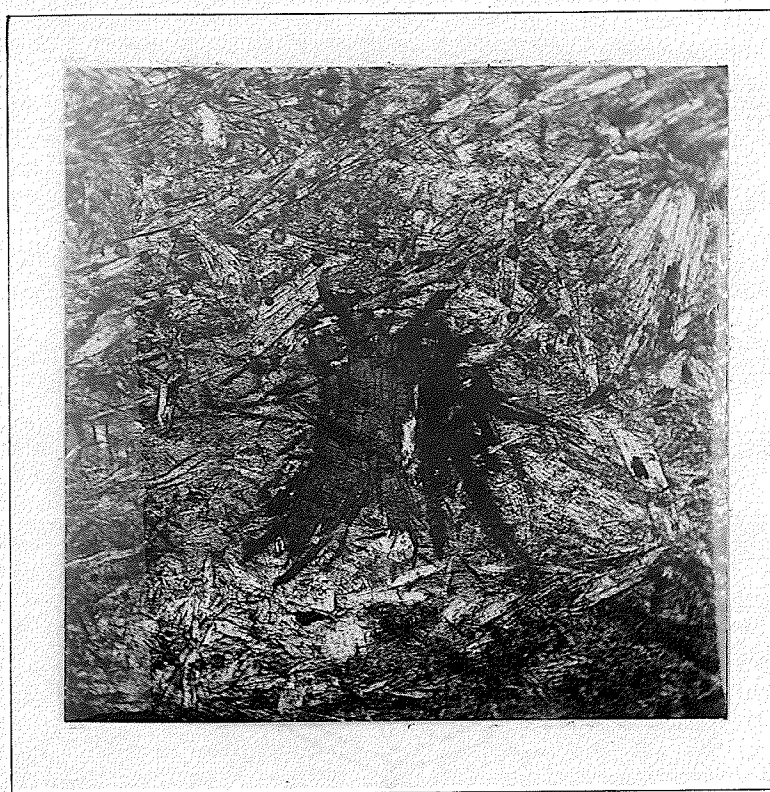
Some of the iron formation from the diorite is not much different than that from the greywacke; some specimens are all grunerite and magnetite, others are quartz, grunerite and magnetite; only one differs in that it is permeated along one band by blue amphibole and epidote, so that this band consists of slightly rounded or irregular magnetite grains in a matrix of epidote and blue amphibole.

In grunerite-bearing specimens, the grunerite crystals are tinted pale blue in places, especially wherever stilpnomelane laths occur.

One specimen consists of bands of almost pure epidote alternating with bands of an epidote-grunerite intergrowth. An x-ray powder photograph was taken to confirm the identity of the epidote, which makes up about fifty percent of the specimen.

Polished sections of the specimens from the Garner-Beresford-Moore lakes band show occasional large pyrite cubes, usually altering to limonite; in fact, a few cubes of pure limonite





X 60

FIGURE 9

Grunerite iron formation without magnetite.  
Dark crystals in centre are stilpnomelane  
Specimen 59

pseudomorphic after pyrite are present. Limonite also results from the alteration of other iron-rich minerals such as siderite, epidote or blue amphibole; but very little of the limonite appears to have come from magnetite; this latter, if it alters, forms hematite (martite) instead.

The whole assemblage -- diorite, greywacke and iron formation -- is cut by granite dikes.

Wallace Lake. The iron formation at Wallace Lake is exactly the same as the magnetite-grunerite-quartz phases of the formation just described. As the Wallace Lake specimens were collected from an area of intense drag-folding, the quartz in them is stretched into long grains with strain shadows. Pyrite is abundant, composing about twenty-five percent. of the opaque minerals.

Lily Lake. Magnetite-bearing slate or metamorphosed tuff grades into slaty iron formation, and this grades in turn into almost pure magnetite-hematite-quartz iron formation with very little chlorite.

The magnetite tuff consists of chlorite, white mica, magnetite, and angular, strained, small quartz grains; calcite is also present as separate patches. Most of the chlorite and mica are oriented parallel to the banding, but a few flakes have assumed oblique directions as a result of folding. Magnetite is in fairly large euhedral crystals.

As the magnetite increases in quantity, chlorite and sericite decrease, and the quartz progressively becomes coarser-

grained and acquires a sutured texture. Thus the composition of the rock grades from magnetite-bearing tuff to true iron formation.

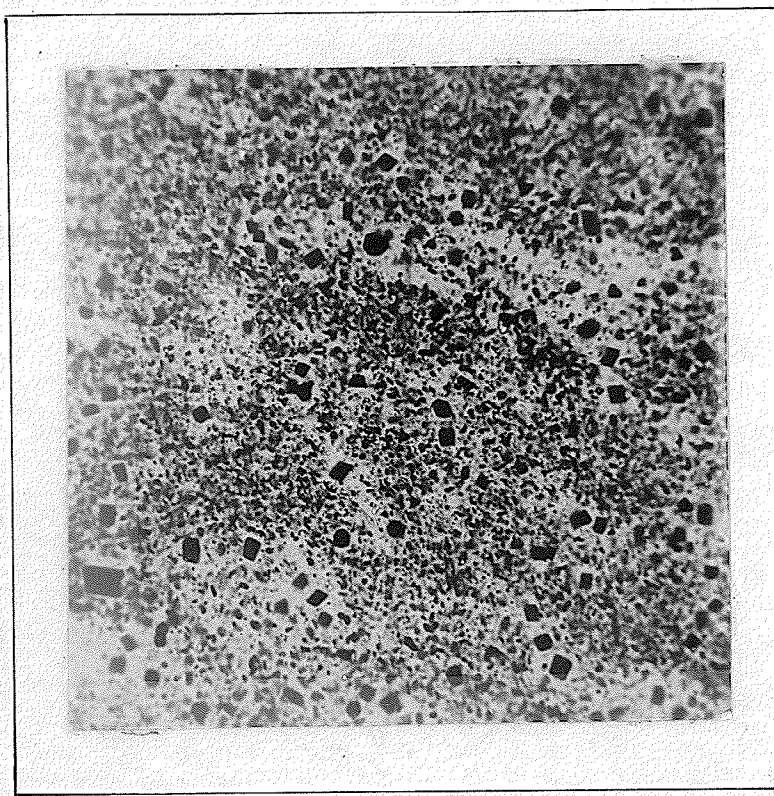
Some of the iron formation at the end of this gradational series is only partly coarse-grained. A few of the bands consist of a fine-grained homogeneous jasper -- fine-grained mosaic quartz containing small magnetite and minute hematite platelets. This jasper phase is interesting because each magnetite crystal is surrounded by a halo of clear quartz free of hematite. Also in the fine-grained jasper are prominent streaks of hematite-free quartz and magnetite in which the magnetite is in larger grains than in the jasper itself (Figure 10).

Much of the quartzose iron formation at some distance from the thick tuffaceous beds contains thin layers of tuff; Figure 11 shows both the tuffaceous and quartzose types in contact; the quartzose band was obviously the more competent during deformation.

Pyrite, though not abundant, occurs in all the iron formation specimens from Lily Lake; chalcopyrite is present but is rare.

East of Slate Lake, an apparent continuation of the Lily Lake band consists of pure magnetite and quartz, with no tuff impurities. Some of the magnetite is partially replaced by hematite.

Banksian Lake. The band which passes through Banksian Lake is adjacent to chlorite tuff on one side, and a metamorphosed rock, which was probably greywacke originally, on the other.

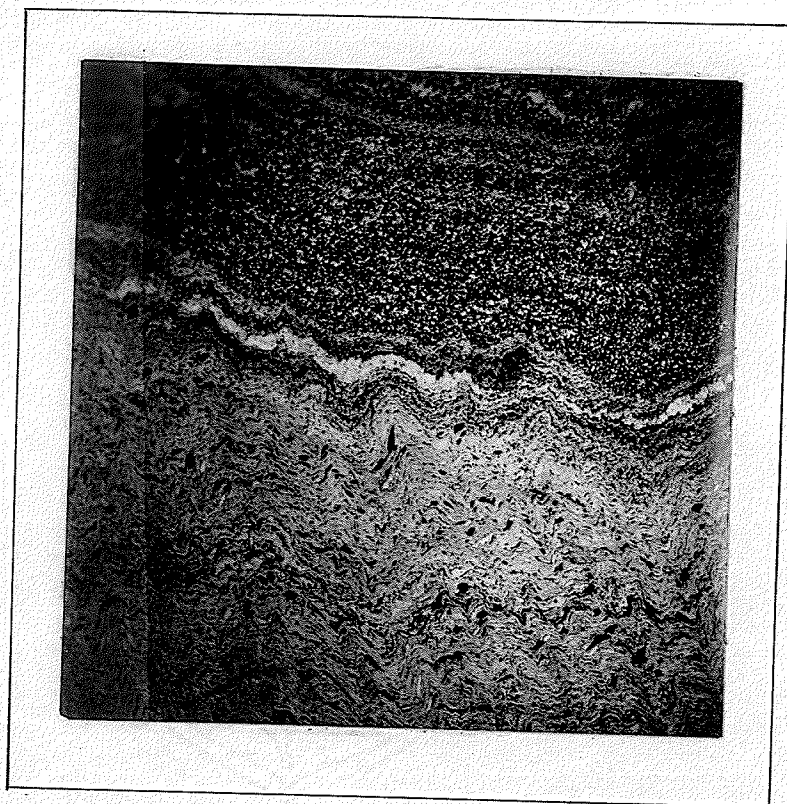


X 250

FIGURE 10

Hematite platelets and magnetite  
octahedra in quartz-magnetite-hematite  
iron formation  
Specimen 3





X 6

FIGURE 11

Both quartzose and tuffaceous iron formation; competent and incompetent beds on a microscopic scale  
of Specimen 13

The greywacke is now quartz-biotite schist; its groundmass is made up of sutured quartz and some plagioclase grains; in it are abundant biotite and muscovite flakes, aligned parallel to the schistosity. Lenses of mosaic quartz of coarser grain than that of the groundmass occur throughout the rock; these are likely of hydrothermal origin, inasmuch as the biotite in their vicinity is altered to chlorite.

Siderite is the predominant mineral in the iron formation of this locality, and magnetite and quartz are subordinate in amount. That is, in a matrix made up chiefly of fine-grained or cherty siderite, there are bands which contain magnetite and quartz, admixed with siderite; other bands consist of almost pure chlorite; others are rich in fine flakes of muscovite and chlorite, and resemble recrystallized tuff. Some of the siderite bands are microscopic breccias -- cherty siderite fragments in a siderite matrix. Some of the quartz-magnetite layers have been sheared along directions which make only a small angle with them; thus they have been stretched, and thereby appear lenticular, though the lenses are merely individual "fault blocks". A few pinching-and-swelling bands of large sutured grains of plagioclase occur at certain horizons. Occasional bands consist of magnetite-bearing jasper, such as those which occur at Lily Lake.

The iron formation described above is further sheared and carbonatized along a different direction. These shears are not parallel to the banding but transverse to it, and are mineralized not with cherty siderite, but with coarse-grained calcite and chlorite; calcite forms the centers of the veins, and chlorite occurs at the margins.

One specimen of iron formation from Banksian Lake is composed almost entirely of fine-grained mosaic quartz and hematite platelets, with only a few euhedral grains of magnetite. This may be a relatively unmetamorphosed phase of the rock.

It will be noticed from these descriptions that the iron formation from Lily Lake and that from Banksian Lake are almost identical, except for the presence of siderite in the latter.

In all but one polished section of Banksian Lake iron formation, the magnetite is fresh; the one exception shows slight alteration of magnetite to limonite.

West of Flintstone Lake. The rock underlying the iron formation band was probably an arkosic greywacke before metamorphism; now it is composed of grains of quartz and plagioclase, mostly untwinned, with subordinate small flakes of biotite. Another specimen of the same rock consists of large ovoid grains of quartz and plagioclase in a fine-grained matrix of kaolinite, sericite and chlorite with aggregate polarization. A few crystals of blue amphibole, slightly bent, are present. Green tourmaline crystals are scattered along one horizon, and pyrite is present throughout the rock. Apatite crystals are sparsely disseminated.

Overlying the iron formation is a quartz-plagioclase-biotite schist. The mineralogy of this schist is similar to the rock on the other side of the iron band, but the overlying rock has more biotite in larger flakes. Some of the flakes are part biotite and part chlorite, and many of them contain pleochroic haloes. Blue amphibole is abundant along certain horizons, occurring as long, thin broken crystals surrounded by biotite.

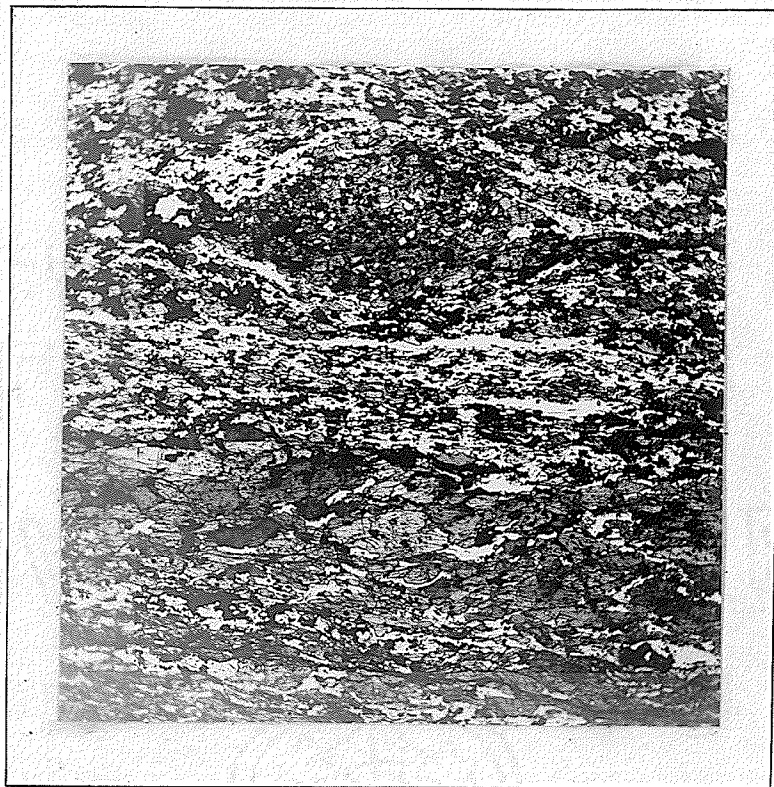
In the field, at one place, a narrow sill of fresh diorite containing pale blue amphibole occurs in the sediments some distance away from the iron formation. The rocks in this locality are all cut by dikes of pink granite.

The iron-rich band itself, like many of the others studied, consists mainly of quartz and magnetite; but it also contains abundant biotite and blue amphibole. Stilpnomelane is not present. Quartz with a definite mosaic texture forms the groundmass together with fine shreds of greenish-brown biotite such as was found in the enclosing sediments; in this matrix are subhedral magnetite grains and large, often euhedral grains of blue amphibole. Many of these amphibole grains are poikiloblastic with rounded inclusions of quartz and subhedral to irregular grains of magnetite (Figure 12), and occur in the same manner as does grunerite in other specimens. Some grains are, in fact, part grunerite.

The magnetite of this locality is fresh -- not altered to hematite. Pyrite is present in most of the specimens of iron formation.

#### Western Australia

Of nine specimens of iron formation from Western Australia, eight are similar in texture and mineralogy to the Manitoba specimens. The minor characteristics which set them apart from the ironstones of Manitoba are the presence of martite in some of the Australian rocks instead of magnetite; a relative abundance of hematite, limonite or goethite; and a lack of chlorite, muscovite and detrital materials.



X 23

FIGURE 12

Blue amphibole with poikilitic magnetite  
and quartz in iron formation  
Specimen 21



Corresponding to the pure magnetite-quartz rocks of Manitoba is a martite-quartz ironstone from West Moyagee in the Murchison gold field. Its texture is no different than that of the Manitoba specimen shown in Figure 5. In the field it is associated with greenstones and metasediments.

The grunerite-magnetite-quartz and grunerite-quartz rocks of Manitoba are represented in Australia by identical-looking rocks from the Yilgarn gold field, which are associated with basic schists.

Carbonate-bearing iron formation, similar to the magnetite-carbonate-quartz types of Manitoba, is found in the Murchison gold field at Austin; the carbonate occurs as small rhombs and larger irregular grains in the quartzose matrix; some of the carbonate is stained, through alteration, to a deep orange or reddish-brown color. Another specimen, from the Mount Margaret gold field, is made up of bands of martite crystals in a mosaic quartz matrix; but instead of rhombs of carbonate, in and near the martite bands are large irregular and angular patches of deep red and orange ferric oxides which show aggregate polarization, and which, because of their outlines, are very likely pseudomorphs of ferric oxides after ferrous carbonate. This rock is associated with basic lavas and ultrabasic rocks.

A second specimen from Austin in the Murchison gold field, associated with metasediments and minor greenstone intrusives, is almost identical with the one from Mount Margaret just described, but for a narrow band of acicular goethite running parallel to a

magnetite band, and immediately adjacent to it. In a second specimen from the Mount Margaret gold field acicular "goethite" is the main iron mineral, occurring in a matrix of very fine-grained mosaic quartz; small clusters of martite grains are present but not abundant. This rock occurs between fine-grained andesitic lava and a medium- to coarse-grained epidiorite.

One specimen which might be considered to be somewhat different from the rest comes from the Ophthalmia range. The matrix of mosaic quartz and needles of grunerite forms only about ten percent of the rock; with these quartz-grunerite areas are associated sharply euhedral magnetite crystals. In addition to the magnetite other iron oxides are disposed in narrow closely-spaced bands, forming the bulk of the rock. Each band is made up of a groundmass of some dark oxide which might be martite; in this groundmass are minute spherules resembling oolites, but having radii of only 0.015 millimeters. Each spherule comprises a dark red nucleus, lighter in color than the groundmass, surrounded by a shell of bright red hematite. The spherules are best observed by viewing the thin section using oblique light from a strong source. These bodies might be solidified gelatinous precipitates (Miles, 1946, p.123). Were it not for them, this specimen of iron formation would be similar to many of the others from Australia and Manitoba. The iron formation is associated with quartzite, shale and thin-bedded dolomite.

Finland

The one specimen of iron formation examined from Porkonen-Pahtavaara in Finnish Lapland is predominantly fine-grained mosaic quartz, the grains of which are filled with a fine dust. This dust, seen under the highest magnification, is made up of rod-shaped particles of some unidentifiable mineral. Also in the quartzose matrix are larger scattered needles which may be grunerite and small irregular shreds of orange material which may be limonite from the oxidation of iron carbonate. Magnetite occurs in the chert either as disseminated grains that seem to be interstitial between the quartz grains, or as irregular grains in cracks in the chert, which then resembles a breccia. In these cracks, that is, in the matrix of the breccia, are other peculiar features; namely, small roughly spherical bodies of a clear colorless mineral, with an index of refraction higher than that of quartz, and which might be apatite. Each of these is dotted with inclusions of a black mineral which might be magnetite, or perhaps carbon. Many of these spherical bodies also have a black irregular grain as a nucleus. Other smaller spherical bodies which are entirely magnetite, or carbon, also occur. These have a fuzzy appearance. Another unusual feature is a veinlet of quartz, coarser in grain than the groundmass, in which agate-like bands of black material run parallel to the margins. This structure resembles that of a fissure which has been filled with colloidal material. If the black substance is magnetite, the structure very likely originated by injection of colloidal silica and small amounts of colloidal ferric hydroxide,



with formation of Liesegang rings. The ferruginous rings were later metamorphosed to magnetite.

The other four specimens from Finland which were studied are similar to the Manitoba specimens in that they are principally magnetite-grunerite-quartz rocks, with small amounts of chlorite. They differ from the Manitoba rocks in containing garnet.

#### Other Localities

A specimen from the Marquette range has a matrix of mosaic quartz in which are bands of siderite and brown iron oxide, probably limonite. A few flakes of chlorite occur with the siderite bands, but there is no magnetite present.

From the Empire mine, south of Negaunee, Michigan, comes a specimen mainly of fine-grained carbonate, probably siderite, which serves as a matrix for thin lenses of fine-grain mosaic quartz and euhedral magnetite crystals. One band consists of large grains of quartz in a fine-grained matrix; the large grains are subangular and have second-growth rings about them, as if they were recrystallized detrital sandy grains. The siderite adjacent to this quartz band is altered to limonite.

A specimen of typical slaty iron formation from the Cuyuna range consists dominantly of very fine-grained carbonate and stilpnomelane; some quartz is also present as fine-grained aggregates. This specimen bears no resemblance to any of the Manitoba specimens; the first-mentioned two, however, are similar to the carbonate-rich ironstones of Manitoba.

A banded ferruginous chert from Great Bear Lake has very fine-grained cherty bands, alternating with bands of coarse-grained mosaic quartz. The fine-grained bands are filled with hematite in the form of either fine dust or minute clods, and contain only a small proportion of magnetite as small, irregular grains. The coarser-grained bands have little or no hematite, but contain larger irregular grains of magnetite. This is in keeping with the idea that magnetite was formed by recrystallization from hematite. If the fine-grained chert was recrystallized to coarse-grained quartz in bands which contained more water before metamorphism, the hematite in the same bands was simultaneously converted to magnetite.

Carbonate forms fifteen per cent of the rock or less. In the coarse-grained phase, the carbonate exists as irregular patches; but in the fine-grained cherty layers it occurs as large rhombic frames, the centres of which are of the same cherty quartz as the matrix. The carbonate also occurs as long transverse lenses or slivers crossing the boundaries between the fine and coarse layers; these lenses or slivers are probably simply cross-sections of the rhombic crystals described above, if these rhombic crystals are flat. The manner in which they cross the boundaries suggests that the carbonate is secondary. Moreover, stylolite seams are present in the fine-grained cherty phase; along these seams are individual carbonate rhombs, evidently localized by the stylolite seams. The carbonate, therefore, must be younger than the other minerals, and must have been introduced along the stylolite seams after the rock was solid.

A specimen of iron formation from the Black Hills of

South Dakota consists almost entirely of magnetite crystals concentrated in bands in a fairly coarse quartz mosaic. Minute needles resembling grunerite are scattered through the quartz, but are not abundant. This rock is thus similar to many of the ironstones from other parts of the world.

## DISCUSSION AND INTERPRETATION OF PETROGRAPHIC DATA

In the following discussion the writer hopes to show that many of the iron formations which were studied are comparable, petrologically at least, in spite of having come from different parts of the world. Thus, when two examples from different localities do not correspond exactly or almost exactly in their mineralogy and texture, the dissimilarities usually can be explained reasonably, in such a way as to show that any differences in the present appearance of various specimens are due not to a different primary mode of origin, but chiefly to outside influences, such as carbonate replacement and different grades of metamorphism, for example. This appeals to the writer as the best of a number of working hypotheses, as it seems to be the simplest concept, and does not require the construction of a different overall hypothesis for every occurrence of iron formation; moreover, it coincides with the most widely accepted general idea about iron formations, that is, that they are sedimentary in origin, and are not igneous intrusives or replacements of tuffs by igneous solutions.

The hypothesis which has been selected to explain the present mineralogy and texture of the iron formations of Manitoba, and of other localities studied, may be stated as follows: in some way, pure iron minerals and silica were deposited in Precambrian time, in alternating layers, by some form of chemical precipitation. The source of the iron and silica is not considered at present, nor is the agency which caused the precipitation, nor any other factor which must be considered in working out a hypothesis on the ultimate origin of these rocks. These questions are believed to be answerable, but not by means of laboratory work alone, nor at this time,

when much more knowledge remains to be accumulated about them.

The silica layers were in all probability gelatinous precipitates which consolidated to form cherts under the influence of pressure from overlying sediments and perhaps of temperature. The iron may have been in any of three possible forms -- as ferrous carbonate, ferrous silicate, or hydrated ferric oxides; all three are possible, depending on prevailing conditions; there is as much evidence for one as there is for another, and all of this evidence is reliable. Whatever the original state of the iron, it did not require a high degree of metamorphism to be converted to magnetite, the chert at the same time becoming recrystallized to a mosaic-like "quartzite". Miles (1946, pp. 146-147) gives plausible chemical equations showing how this could occur. This is another way of saying that if all the iron formations studied were pure, uncontaminated by clastic sedimentary materials, and if they had suffered metamorphism of only moderate grades, such as is manifest in most rocks of the Precambrian shield, they would consist solely of magnetite and quartz. Though such a statement may seem like oversimplification, this ideal of purity was commonly observed in the specimens that were studied. This hypothesis concludes by proposing that any digressions from this ideally simple composition are due not to a totally different mode of origin, but to different kinds of outside influence, as enumerated below.

First, the iron-silica precipitate was contaminated by clastic materials when the sediment-bearing currents changed direction, or when the level of the water in the place of deposition fluctuated, or when anything occurred that would cause pure

colloidal materials to be intimately interbanded or mixed with fine clastic sedimentary material.

Secondly, the ferruginous chert, resulting from the induration of the pure or clastic-bearing precipitate, was contaminated by igneous agencies in the form of direct magmatic intrusion or hydrothermal replacement.

Thirdly, the pure or contaminated iron formation was subjected to various grades of metamorphism, other than hydrothermal alteration.

Fourthly, the pure or contaminated iron formation was hydrothermally altered.

It is hoped that the arguments presented below will supply enough justification for this hypothesis. On the assumption that the "pure" iron formation would consist only of magnetite and quartz, examples will be given of each type of "contamination" to which such an ideal rock could be subjected.

#### No Contamination

Many examples of quartz-magnetite ironstone exist. The examples in Manitoba are too numerous to name; in Australia, a pure magnetite-quartz rock occurs at West Moyagee in the Murchison gold field; the specimen from the Black Hills is also of this type.

In some such pure quartz-magnetite ironstones, veinlets of quartz and magnetite are observed cutting across the banding. The veinlets differ from the bulk of the rock only by being of relatively coarser grain. This might well be used by the advocates of an igneous theory for iron formations, who might call

these veinlets apophyses or later intrusions of iron-formation magma. It seems plausible, however, that the same result would obtain if the original ferruginous deposit was gelatinous; after earlier-deposited beds of gelatinous iron-bearing silica had solidified more or less, by hydration, shrinkage cracks in it could be filled by fresh, more fluid ferruginous silica; or else if the gelatinous layers were buried by later sediments, the dryer and more brittle layers would crack, the cracks being immediately filled by the influx of younger, softer, more hydrated material from fresher overlying layers. Metamorphism of the original iron substance would produce a larger grain size in the veinlet material, as this would be younger and more hydrated, so that diffusion could take place better than in the older, dryer material. These explanations might also account for the "igneous" branches which offshoot from the main iron formation bands into cracks in wall rock at certain localities, as pointed out by Wadsworth and other proponents of the igneous theory (Winchell, 1891).

There is a third way in which coarse-grained veinlets may have formed in fine-grained iron formation: If the original cherty mass were solid, and therefore able to be fractured, then during metamorphism the presence of water in the fractures would enhance recrystallization along these breaks, producing a larger grain size along them.

#### CONTAMINATION BY CLASTIC MATERIALS DURING DEPOSITION

E. L. Bruce (1945, p.595) writes:

The regularity of the banding of most of the iron formations of the Lake Superior basin, the occurrences in many of them of thin beds of clastic sediments (mainly mud rocks), and the gradation from rocks of clearly detrital origin to typical non-clastic iron formations have been rather generally accepted as satisfactory proof of the sedimentary origin of iron formations.

The same sort of interbedding of iron formation with clastic sediments, and gradation between clastic rocks and iron formations, is seen in the specimens of iron formation studied currently.

Bruce further writes (ibid., p.598) of the iron formation of Timiskaming age at Little Long Lac north of Lake Superior:

The typical jaspilite is interbedded in many places with greywacke, and lenses of conglomerate occur at various horizons both above and below the iron formation. Typical jaspilite contains no clastic material, but some of the beds of greywacke contain a considerable amount of iron oxides.

Such gradational rocks as Bruce mentions are plentiful among the Manitoba iron formations studied.

The iron formation from near Gunnar Mine contains minute flakes of chlorite admixed with the quartz and magnetite. At Garner Lake chlorite is abundant at certain horizons in the iron formation; those chlorite bands are evidently layers of recrystallized tuff or greywacke. The iron formation from Lily Lake grades from almost pure magnetite-hematite-quartz ironstone with very little disseminated chlorite, through "slaty" iron formation, to a magnetite-bearing slate or metamorphosed tuff which consists of white mica, magnetite, chlorite, and quartz. At Banksian Lake the iron formation bands contain layers of chlorite, and others rich in muscovite; layers of pure plagioclase are present also. Plagioclase, muscovite, and biotite altering to chlorite are also present in the greywacke wall rock, and therefore the impurities in the iron formation are a result of alternate sedimentation of greywacke and ferruginous silica. Biotite is present in the ironstone from Flintstone lake. Plagioclase is present among the quartz



grains of the matrix of the ironstone east of Beresford Lake, and is usually untwinned so that it can be detected only by its relief in thin section, which is lower than that of quartz. It is unlikely that the plagioclase of iron formations was deposited as plagioclase; more likely it is a product of the recrystallization of detrital muscovite flakes; the serrated interlocking edges of the feldspar crystals imply recrystallization.

Chlorite, muscovite, feldspar, biotite, or other detrital minerals were not observed in the specimens of iron formations from Western Australia; nor was any mention of them found in available literature. Perhaps the deposition of iron formation in Australia was favored by an unusual constancy in the conditions of deposition, so that very little clastic matter reached the site where iron and silica were being laid down. Moreover, the specimens used in this study may have been collected well within the thick ironstone bands, where impurities were least likely to be encountered.

At Porkonen-Pahtavaara in Finnish Lapland, very small amounts of chlorite and sericite are found in only a few places in the iron formation; sodium and aluminum, possibly in the form of albite, are also present. The iron formation has very sharp contacts with its wall rock (Kaitaro, 1949). There, too, the deposition must have taken place under constant conditions.

The above observations appear sufficient to show that the presence of detrital minerals, or recrystallized equivalents thereof, in the body of an iron formation band, does not necessarily imply that the iron formation itself had a clastic origin.

Separation of chemical precipitates from fine-grained clastic deposits during sedimentation is not always ideal. This is especially true when the stratigraphic column under consideration is only four inches high or less, as it is with many of the small bands studied.

Furthermore, zircon grains were not seen in the iron formation bands; but even if their presence had been noted, and if they were present in the chlorite-bearing type of ironstone discussed above, it still would not signify a detrital origin for the ferruginous chert itself; it would only mean that zircon was laid down together with the coarser clastic tuffaceous materials, and that inasmuch as these materials were so intimately intercalated with the ferruginous chert, the zircons would appear to form a part of the ironstone itself. Tyler (1948) suspected that the ferruginous "quartzites" of Brazil were recrystallized chemically-deposited cherts, and proved that his suspicions were correct by showing that they contained no detrital heavy accessories, such as are present in nearly all sediments of truly clastic origin. Such an undertaking would be hazardous, of course, if exercised on the narrow bands of iron formation of Manitoba, for here the unwary investigator might find such detrital grains, and on that basis rush into the peremptory conclusion that the Manitoba iron formations are of detrital origin, whereas the detrital grains could come wholly from the clastic sediments and volcanic tuffs so intimately mixed with the quartz and the iron minerals of the ironstone.

### Contamination by Igneous Material

Evidence observed in thin sections can be interpreted to show that addition of material from igneous sources has wrought four types of change in the iron formations of Manitoba. Constituents have been supplied which caused the formation of blue amphibole instead of grunerite; blue amphibole itself has been introduced as a fracture filling; materials have been supplied which favored the production of stilpnomelane instead of grunerite; and carbonates have replaced certain minerals of the iron formation in places.

Three of the iron formations of Manitoba contain blue amphibole: The one north of Long Lake; the one extending from Garner Lake to Moore Lake; and the one on the west shore of Flintstone Lake.

The introduction of blue amphibole into the iron formation north of Long Lake certainly appears to be an example of direct magmatic intrusion. The mineral occurs only in the cracks of the iron formation, and does not permeate the fragments themselves; it appears to be the same blue amphibole as that which makes up the nearby sill. Figure 6 shows blue amphibole along microscopic oblique breaks in iron formation. The unlikelihood of the existence of a magma of such a peculiar composition is overruled by the existence of the blue amphibole-bearing sill nearby. If one deduces that the veinlets of blue amphibole in the iron formation are of hydrothermal origin, one must deduce a hydrothermal origin for the entire sill as well.

Having seen what thus appears to be a clean-cut instance of small-scale magmatic injection, the writer assumed that the amphibole in the iron formation at the other two localities had also been emplaced by injection, along shears parallel to the banding. A re-examination of specimens, and a more careful consideration of their occurrences, made this appear improbable. At Flintstone Lake, the iron formation is very rich in an amphibole of a strong blue color, pleochroic to faint yellow, but no diorite bodies occur near this iron formation, except a small sill in the sediments some distance away from it at one place. Moreover, the amphibole of the diorite is not nearly so strongly colored as that of the iron formation. This lack of visible connection between the diorite and the blue amphibole of the iron formation makes direct intrusion hard to account for, especially in the case of the Moore Lake iron formation, where bands of ironstone are included in the diorite, yet are hardly affected by it; a few specimens contain blue amphibole as a matrix for their magnetite grains, but there is nowhere near the amount of blue amphibole here as in the specimens from Flintstone Lake. At Moore Lake also, the amphibole of the diorite is lighter in color than that from the iron formation.

The foregoing observations, together with a more careful examination of thin sections and field relationships, have forced the conclusion that only at Long Lake was the blue amphibole introduced directly as a magma; at the other two localities it was produced by the action of emanations, which came not from the diorite, but from the nearby granite, as explained below.

Here are reiterated the main features of the formation which stretches from Garner Lake to Moore Lake. At Garner Lake the iron formation is far away from the granite, and contains abundant grunerite and a few small grains of blue amphibole. At the southern end of Beresford Lake, grunerite is present, but not blue amphibole. East of Beresford Lake, closer to the granite, the iron formation does not contain grunerite (at least not in the specimens at hand) but minute, sparsely disseminated needles of blue amphibole are present in the quartzose matrix, aligned with the banding. At Moore Lake the iron formation is cut by numerous dikes of pink granite; grunerite is very abundant; some bands consist almost entirely of grunerite; but others contain blue amphibole in certain places instead of grunerite.

The conclusions reached from the foregoing observations are as follows. Before intrusion of the granite, the iron formations under consideration had probably undergone little or no metamorphism. The granite, when it arrived, supplied heat which metamorphosed the iron formations so that primary iron minerals and silica were converted to magnetite, grunerite, and quartz. But the granite mass, or its accompanying granite and pegmatite dikes, also supplied constituents which were necessary to the formation of blue amphibole, viz. soda, potash, lime, and magnesia. Alumina would also be required but may have been present in sufficient amounts in the iron formation itself as argillaceous impurities. Wherever these were abundantly added, blue amphibole was developed in the iron formation; otherwise grunerite was formed by simple thermal metamorphism.

At Flintstone Lake the evidence is similar. Diorite, as has been mentioned, is rare and not intimately connected with the iron formation. Yet the iron formation contains abundant amphibole, this being pleochroic from strong blue to pale yellow. Crystals of it are well-formed, long in the direction of banding (the Flintstone Lake rocks show evidences of shearing in planes parallel to the banding), and contain abundant inclusions of rounded quartz grains and euhedral magnetite crystals. Most of the amphibole crystals are uniformly colored, but in one specimen some grains are partly grunerite and partly blue amphibole, both minerals being separated by sharp contacts, but having their cleavages oriented in the same direction throughout any particular grain.

Blue amphibole occurs in a quartz-plagioclase-biotite schist which overlies the iron formation at Flintstone Lake. This amphibole is the same as that occurring in the iron formation. Its origin is not decipherable simply from the examination of one specimen, but granite emanations were probably responsible for its formation. Possibly the areas that are now rich in amphibole were once rich in iron, requiring only the addition of a few constituents from the granite to form blue amphibole when metamorphosed.

Blue amphibole also occurs in the iron formations from other parts of the world. Miles (1946, pp.137-138) has described iron formation containing blue-green amphibole in Western Australia. His drawings of the amphibole show it to be in the form of sut-

ured grains forming part of a mosaic of garnet and grunerite. He considers it to have been produced in place of grunerite wherever small quantities of lime, alumina, and magnesia were available during metamorphism (Miles, 1946, p.150). Richarz (1927, p.154), examining specimens of grunerite from the Lake Superior region, found in some of them a blue-green amphibole in parallel orientation with grunerite, forming the extremities of the prismatic laths; the amphiboles are both fresh, and the transition from one to the other is sharp. He says that apparently the grunerite prisms terminated their original growth with this blue amphibole which, however, also occurs independently. This mode of occurrence is almost the same as in Manitoba.

The presence of abundant epidote in some of the Moore Lake grunerite-magnetite rocks is probably due to metamorphism of thin layers of calcareous shale interbedded with the original ferruginous chert. Harker (1950, p.263) writes that calcite, kaolin, and iron oxide in an argillaceous sediment are converted to epidote by regional metamorphism.

Stilpnomelane occurs in some of the iron formations of Manitoba, in amounts which are subordinate yet large enough to call for an explanation. A pertinent observation in connection with stilpnomelane is that it is not necessarily associated with the blue amphibole formed by emanations from the granite; it does occur in places where these emanations did not seem to play a part. For example, at Flintstone Lake, where blue amphibole is abundant, stilpnomelane is absent, whereas at Moore Lake, and Garner Lake, stilpnomelane is abundant. The clearest rel-

ation between stilpnomelane and the agency responsible for its formation is found in the Long Lake band of ironstone. Here, the iron formation four feet from the amphibolite sill consists simply of euhedral magnetite crystals in a mosaic-like matrix of quartz, in which are minute disseminated laths of stilpnomelane; but where the iron formation is brecciated and intruded by blue amphibole from the sill, the fragments of the breccia are rich in stilpnomelane, and relatively large flakes of it occur in the blue amphibole between the fragments.

The hypothesis that diorite and not granite is responsible for the production of stilpnomelane appears possible at this locality; the fact that stilpnomelane is found in the vicinity of diorite at all the other localities where it is present makes it tenable.

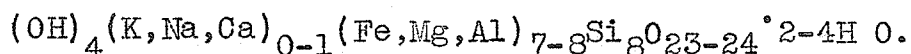
This does not mean, of course, that wherever diorite occurs near iron formation stilpnomelane will also be found. The band of iron formation east of the Gunnar shaft is an example; in iron formation two feet away from a contact between the wall-rock and diorite, there are found neither stilpnomelane nor thermal metamorphic effects. From what has thus far been learned of these blue amphibole sills, it must be supposed that they were deficient in volatiles when they were injected, otherwise they should have evolved quantities of fluids and volatiles, causing more changes in their wall rock than are actually observable; they should have assimilated almost entirely the ironstone bands which they surround at Moore Lake; yet any thermal metamorphic effects due to them are imperceptible, and the only evidence that



they gave up emanations is the presence of stilpnomelane in adjacent iron formations.

Gruner (1944) believes that stilpnomelane is a metamorphic mineral, formed instead of quartz and magnetite whenever magnesium and aluminum were present, these elements being essential to its structure. This implies that these constituents were already present in the rock from the beginning of its history. Gruner's hypothesis is wholly adequate for such rocks as the slaty iron formation from the Cuyuna range, which consists almost entirely of carbonate and stilpnomelane.

Why, then, was not stilpnomelane formed in all those iron formations from Manitoba in which argillaceous and ferromagnesian impurities were originally present? Four answers are possible for this: In the first place, the aluminum and magnesium of chlorite and feldspar were probably "tied up" in these minerals in a manner which precluded their ability to form new compounds. In the second place, stilpnomelane would probably form only at those places where the proper high temperatures were reached; the first such temperatures to be imposed must have depended on the diorite when it was intruded, though whether the mineral was formed at that time or later, during the intrusion of the granite, is not known; Ayres (1940) describes stilpnomelane as a contact mineral, formed where granite pegmatite has invaded ferruginous slate in the Michigan iron district. In the third place, stilpnomelane contains water; its formula is calculated by Gruner (1944) to be



The water, as well as potassium, sodium and calcium, could be supplied by an intruding magma, but might be difficult to acquire in adequate quantities from the iron formation itself. In the fourth place, stilpnomelane might require certain trace elements which determine that it shall form instead of some other mineral; these might be obtainable only from an igneous source, especially if they are emitted as volatile constituents.

Stilpnomelane has not been found mentioned in available literature on the iron formations of Western Australia or Finnish Lapland, nor was any seen in thin sections of the specimens from these localities.

The study of the metamorphic and hydrothermal effects of granite and diorite on iron formation is fascinating. Here only a broad picture has been presented. Although a large number of specimens was obtained from the areas of blue amphibole and stilpnomelane, they are not sufficient to afford a complete study of the problem. In this respect, Moore Lake is a critical area, because it contains iron formation in sediments and in hypabyssal rocks, and younger dikes of granite and pegmatite are abundant. A study confined to this area alone would now be in order. This would have to be a detailed study, involving careful mapping on a scale of about fifty feet to the inch; selection of specimens of every rock type - diorite, granite, pegmatite, greywacke, and iron formation; and laboratory work in the form of petrographic study, accurate mineral identification by any available method most suitable, and chemical analyses of the amphiboles of the

diorite and of the iron formation. Only by such a thorough study could the problem of blue amphibole and stilpnomelane be solved with satisfaction.

Whereas the presence in iron formation of blue amphibole from igneous sources seems to be confined to southeastern Manitoba, the replacement of iron formation by carbonates is probably a more widespread process. Many of the iron formation specimens from Manitoba as well as from other sources contain a carbonate - either calcite, or siderite. Other forms may be present but exact determinations of the type of carbonate were not always made, their identity being only approximately determined by their appearance, their reactions with dilute HCL, their specific gravity as determined on the Berman balance, or their refractive indices, whichever method was most convenient for the particular specimen .

Where carbonate traverses the iron formation as veinlets, there can be no doubt that it is secondary in origin, having originated from igneous sources, and made its way along cracks in the iron formation after compaction. If the carbonate occurs as ragged patches or especially as rhombs in the iron formation matrix, its secondary nature can usually be inferred from the fact that in most such occurrences it is calcite, and patches of it are just as abundant in the enclosing sediments as in the iron formation. An example of this is one of the bands east of Beresford Lake. The presence of calcite veinlets in conjunction with patches of calcite is evidence that the calcite is sec-

ondary. If a crosscutting veinlet of calcite suddenly spreads out at a certain horizon in the rock, and parallel to the banding, this resulting "bed" is most probably secondary.

However, when carbonate occurs apparently as beds interlaminated with layers of quartz, magnetite, or any other mineral of the iron formation, and if no direct evidence can be found as to whether it is primary or secondary, its origin can often be inferred indirectly. North of Garner Lake there is a band of iron formation made up of a marble-like matrix of calcite, in which occur a few grains of quartz, magnetite, grunerite, and chlorite; because this specimen comes from the same band as another specimen which contains very little calcite, the carbonate is considered to be a secondary mineral replacing the quartz.

The siderite in the iron formation from Banksian Lake is more difficult to account for, especially as the whole band is rich in siderite, which is traversed by calcite-filled microscopic shears. This iron formation is described on page 45. Without carbonate, this iron formation would be almost identical with that from Lily Lake; in all probability the two bands were at one time similar. In fact, one specimen from Banksian Lake is a magnetite-hematite-quartz iron formation without carbonate. Being interlaminated intimately with tuffaceous material, the Banksian Lake band was easily sheared in planes parallel to the bedding, and siderite was subsequently deposited by metasomatic replacement of some of the sheared rock. Both the iron-quartz members and the tuff members were involved in this replacement,

and were replaced to about the same extent. Recrystallization of the iron formation must have occurred before the shearing or, at latest, during it; for had recrystallization taken place after the siderite was in place, this should have recrystallized as well, instead of remaining as a fine-grained cherty mass.

The transverse calcite-chlorite veinlets which cut across quartz and siderite layers alike are possibly of the same age as the calcite which replaces, to a greater or lesser extent, many of the other ironstones of Manitoba. That is, the siderite replacement occurred at an early period and was restricted to certain areas, whereas the calcite replacement seems to have been more or less widespread.

The siderite rhombs and irregular grains in the matrix of the iron formation from Austin in Western Australia have the same appearance and relationship as the calcite in some of the Manitoba formations, and may have been introduced by metasomatism.

In Precambrian rocks, a shear zone often loses its identity when it passes from a massive rock, such as a lava flow or a plutonic, into a bedded tuff, providing the bedding of the tuff coincides approximately in direction with the shearing; the shear seems to disappear because Precambrian tuffs are often so highly chloritic, and are so banded, as to resemble a sheared andesite or even diorite. The shear in the tuff is a reality, but is invisible in the field. In like manner, a shear should be able to develop in tuffaceous or slaty iron formation, and in the tuff or sediments adjacent to the iron formation; this shearing could easily be mistaken for the bedding of the tuff or the

banding of the ironstone in the field. If the sheared portion of the iron formation and tuff were replaced by carbonate, the result might be even more misleading, causing the casual field observer to mistake the rock for a magnetite-bearing limestone or siderite bed. Sometimes thin sections can and do show, by such things as stretched magnetite and the presence of comb quartz, that longitudinal shearing played an important part in imparting to the iron formation its limestone-like qualities.

Some writers, notably Collins, Quirke, and Thomson (1926), maintain that certain iron formations were formed by replacement of tuffs by carbonate of iron, or by conversion of the tuffs to carbonate. This might well be true for siderite deposits in which quartz and magnetite are not abundant; but if quartz and magnetite are present in significant amounts, it seems just as likely that the siderite was introduced into already existent, sheared iron formation.

Gruner (1941, pp.1616-1617) describes an iron formation-like band originating by replacement of a shear zone by siderite, cutting across the beds of a syncline. He makes no mention of the presence of magnetite here, however, and in all probability there is none. This is a good example of carbonate replacement of a shear zone, and there is no doubt about its origin.

However, Gruner extends this explanation to account also for the origin of bands of iron formation which are parallel to the bedding of slates and greywackes, and which are constituted of iron carbonate and iron oxides. No evidence is found to indicate that this second occurrence which, Gruner believes, resembles true iron formation, was not formed by carbonatization of sheared pre-existing iron formation. The adjacent slates and

greywackes could have been carbonated<sup>iz</sup> as well, as described, causing the whole assemblage of iron formation and sediments to have the appearance of progressively replaced sediments.

A question which might arise at this point is why the carbonate replacement should sometimes favor the iron-quartz bands, rather than the enclosing sediments or tuffs? The answer to this may be that, during shearing in which both the iron formation and the surrounding tuffs became involved, the quartzose members shattered and became porous, whereas the extreme fine grain of the tuff, and the possible existence in it of colloidal material such as is present in clays, caused it to be "tight" or impervious to carbonatizing solutions. The shattering of the quartz might not have to be on a large scale for this to be possible - a slight displacement of grains would be enough to render the rock porous.

This is not meant to say that ferrous carbonate was not the original iron mineral of sedimentary iron formations; indeed, Miles (1946, p. 150), among other investigators, is inclined to think that it was, because siderite would decompose to form magnetite and, particularly, react with silica to form grunerite, at a lower temperature, better than would greenalite; the carbonate would also be a natural flux for such a reaction, and would cause it to proceed easily at low temperatures of metamorphism. Moreover, says Miles, in order for magnetite or hematite to unite with silica to form grunerite, a powerful reducing agent, such as carbon, would be required, of which there is no evidence,

besides enormous, unlikely temperatures.

It is quite possible, however, that if many iron formations in which primary carbonate is said to exist were re-examined, the same amount of evidence could be found in favor of an epigenetic origin for the carbonate as of a syngenetic one. This applies even more to the iron formations which are said to be replacements of tuffs and other sediments; quite likely these iron formations were formed by carbonate replacement, not of tuffs, but of pre-existing iron formations. This is a statement that cannot be proved by the present writer; but it would be interesting to see whether, in the areas in which the iron formation is supposed to have been formed by replacement of tuff, there is other evidence of contemporaneous carbonate replacement which did not form iron formation as it should have. If two bodies of carbonatized tuff have been thus replaced at the same time by carbonate from the same source, and if both bodies have undergone the same amount of metamorphism as a result of their nearness to each other, but if one turned out to be an iron formation whereas the other became nothing but a carbonatized tuff, then there would be little doubt that the former body was originally an iron formation, and the latter was originally a tuff.

Gruner (1926b, p. 644) has said that calcite, dolomite, and siderite can replace almost any rock, even one containing quartz. He accounts for the origin of the Vermilion ores by saying that brittle iron formation was brecciated by intrusives and



replaced by carbonate which in places followed the bands of the iron formation, and cut across them in brecciated zones. The carbonate was later leached out leaving porous rubble ore. The present writer is merely extending this theory to explain the presence of carbonates in the iron formation itself.

#### Production of New Minerals by Regional Metamorphism

All the iron formations studied have undergone at least some metamorphism. On the assumption that the original iron was some species of hydrated ferric oxide, the lowest grades of metamorphism would be sufficient to dehydrate it (Harker, 1950, p. 64), forming hematite. Much of the iron formation from the Lake Superior region contains red ferric oxides (see page 29). In Manitoba, the specimen from Lily Lake shown in Figure 10 contains minute hematite platelets disseminated in a very fine-grained quartzose matrix. These hematite crystals may have formed by dehydration of original limonite. One specimen from Banksian Lake consists entirely of hematite dust and fine-grained quartz, and is thought to be a similar, though relatively unmetamorphosed, phase.

The specimen from the Ophthalmia range of Western Australia contains minute spherules of bright red oxide, with centres of darker red oxide; the spherules are considered by Miles (1946, p. 123) to be the results of solidification of a gelatinous precipitate. This specimen comes from the Nullagine formation, which is the least metamorphosed of all the Western Australian iron formations, and for this reason it is quite

reasonable to assume that the red oxide is the earliest form of iron in that rock.

Hematite and limonite in iron formation can have a secondary origin, however, by being derived from other ferriferous minerals by alteration or retrograde metamorphism; this sort of ferric oxide can usually be distinguished by its appearance and relation to other minerals, and its discussion is reserved for the section dealing with alteration of minerals in iron formations.

When metamorphism becomes more intense, the ferric oxides are reduced to magnetite (Harker, 1950, p. 64). Thus results the familiar magnetite-quartz ironstone of Manitoba, Australia, the Lake Superior region, and most other Precambrian iron ranges. These reactions so far have been described on the premise that the original iron mineral was ferric oxide. But, as has been mentioned, very little evidence is available either from this study or from the literature, to favor the existence of either one of three possible types of original iron mineral : carbonate, oxide, or silicate. Siderite can, like hematite or limonite, be converted to magnetite by metamorphism. The conversion of the ferrous silicate greenalite to magnetite would seem to be a more difficult process to explain.

Figure 10 shows small magnetite crystals in a matrix of quartz and hematite, each magnetite grain being surrounded by an aura of pure quartz without hematite; there are also diversely-oriented streaks in which magnetite is in larger grains than in the rest of the rock and hematite is absent. The hematite-free parts are believed to be due to the diffusion of the hematite, which once was present there, towards the

magnetite crystals as they grew. Nearly all of the specimens of iron formation studied have undergone at least enough regional metamorphism to convert the original iron minerals to magnetite.

With higher-grade metamorphism, the ferrous silicate grunerite appears. This is an amphibole, usually colorless in thin section, though it may be pale yellow or pale green; it is usually in long prisms or needles, and is easily recognized by its polysynthetic twinning which makes a slight angle with the prism faces.

Although no interaction between magnetite and quartz is perceptible, magnetite and silica are often the only two minerals from which grunerite could form; the rock often contains simply quartz, magnetite, and grunerite, this last occurring in and about the magnetite bands, even though the magnetite crystals are still euhedral. Moreover, some iron formation layers consist almost entirely of grunerite (Figure 9) as if all the magnetite had been used up in the production of the amphibole.

Another concept which might better explain the coexistence of well-formed crystals of magnetite and grunerite is that grunerite was formed, not by metamorphism of a higher grade than that which produced magnetite, but that it was formed at the same time as the magnetite, from primary iron minerals of the ironstone. This would explain the excellence of the crystal outlines of both magnetite and grunerite, but would at the same time introduce the question of why grunerite was formed in some ironstones but not in others. The determining factor might be the presence or absence of certain necessary trace-elements, volatiles,

or other mineralizers without which grunerite could not form. This concept, however, is based on pure speculation, and no direct evidence exists for its support, except the above-mentioned euhedrism of magnetite and grunerite when they exist together.

Stilpnomelane, which occurs together with grunerite in some of the Manitoba ironstones, is believed to have been formed instead of grunerite with the help of magnesium and aluminum introduced from igneous intrusions; this has been discussed on pages 71 and 72. Indeed, most grunerite from iron formations contains at least some magnesium; could it not be possible that if the magnesium were introduced into the original unmetamorphosed iron formation, grunerite would later form, and that if aluminum were introduced as well, then stilpnomelane would form also?

Metamorphism of higher grade than that required to produce grunerite has not occurred in the Manitoba iron formations. Nor are there any high grade metamorphic minerals in the specimens studied from Western Australia, or any other locality except Finnish Lapland. Garnet is abundant in some of the specimens from the latter locality, and in Australia and in the Lake Superior region examples exist of iron formation which has undergone a degree of metamorphism high enough to produce fayalite, hypersthene, augite, hornblende, grunerite, and cummingtonite. Such intense metamorphism of iron formation is rare, however, and occurs only in the neighborhood of large igneous intrusives (Harker, 1950, p. 239).

### Alteration of Iron Formation Minerals

After a superficial examination of the iron formation from West Moyagee, Western Australia, one might pronounce it to be different from certain magnetite quartz ironstones from Manitoba and other localities, because it has martite as the iron mineral instead of magnetite. The same might be said of the specimens from Austin in the Murchison gold field, and from the Ophthalmia range.

Martite is simply hematite, formed by the oxidation of magnetite, and pseudomorphic after it. Several specimens from Manitoba exhibit alteration of magnetite to hematite; in one taken from the band east of the Gunnar shaft, about half of the magnetite is replaced by hematite (Figure 7). This replacement, in this case oxidation, takes place along the octahedral planes of the magnetite, in a manner identical to that described by Gilbert (1925, pp. 589-591), and Gruner (1926a, pp. 392-393). If the magnetite of some of the magnetite-quartz iron formations of Manitoba were thus oxidized in their entirety to hematite, these would then resemble exactly the martite-quartz rock of West Moyagee. The oxidation of magnetite to martite might have been caused by hydrothermal action, but because of the absence of other evidence of such action, it is more likely a result of retrograde metamorphism.

Limonite occurs in some of the specimens in which its origin is undoubtedly secondary. Only rarely was it seen to be formed from magnetite; its chief source seems to be pyrite or

siderite. Limonite from the alteration of pyrite is recognized by its square outlines in polished section, and by the fact that masses of it often contain irregular remnants of pyrite in their centers. Limonite produced from siderite is recognized by similar criteria-rhombic shape of the masses, often with step-like edges characteristic of the crystal form of carbonates; and the presence nearby of recognizable siderite only partly altered to limonite. If this limonitization were complete, and if a mild form of metamorphism were to affect the rock, the resulting hematite or even magnetite formed in the process might be mistaken for hematite or magnetite formed from primary limonite, if its pyrite- or carbonate-like outlines were obliterated, or if it were arranged in bands. The pyrite itself is probably metasomatic in origin.

The goethite-like mineral in two specimens from Western Australia is believed by Miles (1946, p. 128) to be pseudomorphic after grunerite. The orange color and acicular shape of the crystals cause it to resemble goethite, but it may be limonite or partly-limonitized grunerite; probably x-ray work would settle this question. These two specimens of iron formation are thus no different fundamentally than many specimens from Manitoba.

#### SUMMARY OF THE CHAPTER

A comparison of iron formations from different parts of the world has shown that, according to their petrographic characteristics and their association with other rocks in the

field, they all have certain characteristics in common, and for this reason may be regarded as all having a similar origin. In all probability, if enough specimens are studied from each of a number of localities, certain specimens would be found from each locality which would strongly resemble certain specimens from another locality. For example, the specimens from Finland which were examined in this study did not correspond exactly with those from Manitoba; but Kaitaro (1949) describes the jasper-quartzite of Porkonen-Pahtavaara as being composed of well-formed magnetite crystals in a matrix of very fine-grained mosaic quartz which is dusted with hematite, and in which small amounts of siderite can occur as well as magnetite; such a description applies admirably to certain phases of iron formations found at Lily Lake in Manitoba. Another example is Miles' (1946, p. 121) statement that "Comparison of these Western Australian red-banded jaspilites with the jaspilites of the Lake Superior region emphasizes the almost perfect identity of the two types."

If the concept that all iron formations were very much the same in their early history is accepted, then the fact that they are different today can be explained satisfactorily by ascribing their differences to various "accidents". With few exceptions, all the iron formations examined have suffered regional metamorphism of a grade at least high enough to convert the original free silica and iron minerals, whatever they were, to mosaic quartz and magnetite. Magnetite-quartz ironstones can be found in probably all the iron formations of the world.

The types which differ from each other do so because their present constitution depends on the amount of clastic sediments mixed with them during their original deposition; on the amount and nature of material transferred to them from igneous sources; on the degree of metamorphism which they have undergone in addition to that which converted the original iron minerals to magnetite; and on the amount of alteration either by hydrothermal solutions or by retrograde metamorphism which they have suffered.

In short, under the right conditions, the same minerals could have developed in the Manitoba iron formations as in those of Finland, Australia and the Lake Superior region; a difference in the mineralogy between two suites of metamorphosed, replaced, and altered iron formation, not to mention that which is contaminated by clastic materials, need by no means imply a different origin.



## CHAPTER IV

### SPECTROGRAPHIC STUDY OF MAGNETITE

#### Introduction

The original purpose of making a spectrographic analysis of magnetite was to determine what trace elements, if any, are present in the magnetite of the Manitoba iron formations, and whether these are similar to the trace elements found in the magnetite from associated diorites, and possibly to those found in other igneous rocks as described in the literature. A close correspondence between the trace elements in the magnetite of iron formations and that of typical igneous rocks might be useful as evidence in support of a clastic origin for the iron formations in question.

As this study progressed, the diorites associated with the Manitoba iron formations were found to yield insufficient magnetite for a spectrographic analysis. Moreover, the diorites were realized to be younger than the iron formations. Consequently the iron formations could not have been produced as a result of the mechanical disintegration of the diorites.

The spectrographic investigation was nevertheless continued, with the purpose of at least determining what trace elements were present in the magnetite of the iron formations of Manitoba, and recording them, that they might be useful to any later investigators who might require the information.

Completion of the investigation disclosed that the

results were not reliable or sufficient to give rise to definite conclusions, for reasons given in the following sections. The method<sup>of</sup> procedure, however, was thought to be somewhat novel, and accordingly it will be described forthwith. A discussion of some of the difficulties encountered might also be of use to later investigators undertaking this type of work.

#### Experimental Procedure

Magnetic separation was decided on as the best method of separating magnetite from the rest of the minerals of iron formation specimens. The specimens were crushed and pulverized mechanically, the pulverising being regulated so that the product consisted of all grain sizes from very fine to gritty; every specimen then contained grains of various sizes; screens could then be used to isolate grains of a size suitable for most efficient separation of magnetite from each specimen.

Before any actual screening was done, polished and thin sections of all the Manitoba specimens of iron formation were examined under the microscope, and in each specimen the grain-size of larger-than-average magnetite crystals was measured with a micrometer ocular. The purpose of this approach was to determine which specimens had enough grains of magnetite of sufficiently large diameter to be amenable to magnetic separation; the measurements also made possible proper selection of sieves which would enable a sufficient amount of the largest grains to be separated from each specimen.

This preliminary examination disclosed that in most

specimens the grain size of magnetite was less than 0.074 mm., that is, less than the size of the apertures on a 200-mesh Taylor screen. These specimens could not be used; if the grains of such a rock were chosen with a diameter greater than 0.074 mm., each grain would consist merely of quartz or other mineral with inclusions of magnetite. If, on the other hand, grains below 0.074 mm. in diameter were collected, some of them would doubtless consist of pure magnetite, but this could not be separated adequately from the impure grains. Some time was spent in an attempt to separate pure magnetite from the fine material which passed through the 200-mesh screen; the rock powder was panned to remove the finest muddy material, and coarser remainder was dried; several methods of separation were attempted: Magnetic separation in air and under water; bromoform and clerici solution; and manual separation under a binocular microscope. Failure of these methods was due to the attraction of particles of magnetite for particles of other minerals which contained enough minute specks of magnetite in them to render them magnetic. In addition, magnetite grains would join to form chains or strings in which grains of other minerals would inevitably become incorporated.

Further attempts to separate such fine material were dispensed with; usually at least one specimen could be found from each locality in which the magnetite was in grains larger than 0.074 mm.; these specimens alone were investigated. Sieving was carried out with regard to the grain size of the magnetite in each specimen, so that maximum-sized grains of

pure magnetite would be obtained, these being at the same time small enough to exclude larger ones with adhering quartz and other minerals. In order that all fine muddy sediment could be removed, the pulverized rock was washed through the screens with water. The screened material was dried gently over a hot-plate and separated magnetically.

The magnetic separation was performed by spreading the sized granular material to a thickness of one grain on a large sheet of rubberized sheeting, and moving over it a small horse-shoe magnet covered by a plate of copper; the magnet was always kept about half an inch above the rubber sheet.

Examination of the magnetic concentrate so obtained under a binocular microscope showed that a large proportion of the grains were not pure magnetite, but consisted of magnetite intergrown with quartz, blue amphibole, and other minerals. These grains were just as easily attracted by the magnet, apparently, as were grains of pure magnetite; consequently, a clean separation with a magnet by this method was possible only for one or two specimens in which the size of magnetite grains was exceedingly large. Heavy liquids were again tried but were not successful, because many grains of minerals other than magnetite had enough magnetite included in them that they could be dragged down together with the heavy magnetite fraction, probably more due to magnetic attraction than to specific gravity.

In view of these difficulties, the final separation was made in each case by picking out the purest magnetite grains

with a wet, sharp toothpick under a binocular microscope. As most of the grains so handled ranged in size from 200 mesh to 100 mesh, this process was tedious and time-consuming, but it yielded grains of magnetite that were apparently pure. To remove the grains of magnetite from the toothpick, they were immersed in a little water in the bottom of a crucible, whereupon they were freed and sank to the bottom of the vessel. For very small grains, which tended to float by surface tension on the surface of the water, a small amount of weak organic detergent was added to the water; this caused them to break the surface more easily, and sink.

After enough magnetite was obtained for at least one spectrographic determination, each sample was treated with cold 1:5 nitric acid, in order to dissolve out any metal particles which might have been torn away from the pulverizer plates when the rocks were pulverized, and any adhering carbonate if this were present. Washing repeatedly with doubly distilled water removed the nitric acid and any substances dissolved by it. Each sample was then ground fine in an agate mortar, and mixed with an equal amount of finely ground highest purity carbon. The samples were now ready for the spectrograph. Throughout the entire separation, washing, and grinding, extreme care was observed that one sample be not contaminated by another; all apparatus used was cleaned carefully after each sample was handled.

Arc spectra were obtained of the magnetite, on a Hilger spectrograph which employs a 10-inch photographic plate. The

collimator slit was kept fairly wide so that very weak lines would show up. The spectra of all twelve specimens were photographed on one plate; above and below the spectra for these twelve, spectra of pure iron were produced for comparison.

The spectrum of iron contains hundreds of lines; and as the main element in magnetite is iron, each spectrum of magnetite also contained a confusing number of lines. It was difficult to determine whether a certain line on the spectrum of a certain sample of magnetite was due to iron or to some other element. Identification of an element by finding the wave lengths of three of its lines in the customary manner is extremely difficult and uncertain to a novice.

The problem of how to comb the whole spectral range for any trace elements which might be present was solved in the following manner : In the back of the book "Chemical Spectroscopy", by Brode (1939), are reproduced photographs of consecutive sections of a much-extended spectrum of iron with spaces above them in which an unknown spectrum, enlarged to the same scale as the reproductions in the book, can be placed so that it is in coincidence with the iron spectrum; unknown lines can then be referred to pointers in the book which indicate the positions of the important lines of most of the elements, with the wave-lengths and intensities of these lines. By this method, one need not determine accurately, by measurement, the wave-lengths of three of the unknown lines, in order to identify the element to which they belong, this method being unsuitable when the

lines of several elements are present in the unknown spectrum; rather one need only note a line on the unknown spectrum which does not appear on the iron spectrum, determine the element to which it might belong, and then proceed to find enough lines of that same element in other parts of the spectrum; if the unknown element happens to be one whose spectrum contains many lines, identification is certain, because many lines can be found in verification of its identity.

No facilities were available for enlarging the 10-inch plate to the required scale, and juxtaposition of the unknown spectrum with the extended iron spectrum in the book was accomplished by projecting the spectrographic plate itself onto the book held vertical in a glass frame with two C-clamps. The book could then be moved to or from the projector until the projected image was exactly coincident with the reproduction in the book. Lines not on the iron spectrum could then be noted, and the elements to which they belonged could be read off directly. To keep the plate from becoming hot while being projected, a special projection apparatus was constructed in which the plate was not enclosed in the projector but was held outside it, open to the air; an enlarging camera lens in front of the plate accomplished the actual enlarging. The plate was fixed in a makeshift frame from which extended a horizontal flat bar of brass; this bar was inserted into the accessory slot on an older-model petrographic microscope. The plate could then be moved horizontally by sliding the brass bar in or out of the slot,

and vertical motion was afforded by the coarse-adjustment screw of the microscope. The apparatus used in projection of the spectrographic plate is shown in Figure 13.

In addition to the spectrographic work, fifty-six of the iron formation specimens from Manitoba and Australia were fire-assayed for gold at the laboratories of the Manitoba Mines Branch.

### Results

The results obtained from the spectrographic work on magnetite of certain iron formations from Manitoba are shown in Figure 14. Although twelve specimens were investigated, two of these are not strictly iron formation; they have not been considered in the rest of this thesis, and accordingly were excluded from the table. In practice, the spectrum for any one specimen showed several lines for each element; however, only the lines of a given intensity of 10 (on the scale in common use, ranging from 1 to 10) were used in a qualitative sense. The strongest lines due to trace elements were relatively faint when compared with the strongest lines due to iron; an attempt was nevertheless made to represent their intensities on the same scale as is used in Brode's book for iron lines. If a magnesium line, for example, is shown in the table with an intensity of 3, this means that the particular magnesium line considered has a given intensity of 10 if only pure magnesium were spectrographed, but in the table its intensity relative to that of the 10-lines of the iron spectrum is only 3.

Of the fifty-six specimens which were assayed for gold,



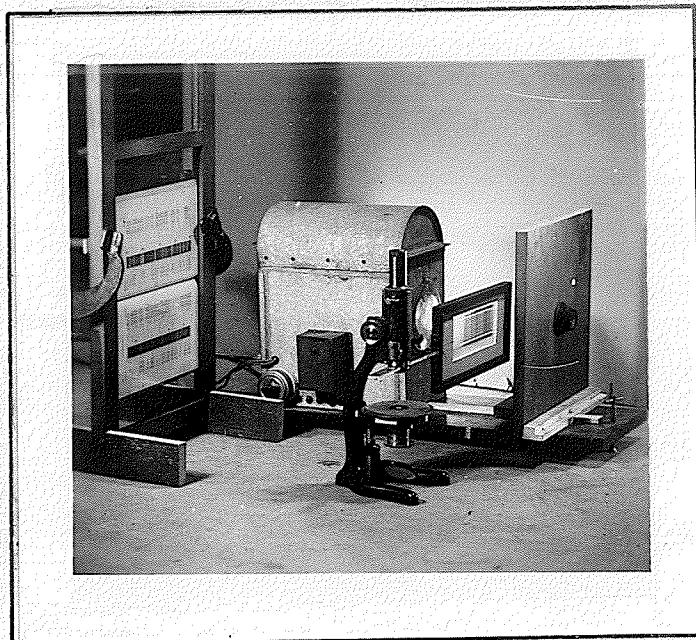


FIGURE 13

Equipment used in reading spectrograms by projection of the plate onto the book held in a makeshift frame

RESULTS OF SPECTROGRAPHIC ANALYSIS  
OF MAGNETITE FROM IRON FORMATIONS  
OF MANITOBA

Specimen number	Locality	Si	Al	Mg	Ti	V
14	Slate Lake	2-	1+	1-	f	f
69	Long Lake	2-	3-	3-	3-	1
56	Moore Lake	2	3	3	0	f
43	W. of Gunnar shaft	2-	2-	1-	1-	1-
40	Wallace Lake	2-	2	3-	2-	1-
36	SE. of Beresford Lake	0	1+	2	f	f
30	Garner Lake	0	2-	1-	0	0
27	Flintstone Lake	3-	3-	2	f	f
9	Banksian Lake	2-	2+	2-	0	0

NOTE: 2+ is stronger than 2;  
2- is fainter than 2;  
f is very faint, hardly perceptible.

Figure 14

only five did not run "trace" or "nil", and of these five the highest gold value was 0.01 ounces per ton.

#### Discussion and Interpretation of Spectrographic Data

Silicon, aluminum, magnesium, titanium, and vanadium were the only five elements that could be identified with certainty; the lines of these elements were the strongest present, except for the lines of iron.

When magnetite grains from the same pulverized and sized specimens as shown in the table were mounted in bakelite and polished as described in Chapter V, not one specimen was seen to consist of grains that were pure magnetite, as had been assumed; in every specimen, there were magnetite grains with particles of quartz or other gangue mineral either included in them or adhering to them. Especially impure were the grains of magnetite from specimens 69, 40, 27, and 9. Thus it is easy to see that the amount of "trace elements" in different specimens of magnetite depends here on the amount of impurities associated with them. Quartz was seen to be abundant in specimen 27, and this accounts for the high silica content of that specimen as shown in the table.

From theoretical geochemistry, magnetite crystallizing from a magma at high temperatures forms extensive solid solutions with elements of suitable ionic radius if such elements are present in the magma. Magnetite crystallizing at low temperatures, and magnetite formed by metamorphism of hematite, do not form solid solutions.

Vanadium, titanium, and magnesium are elements with

ionic radii similar to the ionic radius of iron in magnetite, and are therefore expected to occur in high-temperature magnetite in solid solution. The same applies to aluminum. The occurrence of these elements in the magnetite from the Manitoba iron formations thus apparently contradicts the hypothesis that this magnetite was formed by metamorphism, even if the presence of some or all of the aluminum in the iron-formation magnetite is due to the silicate impurities.

Bray (1942) analyzed magnetic concentrates from several igneous rocks, and found them to contain large traces of aluminum and calcium, and smaller traces of other elements. Ti, V, and Mg were found in very small traces; vanadium was absent in two of his specimens. The magnetite from the Manitoba iron formations contains these same trace elements with the exception of calcium, which is relatively abundant in the igneous magnetite investigated by Bray. Again a sedimentary hypothesis for the origin of the Manitoba iron formations is apparently contradicted.

The limited amount of work done in the present study of magnetite, and the qualitative nature of the results, are not adequate enough to be diagnostic. A more extended and careful quantitative procedure is indicated if an attempt is to be made to discriminate between magnetite of igneous origin and magnetite of sedimentary origin. The trace elements in magnetite from the iron formations should be compared quantitatively with the same trace elements when present in magnetite crystallized at high temperatures from a magma. The magmatic magnetite might

then be found to contain markedly greater quantities of Mg, Ti, V, Al, and other elements than are found in the metamorphic magnetite.

It is further learned from theoretical geochemistry that when ferric hydroxide is chemically precipitated from aqueous solution, it absorbs a characteristic group of trace elements. A quantitative spectrographic analysis of iron formation and of neighboring sedimentary rocks should therefore show a greater quantity of these characteristic elements in the iron formation than in the sediments.

## CHAPTER V

### STUDY OF MOUNTED MAGNETITE GRAINS

#### Introduction

An examination of magnetite grains from suitable specimens from each Manitoba locality was made to observe whether the magnetite is pure and homogeneous, or whether it contains intergrowths of ilmenite. The presence of ilmenite in the magnetite would be evidence against a chemical origin for that particular iron formation, because a chemical hypothesis cannot be extended to explain the deposition of titanium minerals along with silica and iron minerals. Furthermore, ilmenite intergrowths in magnetite would support the idea that iron formations are of clastic origin; they are present in the magnetite grains of many igneous rocks (Newhouse, 1926) and titaniferous iron ores (Schwartz, 1930); an accumulation of such primary magnetite in beds, like the black sands, might conceivably produce iron formation. Stark (1929) prefers such a hypothesis for the Agawa iron formation. Some might even use such evidence in upholding the theory that iron formations are igneous intrusives.

#### Experimental Procedure

In order that ilmenite could be distinguished from magnetite, it was necessary to etch the magnetite with hot concentrated hydrochloric acid. The polished sections of iron

formation were unsuitable for this because so many of them contained carbonate that etching would loosen the magnetite grains from their matrix before they themselves were even slightly affected. It was also desirable to preserve the polished sections in case they were required for further study. Accordingly, grains of magnetite, separated magnetically from the crushed, pulverized, and sized specimens of iron formation, were mounted in bakelite, and these mounts were polished in the usual manner of making polished sections of opaque minerals. Twelve mounts were prepared, representing the same specimens that were used in the spectrographic study.

Each mount was examined, before etching, and any other minerals such as hematite, were noted, so that they would not be confused with ilmenite after etching.

The etching was carried out as follows : Concentrated HCL was brought to a boil in a small evaporating dish; the heat was removed, and as soon as the boiling subsided, one specimen was held face down in the acid for the required length of time, this being between twenty and thirty seconds, and apparently different for different specimens. For each specimen, the acid was brought to the boiling point anew; the purpose of this was to have the acid at the same temperature for each specimen without using a thermometer. After the acid treatment, each specimen was allowed to cool for a few seconds, then washed in warm water; this procedure was followed in order to minimize loss of grains due to sudden differential contraction. The specimens were let dry in air so that any

structures revealed by the etching would remain intact.

### Results

When etched with hydrochloric acid, the polished surfaces of the magnetite grains appeared brown under low power; when examined under high power, the grains did not appear dark but shiny gray, like fresh magnetite, and displayed angular oriented etch-figures. Some of the etch-figures were triangular pits; other resembled imbricating slabs, the surface having the appearance of a schistose rock broken on a plane oblique to the schistosity. For any one grain, the orientation and abundance of the etch-figures were the same throughout the grain. Some surfaces were affected by the etching more than others, and others showed no perceptible effect. The etch-figures undoubtedly owe their shape and depth to the crystallographic direction along which the grains were polished. In none of the specimens were there any signs of ilmenite intergrowths, such as those described by different authors as occurring in magnetite from igneous rocks.

### Interpretation

The statement was made in the introduction to this chapter that the presence of ilmenite intergrowths in magnetite would be evidence in support of the hypothesis that the iron formation from which such magnetite is obtained is of clastic origin. This statement can be made only on the premise that, if all the Manitoba iron formations were derived by sort-



ing of clastic particles of igneous rocks, at least some of these igneous rocks contained magnetite with ilmenite intergrowths - a supposition that can be neither proved nor disproved. Likewise, on the other hand, if the magnetite of a specimen of iron formation contains ilmenite, this alone is not always proof of a clastic origin. Broderick (1917) has found inclusions of Gunflint iron formation in the Duluth gabbro; the titanium content of the inclusions is high, even though the Gunflint iron formation away from the gabbro contains no titanium; Broderick considers this titanium to have been derived from the gabbro.

Kaitaro (1949) points out that, according to the trace-element researches of Th. G. Sahama, titanium, which is typically found in residual quartzites, is absent or negligible in the "jasper-quartzites" of Porkonen-Pahtavaara. The results obtained from etching the magnetite from Manitoba iron formations show an absence of ilmenite, and might be reasonably employed as at least a small contribution to the evidence against a clastic origin for iron formations.

#### Conclusion

The magnetite from the iron formations of Manitoba which were studied does not contain perceptible amounts of intergrown ilmenite; this might be taken to mean that these iron formations are not of clastic origin, that is, they were not formed by mechanical concentration of detrital grains from igneous rocks.

## CHAPTER VI

### SUMMARY AND CONCLUSIONS

An immense volume of literature has been written, since the earliest days of geology, on the subject of Precambrian banded iron formations. Many of the earlier writers, and most of the modern ones, agree that the iron formations have a sedimentary origin. Any sedimentary hypothesis for the origin of iron formations must answer seven principal questions; namely, it must explain the source of the iron and silica; their transportation; their mode of deposition; their place of deposition; the striking banding; their limitation to Precambrian time; and the nature of the original minerals of the iron formations before metamorphism converted them to what they are now. The present writer favors the hypothesis outlined by Woolnough. It accounts for all the phases of the problem, and shows that they are all related to one another by being due to the same set of conditions. A summary of the views held by Woolnough is given on page 22.

Apparent differences in the iron formations from various parts of this continent and the rest of the world have driven students of the problem to devising separate hypotheses to account for the various types, thereby further complicating the problem. The present writer has begun with the concept that all iron formations were much alike in their early history, and has attempted to show that present-day differences in them

depend on various "accidents" which the iron formation underwent during their history. These "accidents" are, namely, mixing of clastic sediments in with the iron and silica components during deposition; addition of material from igneous sources; and metamorphism of the iron formation, including alteration.

The laboratory study of the iron formations consisted of thin- and polished-section studies of iron formation specimens, and of spectrographic and polished grain-mount studies of the magnetite grains derived from iron formation specimens. Nearly all the laboratory information used in the support of the above hypothesis was obtained during thin-section study; the polished-section study was also helpful. The spectrographic investigation proved non-diagnostic, because absolutely pure magnetite grains, without adhering particles of other minerals, were not obtained, and a quantitative study would have been more in order. The grain-mount work revealed no other minerals in the magnetite grains except hematite, which is believed to be not an intergrowth but a replacement of magnetite by hematite. The lack of other minerals (such as ilmenite) intergrown with the magnetite might be taken as one evidence in support of the idea that the magnetite crystals were produced by recrystallization, and not by growth from an igneous melt.

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MAP OF PART OF  
**SOUTHEASTERN  
MANITOBA**

Showing  
Pre-Cambrian Banded  
Iron Formation

Scale: 1 inch = 1/2 mile

**LEGEND:**

-  Diorite
-  Granites
-  Volcanics and Sediments
-  Iron Formation
-  Specimen Location

