Deposition and Metamorphism of Precambrian Banded Iron Ores in Manchuria

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I. General Properties of the "Banded Iron Ores"

A. CLASSIFICATION

The "banded iron ores" in Manchuria and other regions can be classified as follows:

Table 1. Classification of "Banded Iron Ores."

Banded iron ores	Poor ores	Hematite-magnetite-quartz-schist ....(1)
		Hematite-magnetite-quartz-schist or Magnetite-quartz-schist with Siderite, Chlorite, Gruenerite, Cummingtonite, Hornblende, Pyroxene, Garnet or Olivine ....(2)
	Rich ores	Sedimentary——Hematite-magnetite-quartz-schist ....(3)
		Hydrotherm——Magnetite-or Martite rock with Chlorite and Dolomite ....(4)
		Weathering——Limonite, Hematite, Martite ....(5)

The major part of the "banded iron ores" in Manchuria consists of a hematite-magnetite-quartz schist (1) or a poor ore with alternating bands of iron oxides and silica which corresponds to jaspilites in Lake Superior and Krivoy Rog, only recrystallized and with coarser grains. The rest of them consist of a finer banded poor ore with alternating bands of three components, i.e., iron oxides, silica and iron silicates (often iron carbonates). This second group occurs in thicker lamina of beds only in locally restricted areas, e.g., in Yuen-chien-shan and Ta-ku-shan areas at An-shan. Those poor ores which contain amphiboles, pyroxenes or olivines represent more highly metamorphosed members of group (2), and occur at Miao-erh-kou, Wai-tou-shan and to the south of Fu-shun, being accompanied with either mica schist or migmatite gneisses. Poor ores of this type are also found in the northern part of Krivoy Rog and in the Vermillion Range to the east of Mesabi, in the United States.

The rich ores of group (3) are found in the local area in Krivoy Rog and An-

shan, but their mode of formation has not yet been determined. The big deposit in Brazil is thought to be in this class. The ores in group (4) are found in Krivoy Rog and Miao-erh-kou. The ores in group (5) forms exceedingly large deposits in the India, Krivoy Rog and Lake Superior districts. From the economic standpoint, the value of the "banded iron ores" throughout the world, rests in the class of rich ores of group (5).

B. STRATIGRAPHY

The iron formations are found in the Precambrian Group of each continent, but do not cover all the Precambrian terrane. Their thickness is usually 100–200 meters, the maximum being 450 meters in the Lake Superior region. They are found at three horizons in the Keewatin and Huronian Systems. Although their age is considered Archaean in Fennoscandia and India, they are usually found among intermediate members between the most highly and least metamorphosed members of the Precambrian: e.g., among the Wu-t'ai System (Liao-ho Syst.) in N. China and Manchuria, the Saksagan System in Ukraina, the Jaturian and Kalevian in Fennoscandia and the Huronian in N. America.

There are iron ore beds in formations of later age, e.g., Wabana, Clinton and Oriskany in N. America, Minette in Europe, Oolitic in England, etc. But these are of an entirely different type, lacking in silica bands, and are much thinner when compared with those of the Precambrian Group. The "banded iron ores" are characteristic to the Precambrian Group, never in any later geological ages are formed similar iron ore beds.

Among highly metamorphosed deposits stratigraphical horizons could be decided only with difficulties owing to their lithological and structural features; while among little metamorphosed deposits they are extremely clear.

All over the world, the banded iron formations are formed in the Proterozoic Group when their stratigraphical position is known. Besides, it is a striking feature that they are always accompanied by a clayslate formation among the major Proterozoic cycle of quartzite, slate and calcareous rocks.

Table 2. Width of Bands and Diameter of Mineral Grains.

Ores	Width of "bands" (mm)		Diameter of mineral grains (mm)
2-component poor ores	finely banded	0.5–2	Iron-
	coarsely banded ..2–10		minerals ..0.005–0.3
3-component poor ores	silica bands	0.2–3	Quartz 0.05–0.5
	Fe oxide bands....	0.2–2	
	chlorite bands 3–5.5		

C. THE BANDED STRUCTURE AND THE GRAIN SIZE OF COMPONENT MINERALS

The above diameters of mineral grains show those of ordinary hematite-magnetite-quartz schist or cummingtonite-magnetite schist in An-shan; while in

jaspilites, grains are much smaller, but in higher metamorphosed ores, they become a little coarser.

It is a remarkable feature that such fine bands should be piled up in beds, showing regular cycles, and attain thickness of tens or even hundreds of meters without any interrupting beds of other clastic sediments.

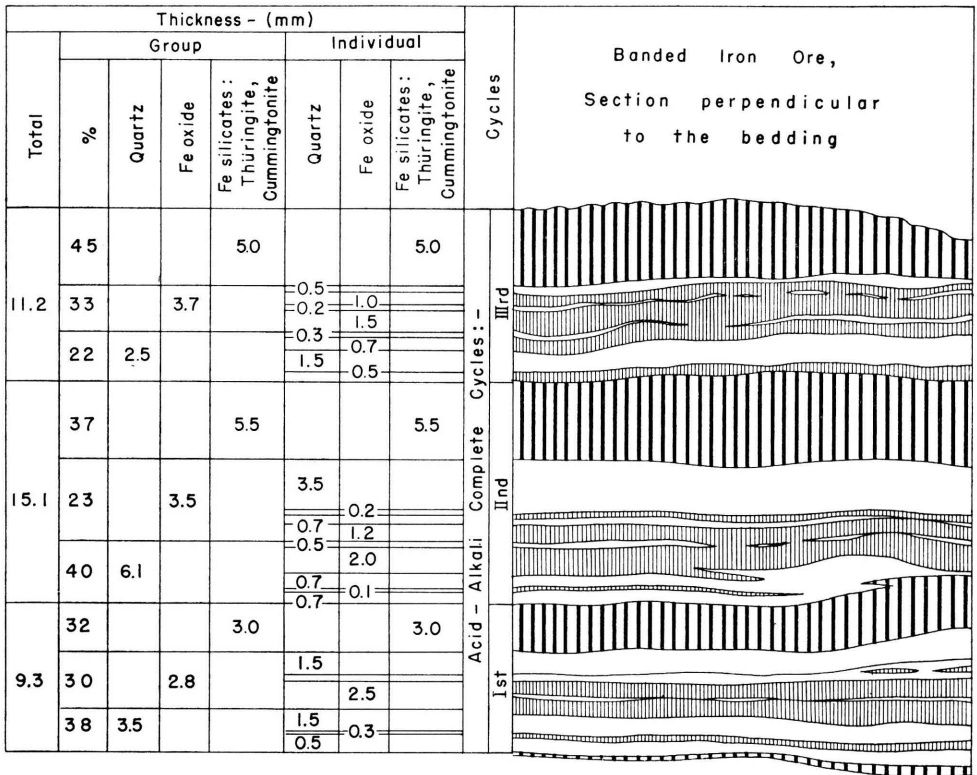Example of bands and regular cycles of three component poor ores are shown in Fig. 1.

Total	%	Group (Thickness – mm)			Individual (Thickness – mm)			Cycles	Banded Iron Ore, Section perpendicular to the bedding
		Quartz	Fe oxide	Fe silicates: Thüringite, Cummingtonite	Quartz	Fe oxide	Fe silicates: Thüringite, Cummingtonite		
11.2	45			5.0			5.0	IIIrd	
	33		3.7		0.5 / 0.2 / 0.3	1.0 / 1.5 / 0.7			
	22	2.5			1.5	0.5			
15.1	37			5.5			5.5	IInd	
	23		3.5		3.5 / 0.7 / 0.5	0.2 / 1.2 / 2.0			
	40	6.1			0.7 / 0.7	0.1			
9.3	32			3.0			3.0	1st	
	30		2.8		1.5	2.5			
	38	3.5			1.5 / 0.5	0.3			

(Cycles column also labelled "Cycles: I", "Complete Acid – Alkali")

Fig. 1. Cyclic Banding in the Banded Iron Ore from Pai-chia-pu-tze, An-shan.

II. Process of Sedimentation and Development of Banding

A. EARLIER VIEWS ON THE ORIGIN

There seems to be a consensus on sedimentary origin of poor ores while the silicification of tuffs, as recently postulated by Dunn, is quite a unique opinion. One point which deeply concerns me, is the interrelation between two-component and three-component poor ores. In all earlier views, two-component ores are believed to be products of secondary oxidation of three-component ores. This is due to the fact that many students followed the views postulated by Van HISE and

LEITH. These authors believed that the original rock with greenalite and siderite, after oxidation, gave rise to ferruginous chert with hematite, limonite and quartz.

On the deposits in Singhbhum, India, Dunn states that "the study of the chloritic phyllites indicates that they are extremely high in iron, in the form of magnetite as well as chlorite. Frequently as these chlorite phyllites are traced laterally along the strike, both chlorite and magnetite are seen to give place to hematite, eventually merging into a hematite phyllite, hematite schist and even iron ore. Again and again this association of hematite phyllite to chlorite phyllite is demonstrated, forcing the conclusion that the large areas of hematite shales and hematite phyllites are merely another form of the chloritic phyllites completely oxidized."

Svitalsky, on the Krivoy Rog deposit, made following statement; "the ore beds were precipitated from colloidal solutions by electrolytes, and that the primary precipitates of ferric iron were changed into ferrous iron, and by a diagenetic reaction between this ferrous iron and silica and other elements, ferrous silicates and carbonates were formed. Later these primary iron silicate and carbonate sediments were oxidized by hot solutions emanating from intrusive granite magma resulting in the formation of first, a jaspilite and ferruginous chert from a siderite chert, and also ferruginous chert from chloritic hornstone. This hydrothermal action in certain localities, dissolved silica and deposited magnetite in its place. Thus the transformation of iron silicates into jaspilite and ferruginous chert by the oxidation and the formation of rich ores were accomplished simultaneously by the hydrothermal action."

On basis of my recent studies on the ore beds at An-shan I now assume that the interrelation between the two-component ore beds and the three-component ore beds can be accounted for by a sedimentary mechanism under a special environment, and that such an environment was characteristic only in the Precambrian; thus the elucidation of this problem of sedimentation gives a clue to the solution of important problems in the historical geology. In the following sections I will state my ideas about the mechanism of sedimentation of the iron formation and, further, about the environment of sedimentation of the whole Precambrian Group.

B. THE ENVIRONMENT OF DEPOSITION

Iron migrates in acid environments and is precipitated in neutral and alkaline environments. Silica, on the contrary, migrates in alkaline and is precipitated in acid environments. This fact, as the phenomena in the weathering crust, has been quantitatively established by the experiments on the "isoelectric points" by Sante MATTSON.

In my former studies upon the weathering and sedimentation of bauxites and "bando-Ketugan" (aluminous shale), I found that the distribution of soil colloids are in close connection with the acidity of the environment and that the result of MATTSON's experiments upon the isoelectric points are in good harmony with the distribution of soil colloids in natural soil profile. I, then, found out that the systematic distribution of soil colloids in a generallized soil profile of humid soils through-

out cold, temperate and tropical zones, could be demonstrated with the "equal silica-alumina molecular ratio lines" inclining towards the south, in the northern hemisphere, to which I proposed a new term "Isosials" (see Fig. 2).
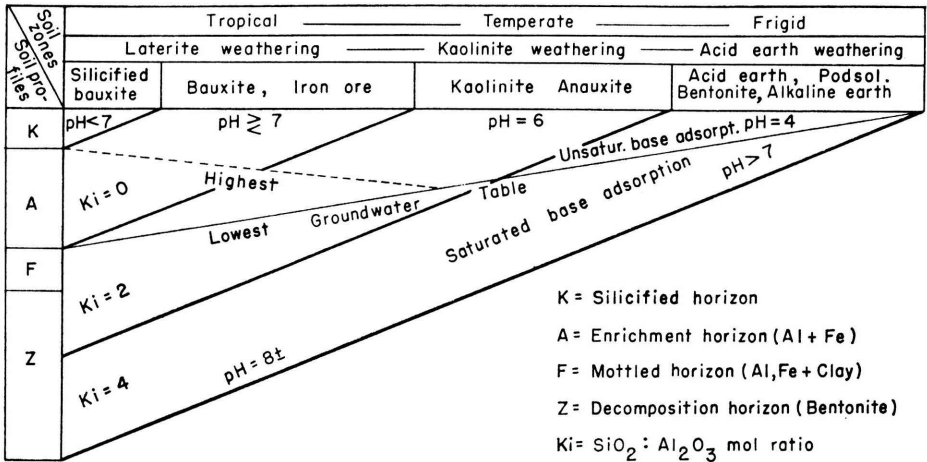

Fig. 2. Diagram Showing "Isosials" or Equal SiO_2: Al_2O_3 Molecular Ratio Lines in Natural Soil Zones and Profiles.

In short, according to the acidity of the environments, the most stable components among the soil colloids remain in situ, while unstable components are dissolved out of the system. Taking into account the above-stated facts, it is known that the iron in the acid environment above the water table and the silica in the alkaline environment below the water table are unstable and migrate until they reach an opposite environment and are redeposited. Especially in the profile above the water table in regions of higher latitudes, the environment is highly acidic and the iron (also part of the alunina) is dissolved out, while in the profile below the water table in tropics, the environment being highly alkaline, the silica is dissolved out.

Taking these facts into consideration in the inference of the Precambrian environmental conditions of weathering, it seems to me that a gleam of light is thrown upon the question of accumulation of unusually large amount of iron and silica. The lack of coarse debris, the homogeneous and normal cycles as in Lake Superior, all point to a mature weathering, as is already pointed out by LEITH. Also it is generally accepted that the Precambrian atmosphere was very rich in CO_2 gas. Under such physiographical conditions, chemical weathering predominates, and especially when the atmosphere contains much CO_2, the surface water in contact with the atmosphere can retain much bicabonates in a solution whose vapor pressure is in equilibrium with the large pressure of the CO_2 in the atmosphere. In other words, rocks are rapidly decomposed and hence, give rise to a condition of a deep going weathering. If so, it is inferred that the soil solution above the water

table was acidic with free CO_2 while that below the water table was alkaline with alkali bicarbonates.

Suppose that the annual rainfall was great and divided into periodically dry and wet seasons, or that the same meteorological conditions as the present "monsoon" climate existed; then in dry seasons, the shallow grounds above the water table become neutral or alkaline, while in wet seasons the phreatic zone near the water table become again neutral or acid. Consequently, in wet seasons iron migrates in acidic surface water, while in dry seasons, silicon migrates in alkaline ground water. The majority of iron and silica, though partly consumed in the formation of fer-ruginous "Ortstein" or silicification of the country rocks, goes into solution and are transported into basins and depressions to get precipitated there as "Fern-faellung."

Suppose, further, that these basins and depressions were wide but shallow, and between the open sea there were only low barriers which separate these basins or lakes from the sea. When, in wet seasons, there is much influx of the surface water, the lake water easily overflows into the sea; while in dry seasons, the influx stops and the lake becomes an inland lake of an arid rigion. The lake water becomes acid in wet seasons, and by convection, the cool, surface water with free oxygen cir-culates down to the bottom, so all of the whole lake water becomes acid and oxidizing. In dry seasons, on the contrary, the influx of a fresh supply of oxygen-bearing and oxidizing water stops, and owing to the seepage of alkaline under-ground water, the lake water gets neutralized, and owing to the subsequent evaporation the lake becomes at last an inland lake in the arid region, in which the lake water stays stagnant, oxygen is lost and as the level of the lake water goes down, its reaction becomes alkaline. In the next wet cycle, a fresh influx begins and the level of the lake water rises, the reaction becomes neutral and finally, when it begins to overflow, it becomes acid again.

Similar phenomena can be observed, at present, in rivers and lakes in the semi-arid region in N. W. Manchuria. In the river Sungari, the pH falls in the flood seasons in summer, it rises in low water in winter. Many small lakes around Hailar are all weakly to strongly alkaline and none is acid.

C. DEVELOPMENT OF BANDING

In the lakes where the reaction of water repeats regular cycles of acid-neutral-alkaline-neutral-acid, the condition under which silica and iron are precipitated is inferred as follows:

The iron, either in the form of colloids or true solution, is supplied to the lake in wet seasons. Ferrous iron is oxidized into ferric iron due to an aeration. Then, in arid seasons, when the influx of the surface water stops and the pH of the lake water gradually rises to neutral, ferric hydroxide gets precipitated very rapidly, because its isoelectric point is pH: 7. A little iron still remains in the solution. Due to the seepage of underground water and evaporation, the reaction becomes alkaline, when silica is supplied to the basin as colloidal solution, gradually in-

creasing its concentration as the evaporation goes on. Under an increased alkaline condition, colloidal silica and iron hydroxide combine to form iron silicates (greenalite, chamosite, etc.,), and the rise of the temperature accelerates precipitation of carbonates of iron and other elements. Again, upon the return of a wet season and the influx of fresh surface water, the reaction returns through neutral
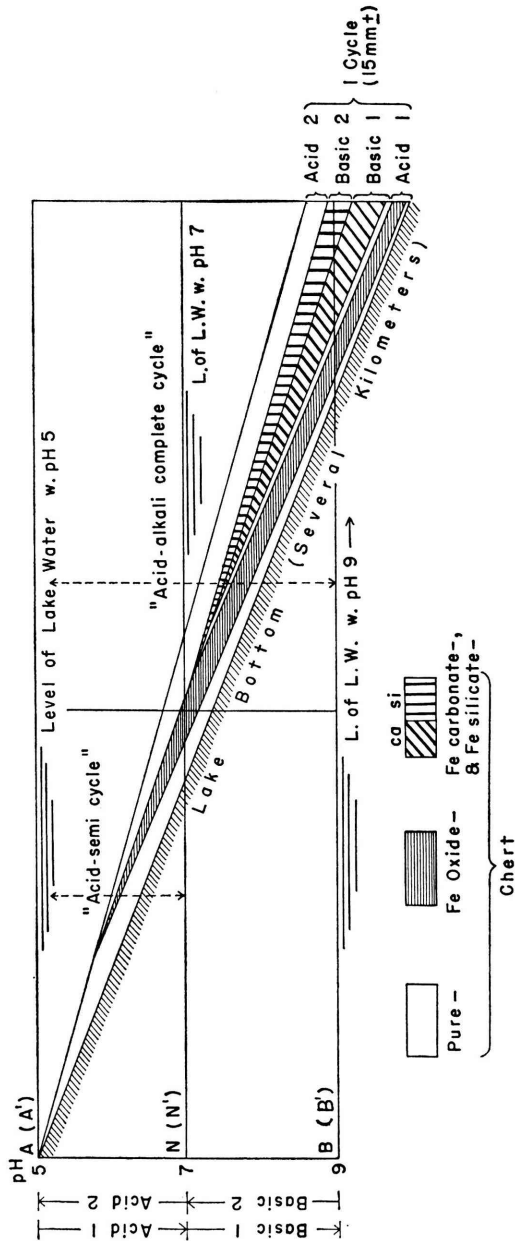

Fig. 3. A Diagrammatic Cross Section Showing the Deposition of Silica, Ferric Oxide, Ferrous Carbonate, Ferrous- and Ferric Silicates in Relation to the Reaction (pH) and Change of Level of Lake Water.

back to acid again. In this stage, silica is totally precipitated, the lake water is acid and contains free oxygen and receives a new supply of iron in solution thus the second cycle gets started and repeated.

The above-stated sequence is diagrammatically shown in the cross section of a lake basin in Fig. 3 and Table 3.

Table 3. The Reaction (pH) of Lake Water and Sediments.

Stage and Reaction	Sediments (Bands)	Area of deposition
A–N (Acid 1)	Ferruginous chert	Entire lake bottom
N–B (Alkaline 1)	Siderite chert	Small area around the center of lake
B'–N' (Alkaline 2)	Chlorite chert	Small area around the center of lake
N'–A' (Acid 2)	Pure chert	Entire lake bottom

In the case of a complete cycle, as is seen in the above figure, or a cycle with the succeeding stages of acid-neutral-alkaline-neutral-acid, the sediments shall be, from the bottom upward, a ferruginous chert, siderite and chlorite chert, and pure chert, thus giving rise to a distinct banding. In the deeper portion near the lake center, a three-component poor ore is deposited, while in the shallow, marginal portion, a two-component poor ore.

While, in the case of an incomplete cycle, or a cycle with the succeeding stages only of acid-neutral-acid (or a cycle which may be called an acid semi-cycle), only a two-component poor ore is deposited all over the lake bottom; in the other case of an incomplete cycle of neutral-alkaline-neutral (or a cycle which may be called an alkaline semi-cycle), only three-component poor ore is deposited within a restricted area around the lake center.

The banded structure described in the foregoing chapter, especially the one in the example taken by me from Pai-chia-pu-tzu, An-shan, show a remarkable coincidence with the banding in the acid-alkaline complete cycle in the above figure. And the cycles in the banding of the ore from Yuen-chien-shan taken by ASANO, shows, beside acid-alkaline complete cycles, alkaline semi-cycles.

That, each of the two- and three-component poor ores, according to field observations, has locally separate areas of distribution, has been stated in a foregoing chapter. This peculiarity is very easily explained by the scheme of deposition stated above.

The view that the two-component poor ore is secondarily derived from the three-component poor ore by an oxidation seems to have been entertained almost universally. Yet, the fact observed in those ores in which finely banded structures are extremely well preserved like those in An-shan, clearly shows that it is more reasonable to assign this to the primary sedimentational structure and distribution.

The two-component poor ore may, at a glance, seem an entirely different type

of ore from the three-component poor ore, yet, upon closer observation, the latter ore is known to be the same as the two-component ore only added with a band of silicates or carbonates of iron in cherts. This is naturally expected from the above-stated condition of sedimentation, that is, an acid semi-cycle is included in an acid-alkaline complete cycle; in fact, the two-component ore, in the lake margin, of the complete cycle, is traced laterally into the lake center, into the constituent bands of the three-component poor ore. Consequently, it is quite impossible that such two-component ore should be derived from a three-component ore by a later oxidation. If oxidation is a necessary procedure, it must have operated exactly at the same time with the deposition of those thin bands, and that, with a regular intermittent recurrence. Such syngenetic oxidation, if present, is only one of the sedimentary conditions under a well aerated, hence oxidizing, lake water. Thus, this coincides with my "acid 1" or "acid 2" stages of the sedimentation.

III. Progressive Metamorphism of "Banded Iron Ores"

A. METAMORPHISM OF POOR ORES

In the preceding section, the stratigraphy of the iron-bearing formation, the banded structure of the iron ores, the mechanism of their sedimentation were considered in the deposits of Lake Superior, Krivoy Rog and An-shan. In these deposits, the "banded iron ores" consist of following mineral components:

Table 4. Poor ores and their mineral components.

Classification	Ores	Component minerals
Two-component poor ore	Ferruginous chert, Jaspilite	Chalcedonic quartz, Red and purple hematite
	Hematite-magnetite- quartz schist	Quartz, Black hematite, Magnetite
Three-component poor ore	Siderite-chlorite- hematite chert, and Siderite chert	Chalcedonic quartz, Siderite, Chamosite, Greenalite
	Thüringnite-magnetite- Gruenerite- cummingtonite- magnetite schist	Quartz, Thüringite, Gruenerite, Cummingtonite, Magnetite

The poor ores in Lake Superior and Krivoy Rog consist largely of compact jaspilite, ferruginous chert or siderite-chlorite chert, while those in An-shan crystalline hematite-magnetite-quartz schist and thuringite-gruenerite (or cummingtonite)-magnetite-quartz schist. In the eastern part of the Lake Superior (Masabi) deposits and in the northern part of the Krivoy Rog deposits are met with crystalline thuringite-cummingtonite-magnetite schist, gruenerite-magnetite schist and further eulysitic ores with pyroxenes and olivines.

In Manchuria, to the east of An-shan, there are many deposits with more highly recrystallized ores than those at An-shan, i.e., such as Miao-erh-kou, Wai-tou-shan and the region to the south of Fu-shun. I have had chances to make field observations of these deposits, but I owe the details of following descriptions to the recent works by ASANO.

In the deposit at Miao-erh-kou, the footwall consists of mica schist and is intercalated with limestones. The iron formation itself and its hanging wall consist of chlorite schist, hornblende schist and injection gneisses and the ores are tremo-lite-magnetite and hematite-magnetite schists.

At Wai-tou-shan, both in hanging and footwalls are developed actinolite schist, hornblende schist and mica schist, suggesting a mode of emplacements of a large xenolithic mass engulfed in an injection gneiss.

In Kung-chang-ling deposit, on both the hanging wall and footwall of the poor ore bed, a garnet-anthophyllite-fels develope. This rock is believed to have been derived from the chlorite-amphibole schist by a contact metamorphism due to an intrusion of granite.

The latter is very widely developed in the area either in the hanging wall and footwall sides or in an alternation with the poor ore beds. I believe that the garnet-anthophyllite-fels is the metamorphosed equivalent of a three-component poor ore. Therefore, in this deposit, unlike in Miao-erh-kou and Wai-tou-shan, an effect of local superimposition of a regional and a thermal metamorphism is observed.

At Hui-nan and Chin-chuan-hsien, east Manchuria, a green hornblende-magnetite schist is found; at Ma-ho-ssu, Fu-shun-hsien and other small deposits, a pyroxene-olivine-garnet-magnetite schist and coarse grained magnetite-quartz schist are found, all of them being in the form of xenoliths or melanocratic bodies in migmatite gneisses. These correspond to the eulysite in Sweden and show the highest grade of metamorphism.

The above-mentioned deposits are arranged according to degree of metamorphism, and they can be classified into five successive stages as in the following table (Table 5). In this table the formation of rich ore deposits along with the main deposits is also shown. As the metamorphism of the poor ores can be traced in progressive stages, I refer to it as the "ordinary phase," while the formation of the rich ores takes place at any stage irrespective of their grade of metamorphism and I refer to it as the "extraordinary phase."

The fact that the metamorphism of the "banded iron ores" in Manchuria can be traced in progressive stages has already been noticed by ASANO. In this paper, I have completed the list adding the deposits of Lake Superior and Krivoy Rog, both of which I have had opportunity to visit during field observations, to the earlier stages of the series, covering the whole metamorphic history.

In the above list, it is in poor ores with three components that the successive stages of advancing metamorphism are clearly indicated by corresponding mineralogical changes. On the other hand, the poor ores with two components are turned into a hematite-magnetite schist already at the second stages and later at

Table 5. The Progressive Metamorphism of "Banded Iron Ores" and the Formation of Rich Ores.

Stages	I. Siderite-Chlorite Stage →		II. Chlorite-Grüünerite Stage				
Phases	Ordinary Phase	Extraord. Ph. Hydrotherm Weathering	Ordinary Phase			Extraordinary Hydrothermal	
Ore Deposits	Mesabi Iron Form.	Mesabi Rich Ore	Krivoy-Rog Iron Form.	Singhbhum Iron Form.	An-shan Iron Form.	An-shan Rich Ore	Krivoy-Rog Rich Ore
Ores / Original Sediments	Taconite, Jaspilite	Compact, red hematite	Jaspilite, Fe-chert	Banded Fe-quartzite	Hematite-, Magnetite-q-schist	Magnetite	Martite, Magnetite
Fe_2O_3 or $Fe_2O_3 \cdot nH_2O$	Taconite, Jaspilite	Hematite	Jaspilite, Fe-chert	Banded Fe-quartzite	Hematite-q-, Magnetite q-schist	Magnetite	Martite, Magnetite
Ankerite $(Ca, Fe)CO_3$	Siderite		Siderite-cummingtonite-thüringite-schist	Banded chloritic quartzite, Grünerite-schist	Siderite-magnetite-cummingtonite (grünerite) thüringite-schist	Thüringite-magnetite-schist	Cummingtonite-magnetite-schist
Greenalite $FeO \cdot SiO_2 \cdot nH_2O$	Greenalite	Hematite					
Chamosite $3FeO \cdot Al_2O_3 \cdot 2SiO_2 \cdot 3H_2O$	Chamosite						
Progressive metamorph. of basic Igneous rocks			I. Chlorite facies				
Shale	Slate	Slate	Actinolite-schist, Sericite-schist, Phyllite	Chloritic phyllite, Mica schist w. Ottrel., Staurol., Andalus., Cyanit.	Biotite-, Biotite-sericite-, Chlorite-, Graphite-phyllite, Sericite-, Chlorite-, Actinolite-schist.	Garnet-thüringite-, Tourmaline-sericite-schist	Chlorite-garnet-cummingtonite-schist w. alkali minerals
Sandstone	Quartzite		Sandstone, Quartzite (w. Sericite)		Quartzite, Sericite-q-schist		

(Left column spanning lower section: "Chert with")

		III. Tremolite-Actinolite Stage →		IV. Green Hornblende stage →	V. Pyroxene-Olivine Stage		
Phase		Ordinary Phase		Extraord. Ph.	Ordinary Phase.	Ordinary Phase		Extraord. Phase
Weathering				Hydro-therm.				Thermal
Krivoy-Rog Rich Ore	Singh-bhum Rich Ore	Miao-erh-kou Iron Form.	Wai-tou-shan Iron Form.	Miao-erh-kou Rich Ore	Chin-chuan & Hui-nan Iron Form.	Ma-ho-ssu Iron Form.	Ma-ho-ssu & Wang-chiang-tze Iron Form.	Tung-yuan-pu Rich Ore
Limonite	Hematite	Hematite-q- sch. Magnetite-q-schist	Magnetite-q-schist	Magnetite	Magnetite-hornblende-schist	Hedenber-gite-amphibolite-magnetite schist	Hypers-thene-fayalite magnetite-schist	Mg-Ca-Fe-.Mn-carbonate-magnetite-schist
Limonite	Hematite	Hematite-q-, Magnetite-q-schist	Magnetite-q-schist	Magnetite		Magnetite-q-schist	Magnetite-q-schist	
Limonite	Hematite	Tremolite-magnetite-, Anthophyllite-magn-, Chlorite-magn-sch.	Actinolite-magnetite-. Anthophyllite-magnetite schist	Magnetite with dolomite	Magnetite-green horn-blende-grünerite sch.	Hedenberg-grüner.-green hornbl.-hemat.-magn.-q-anthophyll.-fels	Hypersth.-hedenberg-fayalite(garnet)-magnetite-fels	Mg-Ca-Fe-Mn carbonates-magn.-fels, Garnet-hypersth.-xanthophyll.-olivine-fels
		II. Amphibolite facies				III. Eclogite facies		
		Mica schist, Amphibolite, Chlorite-sch., Injection gneiss, Phyllite	Amphibolite, Actinolite-schist, Injection gneiss		Mylonite granite, Gneiss	Migmatite gneiss	Migmatite gneiss	
		Quartzite with sericite	Quartzite					

higher stages, they become very stable and undergo little change in components.

In reviewing the whole metamorphic history, I found that the first and second stages may be called a "chlorite facies," the third and fourth an "amphibolite facies" and the fifth an "eclogite facies." These three facies are the classification given by Eskola of Finland, to the progressive metamorphic facies of basic igneous rocks. It is important that the metamorphic history of the banded iron ores, beginning with iron carbonate and iron silicate as their main components, can be closely correlated with that of basic igneous rocks in general.

Along with the advancing metamorphism of the iron ores, the metamorphism of argillaceous and arenaceous members of the series are shown on the list. In reviewing the whole history it is recognized that the first and second stages are mainly dynamic, and passing through the later second and third stages the change in the fourth and fifth stages is more and more characterized with features of thermal metamorphism.

In the main ore bodies at the Mesabi Range, no direct effect of any batholithic intrusives is observed. Regarding the formation of rich ores, there have long since been controversies between a "descending meteoric water" theory of the Wisconsin school and an "ascending hot water theory" of the Minnesota school. However, in the Vermillion Range to the east of Mesabi, highly metamorphosed members such as amphibole-magnetite schist and even eulysitic ores are produced by the contact effect of basic intrusives.

In Krivoy Rog, it is generally accepted that the enrichment was caused by an ascending hot solution, because of frequent occurrence of soda minerals, a batholithic intrusion is inferred in depth.

In An-shan deposit, granitic intrusions are so extensive that the iron formation at Wang-chia-pu-tze and Ying-tao-yuan is in part completely captured in the granite. Also rich ores with thuringite and magnetite, and locally sericite schist from chlorite phyllite are formed by the action of a hydrothermal solution.

At Miao-erh-kou in the hanging wall, and at Wai-tou-shan, in both hanging and footwall, are developed injection-gneisses.

At Chin-chuan, Ma-ho-ssu and also at Wang-chiang-tze, Ching-lung-hsien, Jehol, the iron formations are represented by xenoliths or sometimes merely melanocratic bodies as assimilation relics floating amid the extensive migmatitic gneisses.

The interrelations between the metamorphics and intrusives are thus clearly demonstrated, the higher the metamorphic stages the relation being the more intimate. This fact bears witness to the phenomena which are interpreted with the belief that the "isodynamics are also the isotherms" in a region of an advancing metamorphism. The advancing metamorphism of poor ores with three components is correlated with that of ordinary basic igneous rocks; further, the parallelism between the metamorphism of poor ores of known compositions on the one hand, and that of argillaceous sediments in the series of iron formation on the other hand, can be well established. This is another point worth paying attention to.

B. GENESIS OF THE RICH ORES

In the present status of world technology the economic value of the "banded iron ores" is linked with that of rich ores. The weathering and hydrothermal actions are responsible for the formation of main rich ore bodies, and those deposits in the earlier stages of the advancing metamorphism seems to be more susceptible to those processes of enrichment. It has already been stated above that there are two opponent theories of weathering and hydrothermal processes upon the enrichment of the Lake Superior deposits. I suspect, however, that this enrichment is accounted for by the dissolution of chalcedonic quartz under the lateritic weathering which prevailed over the whole area in the circum-Gulf regions during the Eocene, Wilcox stage. The rich ores in India are surface debris ("Float ores") and powder ores ("Blue dusts") which have been formed under the lateritization process in the Tertiary and Recent.

The process of a hydrothermal action is most pronounced in Krivoy Rog, and is characterized with the association of soda minerals (aegirine, alkali-amphibole, albite, etc.) and chlorite. The formation of soda minerals in a hydrothermal action is also pointed out by T. KATO in the Mosan deposit, N. Chosen.

As an example of rich ores of the thermal metamorphism may be taken the Mn-carbonate-bearing magnetite at Tung-yuan-pu, on the Mukden-Antung Railway line. The co-existence of thermal and dynamic metamorphic minerals in this deposit was noticed by TSURU. This seems to be of the same type as the skarn ore in the Leptite series in middle Sweden which was described by Magnusson.

C. METAMORPHISM OF THE PRECAMBRIAN GROUP

Although it is usually the case with the world occurrence of the iron formations that they are comprised in the series showing a medium grade of metamorphism among the whole Precambrian of the regions, the iron formations themselves show the advancing metamorphism from the earliest stage of jasper (chert) and phyllite, through amphibole schist and mica schist, up to eulysite and migmatitic gneisses.

Consequently, from point of view of only metamorphism, the formations containing jasper and phyllite are not different from those of neo-Proterozoic (Sinian) System and even Paleozoic Groups; and eulysite and migmatites are not different from some of the member of so-called Sang-Kan gneiss "nor from those migmatites developed by the injection of TOMITA's so-called older Archaean granite" into his Tscha-nan series, Sui-yuan series and Ta-ling series.

According to TOMITA, the "Sang-Kan gneiss" together with the Tscha-nan and other series as well as the injection gneisses derived from them, correspond with the lower part of his "Shieh-hu-shan series." The Shih-tsui and the Pai-yun-ssu (Nan-t'ai) series of the Wu-t'ai System correspond with the upper part of the said series. And further, according to him, the lower, highly metamorphosed part was simply assigned to the Archean (Tai-shan complex) and the upper, less metamorphosed part was simply assigned to the Proterozoic, since the time of Willis and Blackwelder.

Now, in such eulysite and migmatite gneisses as those in the southern part of Fu-shun or in Wang-chiang-tze, Jehol banded iron ores with two components or silica and ferric oxides are still retained, pointing to the sedimentaly origin of the metamorphics.

Limestones and highly aluminous minerals such as sillimanite and cyanite, similarly serve as sedimentary criteria. However, there are frequently the cases in which no such criteria can be discernible, and original rocks are not known.

In short, at the highest metamorphosed stage of the "banded iron ores," their lighologic types show quite similar appearances as those assigned to the Archaean. But it is very important that poor ores with two components if included in them, clearly indicates sedimentary criteria.

TOMITA, taking up the cycles of igneous intrusion and lithologic characters, tried to establish a criterion to distinguish the Proterozoic from the Archaean. In my opinion, however, it is more important to find a criterion by which the sedimentary and igneous origin of metamorphics can be distinguished with more accuracy. In this sense, "banded iron ores" offer excellent criteria.

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