A STUDY OF PRECAMBRIAN BANDED IRON FORMATION

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ABSTRACT

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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..

TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

Page

Nature of the problem 1
Importance of the investigation 1
Definitions 2
Previous work on the Manitoba iron formations 4
Sources of specimens 4

CHAPTER II

REVIEW OF THE LITERATURE

Introduction 5
Earlier theories 7
  Theories of extraneous origin 7
  Theories of indigenous origin 9
Modern theories 15

CHAPTER III

PETROGRAPHIC STUDY

Introduction 27
Petrographic description of iron formations 27
  Lake Superior region 27
  Southeastern Manitoba 30
  Western Australia 50
  Finland 54
  Other localities 55
Discussion and interpretation of petrographic data 58
  No contamination 60
  Contamination by clastic materials during deposition 61
  Contamination by igneous material 65
  Production of new minerals by regional metamorphism 79
  Alteration of iron formation minerals 83
Summary of the chapter. 84

CONTENTS (Continued)

CHAPTER IV

SPECTROGRAPHIC STUDY OF MAGNETITE

Introduction 87
Experimental procedure 88
Results 94
Discussion and interpretation of spectrographic data 96

CHAPTER V

STUDY OF MOUNTED MAGNETITE GRAINS

Introduction 99
Experimental procedure 99
Results 101
Interpretation 101
Conclusion 102

CHAPTER VI

SUMMARY AND CONCLUSIONS 103

Bibliography 105

ILLUSTRATIONS

Figure

1. Locations of important Lake Superior iron deposits 6

2. Appearance of two parallel thin bands of iton formation in the field, near Gunnar mine 31

3. Grain gradation in tuff 32

4. Pure quartz-magnetite iron formation with small patchws of carbonate 34

5. Same field as Figure 4 but with crossed nicols 35

6. Veinlets of blue amphibole in quartz-magnetite iron formation 36

7. Polished section showing replacement of magnetite by hematite along crystallographic directions 38

8. Quartz-magnetite iron formation with radiating grunerite needles 40

9. Grunerite iron formation without magnetite, showing dark crystals of stilpnomelane 43

10. Hematite platelets and magnetite octahedra in quartz-magnetite-hematite iron formation 46

11. Both quartzose and tuffaceous iron formation; competent and incompetent beds on a microscopic scale 47

12. Blue amphibole with poikilitic magnetite and quartz in iron formation 51

13. Equipment used in reading spectrograms by projection of the plate onto the book held in a makeshift frame 95

14. Results of spectrographic analysis of magnetite from iron formations of Manitoba 95a

Map of part of Southeastern Manitoba showing Precambrian banded iron formation . . . . .in back.

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. Localitities 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.[1] 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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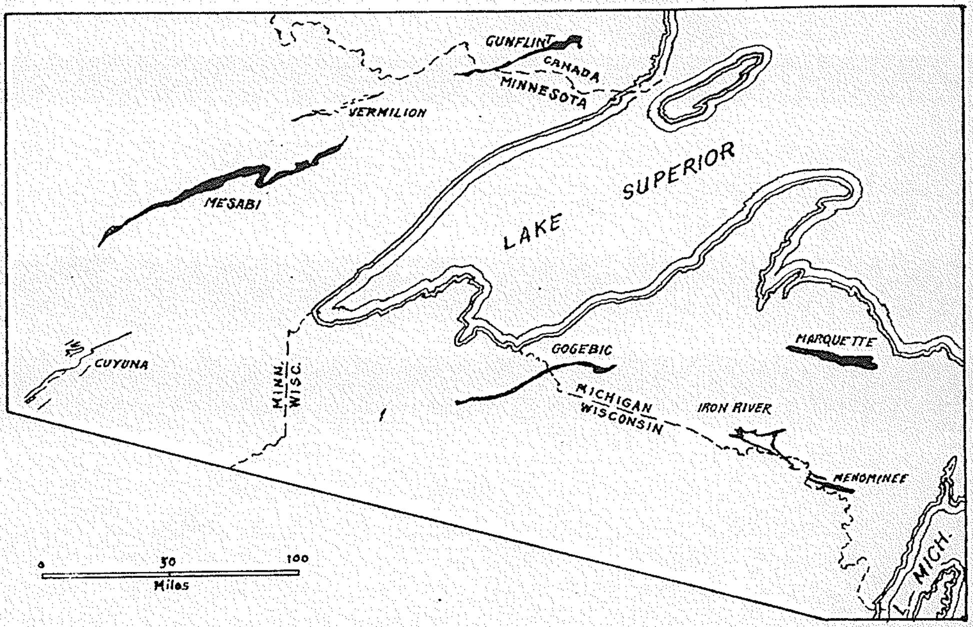
[1] References are not given here, but are quoted by N. H. Winchell and H. V. Winchell (1891).



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 minerals 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 moderntheories.

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 judtified 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 titanic acid is found in bog ores; therefore the presence or absence of titanic 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 repaidly 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 containing CO_2, Fe, 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 subaerial 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 peneplaination 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 hydroxie, 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 reaearches 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-bearingsand 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 localitities 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[1]

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 seenin 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 course-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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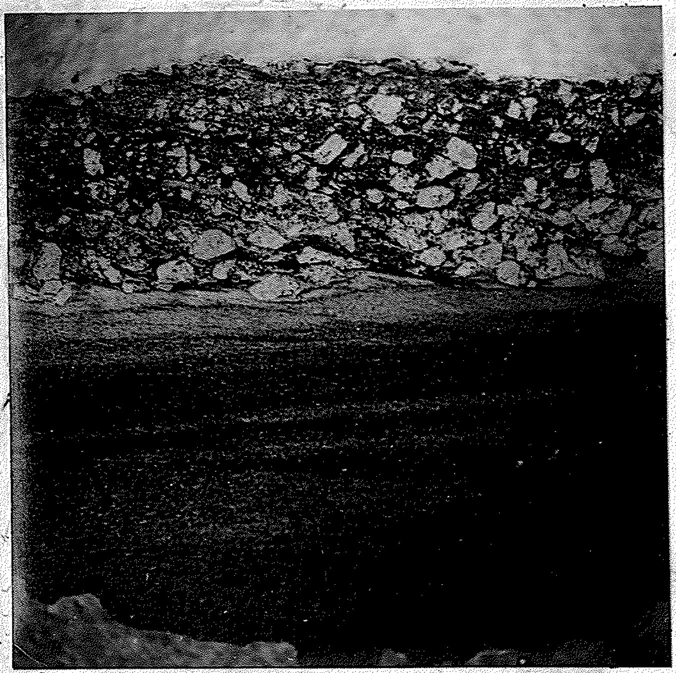
[1] For localities of Manitoba specimens see the index map in back.

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

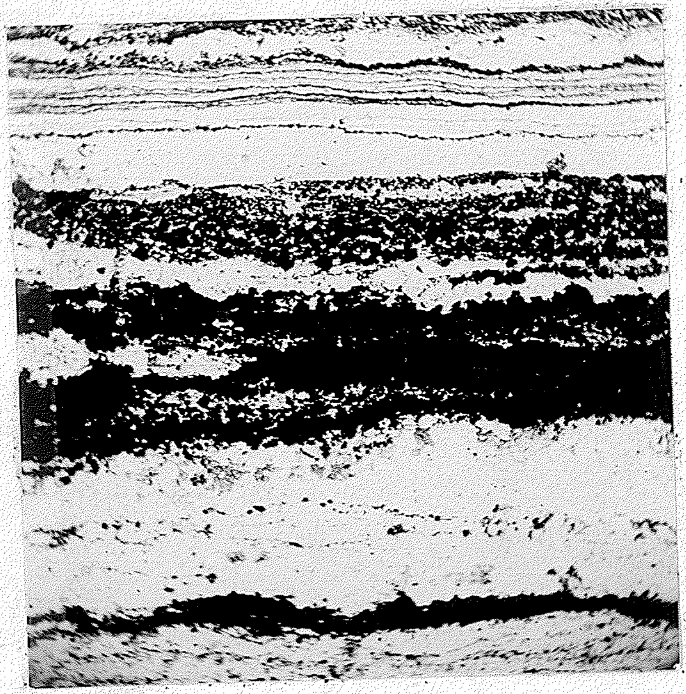
Nearer the sill the cherty tuff is richer in epidote and chlorite (though these may be part of the original tuff), and is cut by veinlets of blue amphibole; near the veinlets in the tuff are a few minute dark blue tourmaline crystals.

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