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THE ORIGIN OF THE PRE-CAMBRIAN BANDED IRON ORES

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ABSTRACT. The cause of banding in the Pre-Cambrian banded iron ores is sought in a cyclical deposition of colloids due to a periodic change of reaction (pH) of lake water. The two-component poor ores, with alternating bands of ferric iron oxides and silica, are the product of an acid-neutral semi-cycle; while the three-component poor ores, with alternating bands of the above two plus a third of iron silicates (often of iron carbonates), are the product of an acid-alkaline complete cycle. The interrelation between these two types of ores seems to be one of a primary sedimentation and not of a later oxidation of the latter into the former.

Both iron oxides and silica are the products of a mature weathering. The behavior of these components in solution is supposed to have been in the same general trend as in the present soil profiles that have been generalized by the writer with his "ISOSIALS" in his recent paper (1944) on the genesis of bauxite deposits, the generalization upon chemical changes being based upon Sante Matson's experiments on the isoelectric points of soil colloids (1932).

In view of the regularity and purity of the bands as well as the vast thickness of the total iron ore beds, chemical weathering and deposition are known to have been preponderant and to have given rise to the most perfect "sedimentary differentiation" in the earth's history.

It is inferred that shallow lakes in a paralic basin and a monsoon-like climate were responsible for the unique environmental condition. That environment obtained only in the Middle Pre-Cambrian or only once in the history of the gradually cooling earth's surface, and its like has never been reproduced in any later geologic ages.

PREFACE

DURING his service, from 1924 to 1945, in the Geological Department, South Manchuria Railway Co., the writer had opportunities of visiting large and small deposits of banded iron ores in Manchuria, representing successive stages of progressive metamorphism. In 1927, he visited the Mesabi Range deposits in the Lake Superior Region, U. S., and in 1937 the Krivoy Rog deposits in the Ukraine, U.S.S.R.

In 1939, the Geological Department, with the writer as the Chief, found a magnetic anomaly of over 6,000 γ in a wide area

in the plain adjacent to the An-shan deposit, which was then prospected with deep borings over a period of years. The writer again visited the deposit and found three-component ores at P'ai-chia-pu-tzu in which the original sedimentary structure was unusually well preserved.

Mr. G. Asano was then engaged in the studies on the banded iron ores and had published detailed studies in a series of papers, especially on lithologic characters of the ores. He pointed out that different deposits in Manchuria showed successive stages of progressive metamorphism, leading to the formation of eulysite.

The writer found that, if the Lake Superior and the Krivoy Rog be added to the top of the list, the series would become complete, because the bulk of the primary ore beds in these deposits consists in little-metamorphosed jaspilites.

The writer has made studies upon the mechanism of sedimentation and upon the progressive metamorphism. He has written a large paper upon the significance of the banded iron ores from the point of view of Pre-Cambrian historical geology. The present paper is a part of the larger paper, relating to the genesis of the banded iron ores.

THE GENERAL PROPERTIES OF THE BANDED IRON ORES STRATIGRAPHY

The iron formations are found in the Pre-Cambrian rocks upon each continent, but not in all the Pre-Cambrian terranes. Their thickness is usually 100-200 m., the maximum being 450 m. in the Lake Superior region. In the latter region, they are found at three horizons in the Keewatin and the Huronian Systems. Although their age is considered to be Archean in Fennoscandia and India and in the Keewatin in North America, they are usually found among intermediate members between the most highly and the least metamorphosed rocks of the Pre-Cambrian: *e.g.*, in the Wu-t'ai (Liao-ho) System in Manchuria and North China, Saksagan System in Ukraine, Jatulian and Kalevian in Fennoscandia, and Huronian in North America.

There are iron ore beds in formations of later ages, *e.g.*, Wabana, Clinton and Oriskany in North America, Minette in Europe, Oolitic in England, etc. But these are of entirely different type, lacking in siliceous bands, and are much thinner

when compared with those of the Pre-Cambrian. The banded iron ores are characteristic of the Pre-Cambrian, and in no later geologic ages were similar iron ore beds formed.

Where the iron deposits have been highly metamorphosed, their stratigraphic position can be determined only with great difficulty, but where the stratigraphic position is clear they are found, all over the world, in Proterozoic rocks. Moreover, it is striking that, within the Proterozoic cycles of quartzite, slate and calcareous formations, they are always associated with the clay-slate.

THE ORES, THEIR BANDED STRUCTURE AND THE GRAIN SIZE OF COMPONENT MINERALS

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

TABLE 1
The Classification of the Banded Iron Ores

Banded iron ores	{ Poor ores Rich ores	{ Hematite-magnetite-quartz schistClass 1
		{ Hematite-magnetite-quartz schist or magnetite-quartz schist with siderite, chlorite, grunerite, cummingtonite, hornblende, pyroxene, garnet or olivineClass 2
		{ Sedimentary — Hematite-magnetite-quartz schistClass 3
		{ Hydrothermal — Magnetite or martite rock with chlorite and dolomiteClass 4
		{ Weathering — Limonite, hematite and martite . Class 5

The bulk of the banded iron ores in Manchuria consist of the hematite-magnetite-quartz schist (Class 1) or the poor ores with alternating bands of iron oxide and silica which correspond to jaspilites of Lake Superior and Krivoy Rog, only recrystallized and with coarser grain. The rest of them consist of finer-banded poor ores with alternating bands of three components, *i.e.*, iron oxide, silica and iron silicates (often iron carbonates). This second group occurs in An-shan in thick beds in locally restricted areas, *e.g.*, in Yuen-chien-shan and Ta-ku-shan areas. Those poor ores which contain amphiboles, pyroxenes or olivines represent successively higher-metamorphosed members of the group (Class 2), becoming similar with a eulysite in Sweden at their extremity. They occur

at Miao-erh-kou, Wai-tou-shan and to the south of Fu-shun, being accompanied either by mica schists or by migmatite gneisses. In the northern part of Krivoy Rog and in Vermilion Range to the east of Mesabi, are also found poor ores of this type.

The rich ores (Class 3) are found in local areas in Krivoy

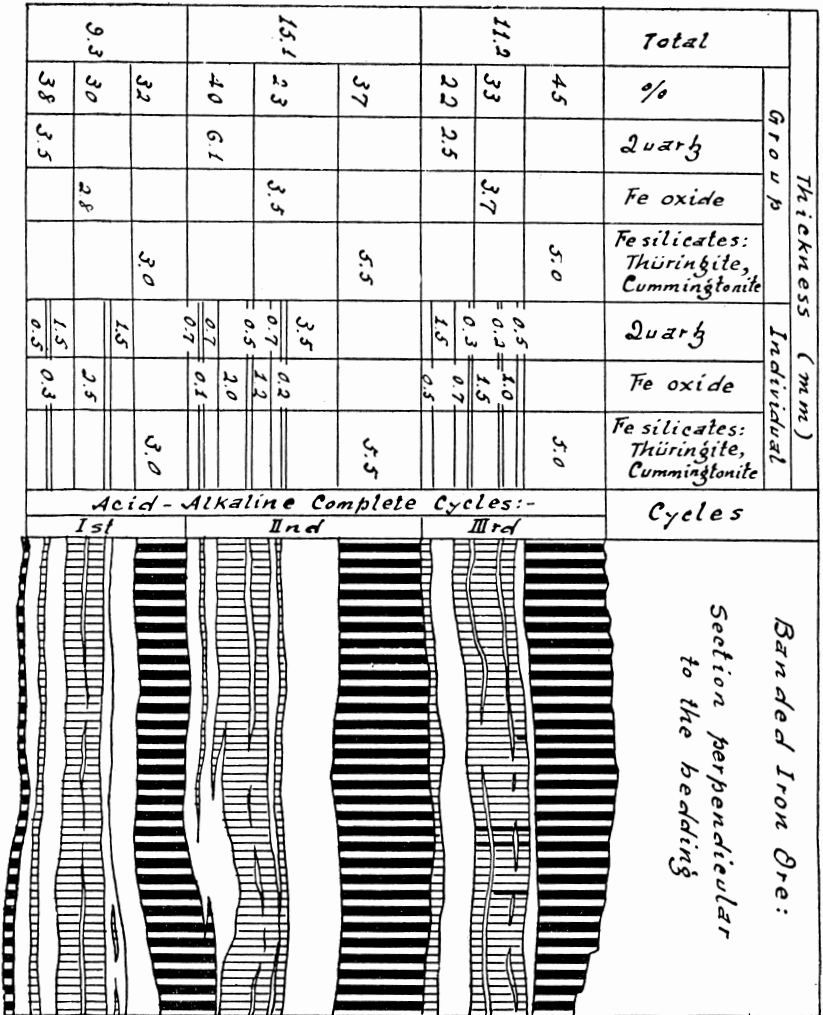


Figure 1. Cyclic banding in the banded iron ore from P'ai-chia-pu-tzu, An-shan.

Rog and An-shan, but their mode of formation has not yet been determined. The big deposit in Brazil is thought to be of this class. The ores of Class 4 are found in Krivoy Rog and in Miao-erh-kou. The ores of Class 5 form vast deposits in Central India, Lake Superior and Krivoy Rog regions. From an economic standpoint the value of the banded iron ores throughout the world rests on the rich ores of Class 5.

TABLE 2

The Width of Bands and the Grain Size of Component Minerals

Ores	Width of bands (mm.)	Diameter of mineral grains (mm.)
Two-component poor ores	{ Finely banded 0.5-2 Coarsely banded 2-10	Iron-minerals 0.005-0.3
Three-component poor ores	{ Silica bands 0.2-3 Fe oxide bands 0.2-2 Chlorite bands 3-5.5	Quartz 0.05-0.5

The above diameters of mineral grains are those of ordinary

Cycles	No	Bands	mm	No	Q	Gr	Ca	Th	M	Remarks
Acid-alkaline complete-cycles	4	1	0.3	1				⊕	+	Th > M
	3	2	0.4	2	⊕	+		+	+	mainly Q
	4	3	1.8	3	+	⊕				Gr > Q
	3	4	0.3	4	⊕	+	+			mainly Q
	2	5	0.8	5	⊕				⊕	M = Q
	1	6	0.3	6	⊕	+				mainly Q
	4	7	1.0	7	+	⊕				Gr > Q
	3	8	0.3	8	⊕	+				mainly Q
	2	9	0.4	9	⊕	+		+		mainly Q
	1	10	0.3	10	⊕				⊕	M = Q
Alkaline semi-cycles	4	11	0.8	11	⊕				⊕	M = Q
	3	12	0.3	12	⊕					mainly Q
	4	13	1.0	13	⊕			+		mainly Q
	3	14	0.8	14	⊕	⊕			+	mainly Q
	4	15	2.0	15			⊕	⊕	⊕	Banding w. Th+M → Ca+M
	3	16	0.3-0.8	16	⊕	+	+	+	+	mainly Q
	4	17	2.0	17			⊕	⊕	⊕	Banding w. Th+M → Ca+M
	3	18	0.3-0.8	18	⊕		+	+		mainly Q

Figure 2. Banding and mineral components of grunerite-thuringite-magnetite schist at Yuen-chien-shan. Q, quartz; Gr, grunerite; Ca, siderite; Th, thuringite; M, magnetite; ⊕, main component, (Materials after G. Asano).

hematite-magnetite-quartz schist or cummingtonite-magnetite schist in An-shan district. Those in jaspilites in foreign deposits are much smaller, while those in metamorphosed ores are a little larger.

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

Examples of bands and regular cycles of three-component poor ores, which are exceptionally well preserved in some ores in the An-shan deposit, are graphed in figures 1 and 2.

G. Asano recently published very detailed studies upon the An-shan deposit and stated his views on the banded structure as follows:

“At the time of deposition, they were deposited as thin bands

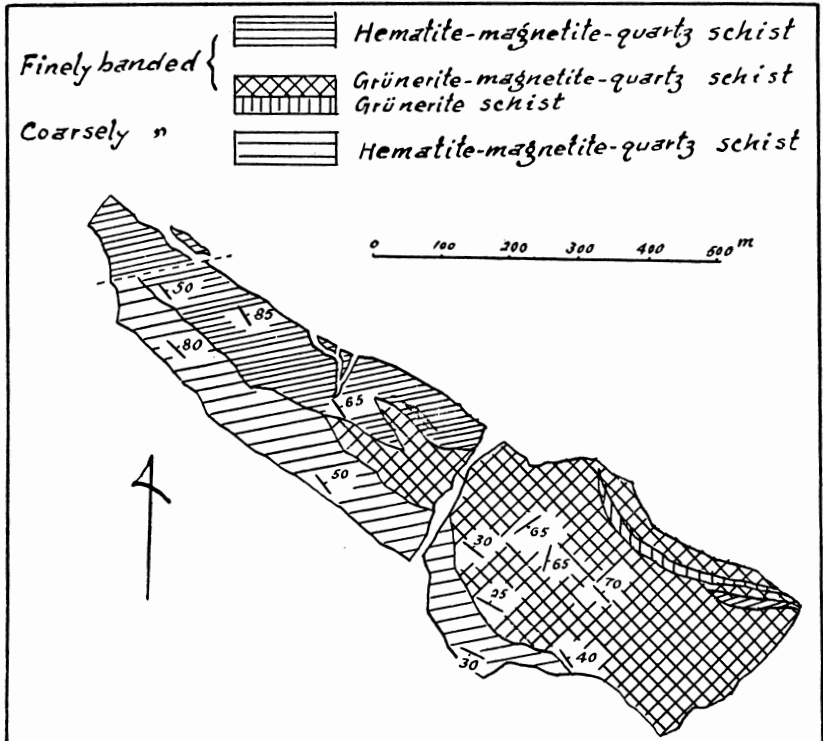


Figure 3. Ta-ku-shan ore body showing the distribution of different types of the banded iron ores (after G. Asano).

with different components and later partially oxidized and then subjected to regional or thermal metamorphism. According to their original constituents, they are either simply recrystallized or changed into certain suite of new minerals that are in equilibrium under new conditions. Since such suite become different from each other as the original constituents are different, they again result in different component minerals in each of the thin bands (Asano, 1941, p. 37)."

Asano further gives the following description regarding the mode of occurrence of three component ores with grunerite, cummingtonite, thuringite and siderite:

"Both at Yuen-chien-shan and Ta-ku-shan, ores with amphiboles occupy the whole thickness, from top to bottom, of the iron formation, but only in certain locally restricted areas among two component poor ores. When traced laterally in their prolongation, they entirely disappear from every horizon of the iron formation."

That is, the whole of a given iron ore bed may change from two-component into three-component ores according to locality and not to stratigraphic horizons (see fig. 3).

EARLIER VIEWS REGARDING GENESIS

Earlier views regarding genesis are summarized in the following table:

There seems to be a consensus of opinions as to the sedimentary origin of the poor ores. That they are formed by silicification of tuffs, as recently postulated by Dunn, is a unique view.

THE PROCESS OF SEDIMENTATION AND THE FORMATION OF THE BANDED STRUCTURE

POSITION OF THE IRON FORMATION IN THE PRE-CAMBRIAN CYCLE OF SEDIMENTATION

Deformation and progressive metamorphism of the Pre-Cambrian rocks containing the banded iron ores has in many places produced badly folded and contorted crystalline schists and gneisses, rendering determination of thickness as well as of the nature of the original sediments very difficult. However, in less metamorphosed areas, the iron formations are clearly interbedded with quartzite, clay-slate, limestone, etc., and not

TABLE 3

Earlier Views Regarding the Genesis of Pre-Cambrian Banded Iron Ores

Genesis of poor ores

	Raw materials	Transportation and deposition	Environment of deposition	Authority
Aqueous	Weathering products of volcanic rocks	Chemical deposition	Sea bottom	Van Hise & Leith, 1911
	Magmatic solution			
	Weathering products of volcanic rocks	Transported as colloids protected by organic matter, deposited by bacteria	Lake bottom	Gruner, 1937
	Weathering products of Pre-Cambrian rocks	Transported as colloids protected by organic matter, deposited by electrolytes	Lake bottom	Moore & Maynard, 1929
sedimentation	An-shan Weathering products of basal metamorphics	Deposited by bacteria	Marsh	Murakami, 1922
	Krivoy Rog Lateritic weathering products of Archaean gneiss	Transported as colloids protected by organic matter, deposited by electrolytes	Lake bottom	Svitalsky, 1937
	Middle Sweden "Volcanic solution"	Chemical precipitates	—	Magnusson, 1936
	Western Australia Weathering products on peneplain	Chemical precipitates	Peneplain	Woolnough, 1941
Replacement	Lake Superior Volcanics	Ascending hot solution	—	Collins, Quirke & Thomson, 1926
	India Banded tuffs	Hot spring	—	Dunn, 1941

Genesis of rich ores

Genesis	Ore deposits	Ores	Authority
Weathering:— dissolution of SiO ₂ by descend- ing meteoric water	Lake Superior	Red hematite, limonite	Van Hise & Leith, 1941
	Singhbhum, India (float ore, blue dust)	Black hematite	Dunn, 1941
	Part of Krivoy Rog	Limonite	Svitalsky, 1937
Hydrothermal:— replacement by ascending hot solution	Lake Superior	Red hematite, limonite	Gruner, 1937
	Part of Krivoy Rog	Martite, magnetite	Svitalsky, 1937
	Miao-erh-kou	Magnetite	Tsuru, 1931
Sedimentation	Part of Krivoy Rog	Magnetite, hematite	Svitalsky, 1937
	Brazil	Magnetite, hematite	Leith & Harder, 1911

only accurate measurement of their thickness but also close observations upon their environments of deposition are possible.

In the Lake Superior area, the main iron formations (Biwabik and Ironwood) belong to the Middle Huronian, while there are other iron formations in the Upper and Lower Huronian. The Upper, Middle and Lower Huronian Systems each reaches nearly 1,000 m. in thickness. Each begins with a quartzite at its base, comprises thick clay-slate and marl or limestone in an ascending order; each shows a normal cycle of sedimentation. That is, normal cycles were repeated three times, each attaining a remarkable thickness. Besides, what is worth attention is that the iron formation in each case is associated with the clay-slate. The iron formations themselves reach thicknesses ranging from several meters to 450 m.

At Krivoy Rog, there is a quartzite at the base, next a thick phyllite, and above an alternation of phyllites, carbonaceous slates and limestones. The iron formation is associated with the phyllites. It occurs in a complicated synclinorium, so that the measurement of thickness is difficult. According to Svitalsky (1937), however, the thickness is around 50 m. on an average, but near Ingulets Mine it reaches the tremendous figure of 1,500 m.

At Singhbhum in India, also, the newer Dharwar series, which contains the iron ore series, consists of sandstones and occasional conglomerate below and of shales above, the iron ore series being situated between the "Lower shales" and the "Upper shales" (Jones, 1934).

At An-shan, later granitic intrusions and overthrusts render the measurement of thickness difficult. Both hanging wall and footwall of the iron formation consist of intensely folded, gray, graphitic slate and phyllite. Those in the hanging wall are intercalated with beds of a black limestone. In those parts close to the contact with the iron ore beds, the cleavage of the slate and phyllite is usually parallel with the plane of contact with the ore, and consequently is apt to be mistaken for the bedding of the slate and phyllite. Therefore, the thickness of the latter is difficult to determine accurately but a reasonable assumption is over 900 m.

As stated above, the Pre-Cambrian systems show normal cycles of sedimentation and attain a remarkable thickness. Such large cycles as these are not always found in later geologic systems. This testifies that the Pre-Cambrian environments of sedimentation were unique.

THE MATURE WEATHERING

The fact that the iron formations in these cycles are always associated with clay-slates or phyllites, shows that the source of the materials of the ore beds may be found in the weathering and sedimentation in the particular environment under which the clay-slates or phyllites were produced, and that the views, long entertained in some quarters, that the iron was derived from submarine volcanoes or special volcanic rocks, are quite untenable. The ferruginous material should be reckoned as the product of mature weathering on a land surface. Indeed, iron oxide, free silica and aluminum hydroxide are three main products of mature weathering. Iron oxide and silica are constituents of all the banded iron ores, while the presence of aluminum hydroxide is not prevalent. According to Dunn (1941), however, frequent occurrence of kyanite and sillimanite deposits in the "Gondite series" of the Pre-Cambrian in India are derived from aluminous sediments, which in turn might have originated from ancient bauxites. According to

this view, the Pre-Cambrian of India contains all three main products of mature weathering.

According to recent observations by Woolnough in western Australia, there is widespread formation upon the surface of peneplaned regions of colloidal deposits, called by him "duricrusts," which have different chemical compositions according to the nature of the country rocks. Woolnough believes that the Pre-Cambrian banded iron ores were formed in the same way as these "duricrusts" upon a peneplain (1941).

Disregarding the presence or absence of all of the above three constituents at the same time, at least the development of such a large cycle and its regular repetition clearly point to constant physiographic and meteorologic conditions over a long period of time. Accordingly, after a period of deposition of a quartzite and like coarser materials, in the stage of deposition of finely divided suspensoid or colloid like clay-slates, the land became low and flat, and chemical weathering became predominant over a long period of time. Under such an environment of weathering, silica in colloid form and partly in true solution, is removed from the weathering crust and accumulates in basins. The physiographic condition of the sedimentation of the Huronian System is believed to have been shallow seas or inland lakes and not open seas (Leith, 1934, pp. 157-158).

That the land surface was generally flat and lacking in steep topography is inferred from the long history of extensive weathering (being continued from the active primordial weathering in the Archean), and from the lack of coarser conglomeratic sediments comparable with those of the neo-Proterozoic and later systems. The movement of the earth's crust was perhaps epeirogenic rather than orogenic. T. Kobayashi, in his discussion on the sedimentational facies of the Sinian System in Manchuria and Korea believes that the tract as a whole had the nature of a kratogen (Kobayashi and Nakano, 1942).

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. That this holds in the zone of weathering has been quantitatively established by experiments on "isoelectric points" by Mattson (1932). The writer, in his former study

on the weathering and sedimentation of bauxites and bandoketsugan (aluminous shale), found that the distribution of soil colloids is in close connection with the acidity of the environment and that the results of Mattson's experiments are in good harmony with the distribution of soil colloids in the natural soil profile. The writer then found that the systematic distribution of soil colloids in a generalized soil profile of humid soils throughout the cold, temperate and tropical zones, could be shown graphically (fig. 4) by means of "equal silica-alumina molecular ratio lines, deeper in the soil profile toward the south, for which the writer proposed a new term "ISOSIALS" (Sakamoto, 1944).

What can be deduced with certainty from the generalized soil profile is that the soil solution above the water table, except in arid regions or seasons, is acidic, the acidity being highest in the cold zone in higher latitudes; whereas the solution below the water table, disregarding the climatic zones and seasons, is always alkaline (pH $8 \pm$). Iron is dissolved by acid soil solution above the water table, resulting in a bleached soil, called a podsol, in regions of higher latitudes. Iron thus dissolved, upon reaching the water table below where the soil solution becomes neutralized, is precipitated as iron hydroxide, sulphide or phosphate and cements together fine particles of clay suspensoid, giving rise to the so-called "ortstein," or a compact and impervious hardpan. In humid seasons when soil solutions freely circulate and show a high acidity, part of the iron in true solution in the form of bicarbonate, etc., migrates to depressions and rivers and finally is precipitated in basins or on sea bottoms.

Silica is dissolved by alkaline water below the water table, the reaction being most manifest in the case of a laterite profile in the tropics. Rocks are deeply weathered, large quantities of alkalis are set free, mainly in the form of alkali carbonates, and the soil solutions become alkaline with pH around 8.

In this alkaline environment, replete with cations, clay colloids with the $\text{SiO}_2:\text{Al}_2\text{O}_3$ molecular ratio around 4 adsorb alkali and alkaline earth ions and form thick zones of bentonite. In upper horizons closer to the phreatic zone where soil solutions, more dilute with ions, migrate freely, those adsorbed cations are dissolved. Bentonites, becoming unstable, are easily desilicated and become clay colloids with a $\text{SiO}_2:\text{Al}_2\text{O}_3$ molecu-

lar ratio around 2, or a clay corresponding to a kaolinite. Still higher at the base of the phreatic zone, where horizontal flow of the underground water reaches its maximum, desilication is accelerated, finally setting iron and alumina free to form laterite. Where the underground water table fluctuates up and down in wet and dry seasons, as upon the surface of flat plateaus or low hillocks under a monsoon climate, lateritic iron ores and bauxite deposits are formed.

The process of laterization is thus desilication by alkaline underground water produced by the deep weathering characteristic of the tropical zone, with the formation of iron ores and bauxites as its end-product.

The iron ores and bauxites thus formed lose their iron when the environment becomes acidic, owing either to the coming back of a forest or to covering by peats. The bleached portion assumes a mesh appearance in plan and "schecken" or bands in vertical section. Also, in bauxite deposits, either the superficial portion, several decimeters thick, becomes bleached and silicified or the whole deposit becomes penetrated with light-colored kaolinite pipes with a funnel shape. This phenomenon may be taken as a retrogression of the iron and bauxite deposits.

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

TRANSPORTATION AND DEPOSITION OF THE PRODUCTS OF WEATHERING

Taking these facts into consideration along with the inference above concerning Pre-Cambrian environmental conditions of weathering, a gleam of light seems to be thrown upon the

question of the accumulation of the unusually large quantities of iron and silica. The lack of coarse debris and the thick and normal cycles as in the Lake Superior area point to mature weathering as has already been pointed out by Prof. Leith (1934). Also, it is generally accepted that the Pre-Cambrian atmosphere was very rich in CO₂ gas. Under such physiographic conditions chemical weathering predominates, and, especially when the atmosphere contains much CO₂, the surface water in contact with it can retain much bicarbonate in solution whose vapor pressure is in equilibrium with the large pressure of CO₂ in the atmosphere. In other words, rocks are rapidly decomposed, giving rise to deep weathering.

Supposing that the annual rainfall was great and divided into periodically wet and dry seasons, shallow grounds above the water table became neutral or even alkaline in a dry season and the phreatic zone near the water table became neutral or temporarily even acidic in a wet season. (This is the condition which obtains under the present tropical monsoon.) In wet seasons, iron migrated in the acidic surface water, while in dry seasons, silica migrated in the alkaline ground water. The iron and silica, though partly consumed in the formation of ferruginous "ortstein" or local silicification of country rocks, mostly went into solution and were transported into basins and depressions to be precipitated there as the sediments of "fernfällung."

Suppose further that these basins and depressions were wide but shallow, and were separated from the open sea with only low barriers. When there was much influx of surface water in wet seasons, the lake water easily overflowed into the sea; when the influx was stopped in dry seasons, the lake became an inland lake in an arid region. When the lake water became acidic in wet seasons, and cool water with free oxygen circulated down to the bottom by convection, then the whole lake water became acidic and oxidizing. In dry seasons, on the contrary, the influx of fresh oxygen-bearing and oxidizing water was stopped, and the lake water became neutralized owing to seepage of alkaline underground water. Owing to evaporation, the lake at last became an inland lake in an arid region in which the water stayed stagnant, oxygen was lost and, as the level of the lake water went down, its reaction became alkaline. In the next wet cycle, a fresh influx began and as

the level of the lake water arose, the reaction became neutral and finally, when it began to overflow, acid again.

Similar phenomena can be observed at present in rivers and lakes in the semi-arid region in north Manchuria. In the River Sungari, pH falls in flood seasons in summer, and rises in low water in winter. The water in many shallow lakes in the semi-arid steppe around Hailar, north Manchuria, is all weakly to strongly alkaline and none is acid.

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

The iron in the form either of colloids or of true solution is supplied to the lake in wet seasons. Ferrous iron is oxidized into ferric iron due to aeration. Then, in arid seasons, when the influx of surface water is stopped and the pH of the lake water gradually rises to neutral, ferric hydroxide is 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. Then silica is supplied to the basin in colloidal solution, gradually increasing its concentration as the evaporation goes on. Under an increased alkaline condition, colloidal silica and iron hydroxides combine with each other to form iron silicates (greenalite, chamosite, etc.), and the rise of temperature accelerates the precipitation of carbonates of iron and other compounds. Again, upon the return of a wet season and influx of fresh surface water, the reaction returns through neutral back to acid again. In this stage, silica is totally precipitated, and the lake water is acidic, contains free oxygen and receives a new supply of iron in solution. Thus the second cycle is started and repeated.

FORMATION OF THE BANDED STRUCTURE

The relation between the periodic change of the reaction of the lake water and the supply and deposition of elements is shown schematically in figure 5.

The reaction of the water, beginning with acid (say pH $5\pm$) at A, passes neutral (pH 7) at N and reaches alkaline (say pH $9\pm$) at B; then returns through neutral at N' back to acid at A', completing the cycle. The supply and deposition

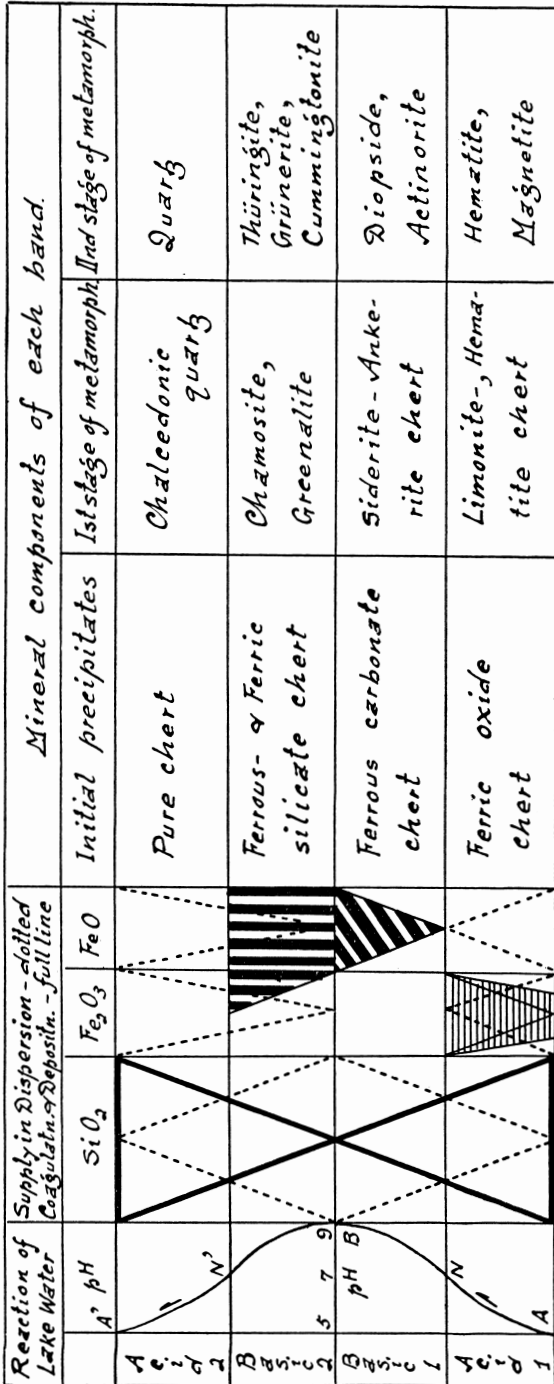


Figure 5. Supply and deposition of SiO₂, Fe₂O₃, and FeO in relation to reaction of lake water, resulting in regular banding with corresponding mineral components.

of each constituent are indicated by the areas cut, respectively, by the dotted and the full lines in the column of each constituent. The process in each of the four stages of one cycle is shown in the following table:

TABLE 4

The Sequence of Sedimentation Resulting in the
Formation of Banding

Reaction & Stage	Supply & deposition	Products (Bands)
Acid 1 N—N	SiO ₂ { Sup—gradually increases from minimum Dep—as chert, gradually decreases	Ferric oxide chert
	Fe ₂ O ₃ { Sup—decreases from maximum to minimum Dep—as limonite, concentrates in this stage, reaching maximum at N	
	FeO { Sup—decreases from maximum to minimum Dep—none	
Basic 1 N—B	SiO ₂ { Sup—increases to maximum Dep—as chert, decreases to minimum	Siderite chert
	Fe ₂ O ₃ { Sup—none Dep—none	
	FeO { Sup—none Dep—as siderite & greenalite begins and increases	
Basic 2 B—N'	SiO ₂ { Sup—decreases from maximum Dep—as iron silicates, gradually increases from minimum	Chamosite greenalite
	FeO & Fe ₂ O ₃ { Sup—begins Dep—as iron silicates, completed	
Acid 2 N'—A'	SiO ₂ { Sup—decreases Dep—as chert, increases to maximum	Pure chert
	FeO & Fe ₂ O ₃ { Sup—increases to maximum Dep—none	

The concentration of electrolytes (dissociated ions of salts of alkalis and alkaline earths in the solution in the above cycle is at a minimum at A and a maximum at B. According to the experiments by Moore and Maynard (1929), "hydrosols of iron and silica stabilized by organic matter are preferentially precipitated by electrolytes with the same composition and concentration as in natural sea water. Iron is instantly pre-

cipitated while silica is precipitated much more slowly and incompletely.”

As the concentration of electrolytes increases at the stage A-N in fig. 5, the deposition of ferric hydrosol is doubtless intensified; that of silica is partly deferred to the next stage N-B where, being mixed with carbonates, it forms a siderite chert. The deposition of carbonate here is accelerated by the increase of temperature.

When the concentration of electrolytes reaches its maximum, ferric and ferrous iron combine not only with silica but also with Mg, Ca and Al, giving rise to new silicate minerals. Bauer in Africa has noticed that such laterite constituents as free silica and free alumina recombine to form a chlorite, resulting in a sort of silicification in alkaline inland lakes in the tropics. Moreover, such iron ore beds as the Wabana, the Minette and the Oolitic are characterized by chamosite as one of the main iron minerals. These iron ore beds were all deposited in sea water, and, hence, under a weakly alkaline condition. These facts bear witness to the formation of iron silicates of the chlorite family at the stage B-N’.

That silica is less sensitive to electrolytes than iron is also known by the experiments of Moore and Maynard. On the other hand it is very sensitive to change of acidity, as is very well known from observations of natural soil profiles.

Figure 6 shows a profile of a shallow lake upon whose bottom banded iron ores are being deposited. The supply and deposition of different constituents are schematically shown in the profile.

The level of the lake water is at its highest when the reaction is acidic (A), medium when neutral (N & N’) and lowest when alkaline (B). The reaction of lake water and corresponding sediments and their areal distribution on the lake bottom are summarized as follows:

TABLE 5

Reaction of Lake Water and Corresponding Sediments		
Stage & reaction	Sediments(Bands)	Area of deposition
A — N (Acid 1)	Ferruginous chert	Entire lake bottom
N — B (Basic 1)	Siderite chert	Small area around center of lake
B — N’ (Basic 2)	Chlorite	Small area around center of lake
N’ — A’ (Acid 2)	Pure chert	Entire lake bottom

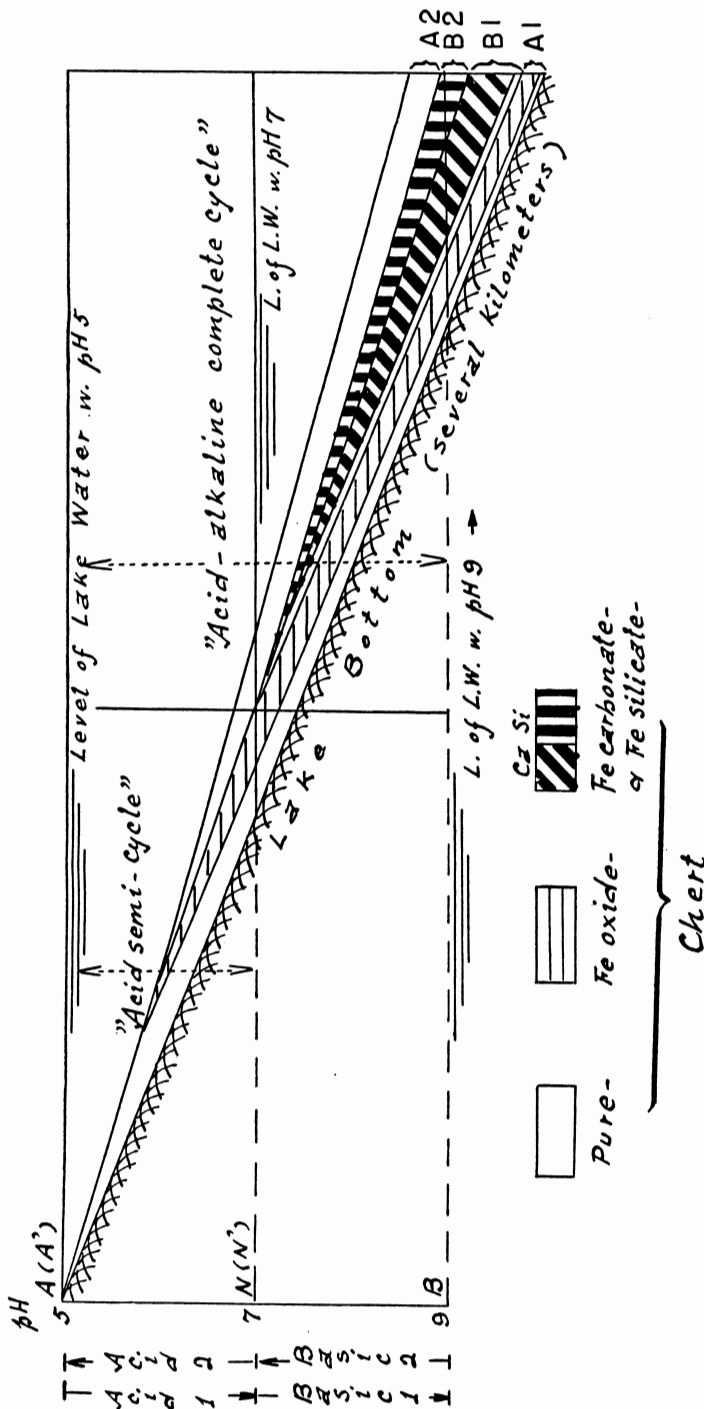


Figure 6. A diagrammatic cross section showing the deposition of SiO_2 , Fe_2O_3 , ferrous carbonate, and ferric silicates in relation to the reaction of (pH) and change of level of lake water. The deposit representing a cycle, A1 to A2, has total thickness of 15 mm.

In case of a complete cycle or a cycle with successive stages of acid-neutral-alkaline-neutral-acid as is seen in this figure, the sediments should be, from the bottom upward, a ferruginous chert, siderite and chlorite chert, and pure chert, thus giving rise to a distinct banding. Three-component poor ores are deposited in the deeper portion near the lake center; two-component poor ores in the shallow marginal portion.

In the case of an incomplete cycle or a cycle with successive stages only of acid-neutral-acid (a cycle which may be called an acid semi-cycle), two-component poor ores are deposited all over the lake bottom. In the case of an incomplete cycle of neutral-alkaline-neutral (a cycle which may be called an alkaline semi-cycle), three-component poor ores are deposited around the lake center.

The banded structure described in the foregoing pages, especially the one in the specimen collected by the writer at P'ai-chia-pu-tzu, An-shan (fig. 1), shows a remarkable coincidence with the banding in the acid-alkaline complete cycle in figure 6. Alkaline semi-cycles beside acid-alkaline complete cycles are shown in the banding of the ore from Yuen-chien-shan taken by Asano (fig. 2).

It has been stated above (and see fig. 3) that each of the two-and three-component poor ores has locally separate areas of distribution according to field observations. This peculiarity is easily explained by the scheme of deposition stated above.

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

The two-component poor ores may, at a glance, seem to be entirely different from the three-component poor ores. Yet, upon closer observation, the latter ores are known to be the same as the two-component ores, only with another band of iron silicates or of iron carbonate cherts. This is naturally expected from the above-stated conditions of sedimentation. That is, an acid semi-cycle is included in an acid-alkaline complete cycle itself. In fact, the two-component ores of the lake margin of a complete cycle, traced laterally into the lake

center, pass into constituent bands of the three-component poor ores. Consequently it is quite impossible that such two-component ores are derived from three-component ores by a later oxidation. If the 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 a syngenetic oxidation, if present, is only one of the sedimentational conditions of well aerated, hence oxidizing, lake water. Thus it coincides with the writer's "acid 1" or "acid 2" stages of sedimentation.

SUCCESSIVE CHANGES IN THE PRE-CAMBRIAN ENVIRONMENTS, AND THE GENESIS OF THE BANDED IRON ORES

The banded iron ores are distributed, on each continent, only in the Pre-Cambrian rocks and duplicates are not present in later geological systems. On each continent they constitute a great formation, the thickness sometimes reaching over 200 m. Sedimentary iron ore beds in the Paleozoic and Mesozoic groups range from one to several meters thick at their maximum.

That the banded iron ores are the product of mature weathering has already been pointed out by Prof. C. K. Leith. According to the writer's study of the compositions and texture of the banded iron ores it is thought that they are products of an environment of distinct chemical weathering and sedimentation. Other sediments with which the banded iron ores are accompanied also point to the predominance of chemical changes.

Precipitates	Medium of deposition
Aluminous argillite	Acidic
Limestone & dolomite	Weakly alkaline
Chloritic argillite	Alkaline

These fine-grained, compact sediments attain a thickness of around 10,000 m. (17,000 m. at Ta-li-tzu-kou, east Manchuria), and sandy and conglomeratic rocks are of very rare occurrence. These facts point to large-scale chemical changes on one hand, and to very subordinate or negligible mechanical weathering and sedimentation on the other.

Thus, we must accept that such an extraordinary environment obtained only in the Pre-Cambrian era and has never been reproduced in later geologic ages. The Pre-Cambrian

environments of deposition can be divided, at least, into three stages. The characteristic features of these three stages, the nature of original sediments and their metamorphic derivatives may be summarized as follows:

Stage	Environment	Original sediments	Metamorphic derivatives
I.	High temperature hydrothermal (alkaline chemical weathering)	Alkali-bentonite	Gneisses with subordinate schists
II.	Low temperature hydrothermal—cold water (alkaline & acid chemical weathering with subordinate mechanical weathering)	Aluminous argillite, limestone & dolomite, chert, iron hydroxide, iron silicate (chlorite)	Phyllite, mica, schist, chlorite schist, hornblende schist, banded iron ores, ferruginous chert, crystalline limestone, dolomite (magnesite), eulysite, migmatite
III.	Cold water (same as Paleozoic & later) (predominating mechanical weathering)	Sandstone with aeolian rounded desert sands & dreikanter, shale, cherty limestone, glacial tillites	Quartzite, phyllite, cherty limestone, tillite

The sequence of the change of environments is supposed to have been the following:

1st stage:—Water vapor began to condense into hot rain which reached the earth's surface and began to act upon the lithosphere. In the atmosphere were still very large quantities of water vapor and CO₂, HCl and N₂. Consequently the density of the atmosphere was very large and, acting as the so-called heat blanket, it hindered the radiation of the earth's heat as well as that from the sun. As the result of the action of such a high temperature water upon the lithosphere, bentonites or active clays of the montmorillonite family were produced not only from tuffs and lavas but also from every kind of plutonic rocks.

Owing to very rapid decomposition of these igneous rocks, a large quantity of alkalies was set free and the earth's surface was strikingly alkaline. Consequently the bentonites adsorbed much alkali to become alkali-bentonites which showed nearly the same compositions as the parent igneous rocks, *i.e.*, the stage is characterized "sedimentary non-differentiation."

2nd stage:—As the temperature gradually decreased, the speed of the rock decomposition slackened and consequently the amount of free alkali was decreased and owing to the presence of hydrochloric, carbonic and, probably, sulphuric acids, regional acidic environments were introduced for the first time upon the earth's surface, and a small amount of mechanical debris began to be produced.

As the acidic environment was introduced, the bentonites were leached of their alkalies, alkaline earths and later iron oxide, the remnants being changed into aluminous argillite. The soluble salts, either in a true solution or in a colloidal solution, were transported and deposited as chemical sediments.

Thus, at this stage chemical sediments gave rise for the first time to a vast amount of extremely well sorted sedimentary rocks on the earth's surface. The separation of easily soluble from difficultly soluble substances had been carried to its full extent in these rocks, *i.e.*, this stage is characterized by the highest degree of "sedimentary differentiation."

3rd stage:—Dry deserts and cold glaciers made their appearance upon the earth's surface and the environment took on features very close to those of the Paleozoic and later. Consequently mechanical sediments began to predominate.

Thus, in summarizing the characteristics of the original sediments in the Pre-Cambrian era, we can state that at the first stage there appeared non-differentiated clayey products still retaining the compositions of parent igneous rocks; then at the second stage there appeared very well differentiated typical sedimentary rocks of chemical deposits; and lastly at the third stage there appeared the alternation of a large amount of mechanical sediments and minor amounts of chemical deposits such as may be found in the Paleozoic and later ages.

The second stage represents a very long period of time during which the earth's crust, from a low temperature hydrothermal stage, cooled down to a stage similar to the Paleozoic and later ages. Its time duration is thought to be much longer than that of the first and the third stages. The banded iron ores are the product of the predominant chemical weathering and deposition under such a particular environment which obtained only once in the history of the earth's surface, toward the middle of the Pre-Cambrian era.

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Since 1940, Mr. G. Asano has published his studies in a series of papers which as a whole makes a comprehensive monograph. His petrographical studies on the banded iron ores in Manchuria are in more detail than any of those of earlier students and, above all, his description of the eulysitic ores and his hints at the progressive metamorphism of the ores are new and instructive.

The writer owes his idea of "ISOSIALS" of the generalized soil profile to the experiments on the isoelectric points of soil colloids by Dr. Sante Mattson of the Agricultural Experiment Station, New Jersey, U.S.A., and to the chemical analyses of clay minerals systematically taken from over 50 meters of a typical lateritic profile at Bintan Island, Netherland East Indies, by Dr. van Bemmelen of the Geological Survey, Bandoeng, Java.

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