THE MINERALOGY AND PETROGRAPHY OF THE NIMBA IRON ORE

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ABSTRACT

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By

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About 300 million tons of high-grade hematite occur in Precambrian iron formation (itabirite) in the Nimba Series. The Nimba Series is a 1,500-meter thick sequence of schists, phyllites and iron formation. The Nimba Series has two units; a lower unit, called the Valley group is composed of metavolcanic rocks (basal rocks and amphibole schists); and an upper unit, the Ridge group consisting of metasedimentary rocks (phyllites and itabirites).

Granitic rocks of 2.5 billion years to 3.6 billion years occur to the southeast of the Nimba Ridge where they formed straight contact with the Nimba itabirites.

The major structural feature of the Nimba Range is a central anticline underlying the Seka Valley to the north and Central Gbahm to the south. This anticline is flanked by two synclines underlying the North Gbahm Ridge to the north, and the Yiti Valley and west slope of Gbahm Ridge to the south. The whole anticline-syncline structure is

plunging to the southeast at a low angle. Only one major fault has been observed in the area and this is to the southeast where the contact of the granites and itabirites has been inferred as a fault. All folds are more or less isoclinal.

There are two major types of iron ore, the blue ore (mainly hematite) containing an average of 67.8 percent Fe, and the brown ore (hematite and goethite) containing 65.5 percent Fe at depth and 63.5 percent Fe at the surface. Each type of ore has its own soft, medium, and hard varieties, however, the soft ores are the predominant type as regards physical quality.

Genetically all ores have been formed from leaching of silica from the iron formation. The iron formation apparently formed along an epi-continental landmass in a shallow basin during Precambrian time under conditions relevant to tropical climate.

Quartz, clays and phosphorous (occurring in phosphatic minerals) are the main impurities in the ore deposits.

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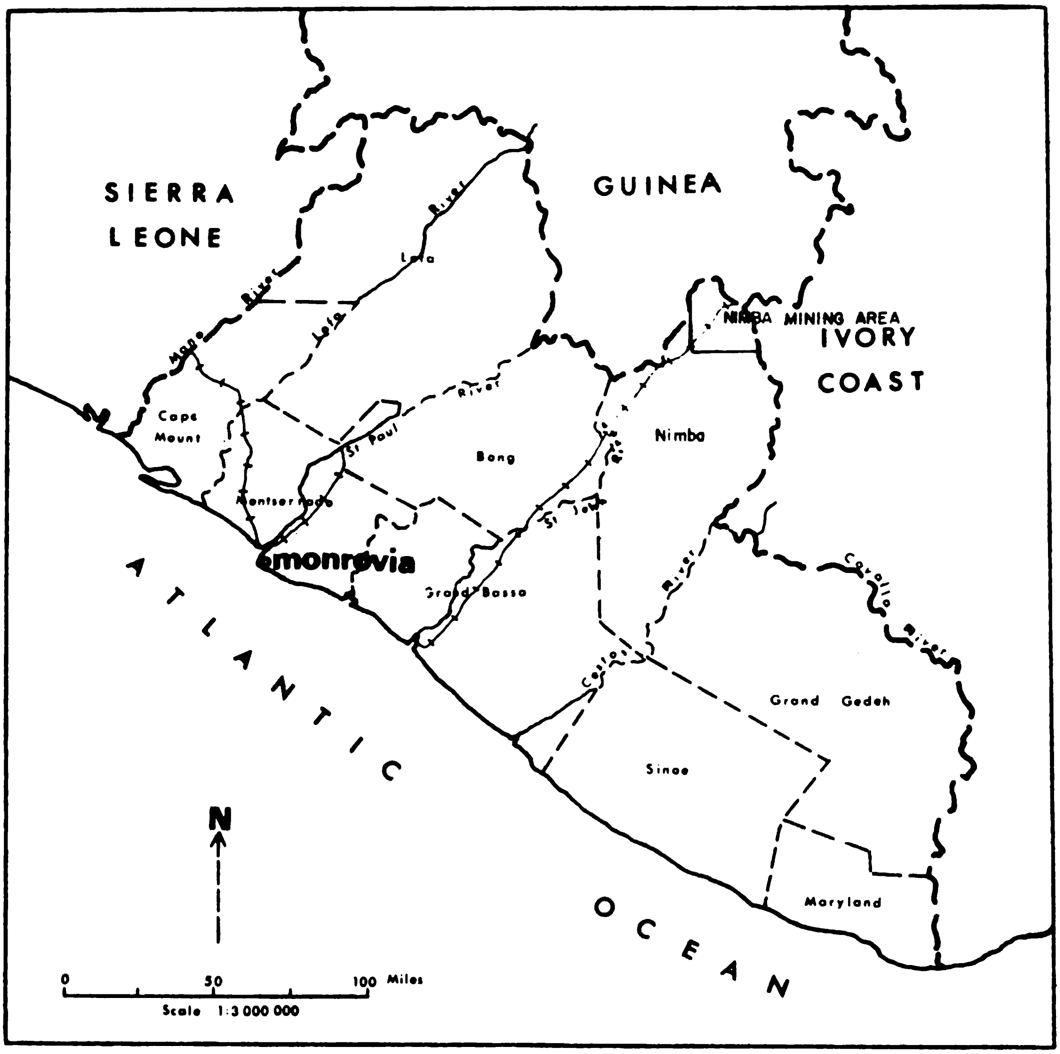
CHAPTER I

INTRODUCTION

The Nimba Range, about 20 miles long, of which 8 miles are in Liberia and 12 miles in Guinea, is located about 200 miles northeast of Monrovia along the international boundary with Guinea and the Ivory Coast (Figure 1). The ore bodies, contained along two parallel bands of Precambrian itabirite iron formation, form a steep-sided ridge, the slopes of which in some places are parallel to the dip at inclinations of up to 70°. The gentler slopes, lower down on either side of the crest, are underlain by phyllites, and the relatively flat-lying surrounding area is underlain by gneisses. The Nimba Ridge which contains the main ore body trends southwest-northeast. Other topographic features include the north-northeast trending Gbahm Ridge, the relatively broad Seka Valley lying between the North Gbahm and Nimba Ridges, the narrow, deep and steep sided Yiti Valley between the Junction-Gbahm Ridge and South Nimba Ridge, and the northeast trending Nimba Ridge.

The high point is 1,384 meters above sea level at Guesthouse Hill on the Nimba Ridge, and the highest point



LIBERIA

FIGURE I

Figure 1.--Map of Liberia, location of Nimba mine area.

on the Gbahm is 1,350 meters. Maximum relief in the area is 750 meters. The terrain is irregular, and the two ridges are steep-sided below the crests.

The mine is located 7½° north of the equator among tropical rain forests. The average annual rainfall is about 120 inches, mainly from violent cloudbursts which occur most frequently between the months of April and October. The highest precipitation in 24 hours since 1957 (when records were first kept) was 6.55 inches, but a rainfall of 1.5 inches within the space of one-half hour is common during the rainy season. Average daily temperature during the dry season are 75-80 degrees Fahrenheit, with extremes of 40 and 90 degrees Fahrenheit.

Previous Study

The Nimba Iron Ore was discovered in the Nimba Mountains in the latter part of 1955. In July 1960, the Liberian American-Swedish Mining Company (LAMCO) came into existence and was given concession rights to explore and develop the iron ore deposits of the Nimba-Gbahm Ridge.

The first geologic reconnaissance mapping over the Nimba-Gbahm area was conducted by LAMCO geologists Lackshewitz and Tremaine. Their results are included in an unpublished report issued in 1962. According to Berge (1968), the Lackshewitz and Tremaine report includes an impressive number of stream valleys and traverse lines mapped by pace and compass with altimetric vertical control; a stratigraphic and structural interpretation was reported with no "concrete proposal" made. The foremost problem was transportation, and access to the ore deposits was by foot only. Furthermore, outcrops were sparse, and those which could be mapped were deeply weathered. Detailed petrographic work was not carried out at that time.

Since the beginning of production in 1963, ore, low grade iron formation, and waste rock have been continuously mapped by the LAMCO Geology Section. Extensive core drilling has been carried out both for production and for engineering studies. The result has been the compilation of much incomplete data pertaining not only to the ores, but also to the petrology, structure and stratigraphy. Petrographic studies of thin sections of rocks collected by Lackshewitz and Tremaine together with samples of ores collected during mining have been studied by LAMCO geologists to some extent.

In 1966, John Berge, Chief Geologist of LAMCO, published an incomplete paper entitled "Genetical Aspects of the Nimba Iron Ores." He attributes the origin of the brown ore to "lateric processes" but gives no explanation to the genesis of the blue ore. In the final analysis, he concludes that "the problem of blue ores is not yet solved."

Method of Study

In the summer of 1969, I spent two months in Liberia doing field work with John Berge and members of the LAMCO Geology Section collecting rock and ore samples together with available information of the Nimba-Gbahm area. Thin sections of the rocks and ores have been made and studied extensively together with polished sections of the ores. These results together with field observations and available data, have led to an explanation of the origin of the Nimba Iron Ore.

CHAPTER II

THE STRATIGRAPHY OF THE NIMBA AREA

John Berge, chief geologist of LAMCO, is responsible for most of the regional stratigraphy and structure of the area. The stratigraphy of the area is divided into the Yekepa Series and the Nimba Series (Table 1), which have their equivalent in other parts of Africa, but no correlation has been made with respect to rocks in other areas. G. W. Leo (1966), has reported a program of geochronology of Liberian rocks at Massachusetts Institute of Technology undertaken in cooperation with the United States Geological Survey and the Liberian Geological Survey. The chief aim of the program is to incorporate ages of Liberian rocks into a comprehensive dating program covering much of West Africa and northeastern South America, in the hope of finding supporting evidence for the hypothesis of continental drift. Twenty-eight age determinations by the Rb-Sr method from 10 separate localities have been made of granitic rocks collected in western Liberia and gneises from the south end of the Nimba Range. The ages fall in the general range of 2.5 billion years to 3.6 billion years, which establishes the Precambrian shield of Liberia

TABLE 1.--Summary of the Nimba Series (after Berge, 1968).

Group	Formation	Rock Types	Conditions of Deposition
Ridge group	Mt. Alpha phyllite	Quartz-biotite-sericite-chlorite phyllite	Mechanical erosion of land mass; clays and fine quartzose sediments
	Nimba itabirite	Itabirite with intercalated silicate iron formation	Chemical weathering; deposition under mildly oxidizing conditions
	Gbahm Ridge phyllite	Quartz-graphite-pyrite phyllites with pelitic intercalations	Chemical weathering; deposition under reducing conditions
Valley group	Seka Valley amphibole schist	Volcanic (probably andesitic) rocks with intercalated calcareous and pelitic sediments	Volcanism and some clastic deposition
	Basal rocks	Quartzites (quartz conglomerate) and ultrabasic rocks	

as one of the more ancient provinces known on earth (Leo, 1967). Age determinations of the gneisses from the south end of the Nimba Range show that the last period of crystallization or recrystallization was more than 2.5 billion years ago (Hurley, 1967).

Yekapa Series

The Yekapa Series comprises the bedrock underlying the broad valley between the Nimba-Gbahm Ridge on the east and the Takadeh-Yuelliton Ridge to the west (Plate I). There are no outcrops of the Yekapa Series in the area, however, as projected from outcrops outside the area, at least two rock types have been recognized--acid rocks which are usually strong foliated assemblages of plagioclase, microcline, quartz and biotite, and the basic rocks which are foliated hornblende amphibolites.

Nimba Series

The Nimba Series has been divided into two groups and five formations. These rocks underlie the Nimba and Gbahm Ridges and the Seka and Yiti Valleys, and continue to the northeast in the Republic of Guinea. Table 1 illustrates the stratigraphy of the area.

Since information about the stratigraphy and structure of the Nimba-Gbahm Range is available only through mining operations, the relation between the Yekepa and Nimba rocks is not well known. In fact, only one observation resembling a contact between the Yekepa and Nimba Series has been made. This is at the base of the northeast slope of Nordhund Hill in the north-central part of the area. Here heavily weathered Yekepa gneisses and sheared quartzite of the Nimba Series appear in adjacent cuts along the LAMCO railroad. It cannot be determined here if there exists an unconformity between the two, but the foliation in the two weathered rock cuts is parallel.

Basal Rocks

Present information about the basal rocks is far from adequate, however, they consist of quartzites and ultrabasic rocks, whose thickness and mutual relationship have not been determined.

Stratigraphically these rocks are considered to be the oldest of the Nimba Series. A railroad cut northeast of Nordhund Hill has exposed this rock which appears to be sheared quartzite. Hand specimens show that it is a greenish, strongly foliated, quartz-pebble rock, with the pebbles elongated to the foliation suggesting that the rock may have been a conglomerate. Berge (1968) reports that a thin section shows about 80 percent quartz and the remainder is fine mica. About half the quartz is fine-grained and the texture is cataclastic.

Seka Valley Amphibole Schist

The lower-most unit of the Nimba Series to be given a formation status is the Seka Valley amphibole schist. Its contact with the underlying basal unit of the Nimba Series has not been observed, but it is presumed to be gradational. The schist has a thickness of about 700 meters and a characteristic topography comprising most of the northwest slope of the Gbahm Ridge, as well as the lower Seka Valley slopes of the Nimba and Gbahm Ridges. The topography is one of gently sloping spurs protruding far out from the main Nimba and Gbahm Ridges, varying from 750 to 920 meters in altitude; alternating with these spurs are deep, steep-sided valleys which also are perpendicular to the main ridge (Berge, 1968). The rock is deeply weathered on these spurs, and includes the amphibole schist and chlorite-amphibole schist members of the Gbahm Ridge, and gabbro diorite, tremolite schist, and talc-tremolite schist units occurring in the Seka Valley.

Gbahm Ridge Phyllite

The lowest unit in the Ridge group is the Gbahm Ridge phyllite which is mostly a graphite-quartz rock. The shallow dip of the formation, but also the fact that it is difficult to determine the contact in weathered rock, led Lackshewitz and Tremaine (1962), to assert that this unit covers much of the Seka Valley slope of the Gbahm Ridge. Outcrops of this formation can be seen as a folded silvery-grey phyllites in road cuts along the Gbahm Ridge portion of the main mountain road. In contrast to the yellow-orange weathering products of the

Seka Valley amphibole schist, Lackshewitz and Tremaine (1962) recorded outcrops of this phyllite in stream cuts also. The thickness of the phyllite is about 250 meters; it forms steep (about 45°-50°) slopes, in contrast to the gentle spurs on the amphibole schist. Berge (1968), has recorded weathering of this phyllite to a depth of at least 40 meters.

Nimba Itabirite

The Nimba iron formation has been called an itabirite and it is 250-400 meters thick. Pure itabirite is a banded iron-formation containing alternating laminae of specular flakes of hematite and/or magnetite and granular quartz (Figure 14). Itabirite has been defined by Dorr and Barbosa (1963) as follows:

> The term itabirite denotes a laminated, metamorphosed, oxide-facies formation, in which the original chert or jasper bands have recrystallized into granular quartz and in which iron is present as hematite, magnetite, or martite. The quartz bands contain varied but generally minor quantities of iron oxide, the iron-oxide bands may contain varied but generally minor quantities of quartz. The term should not include quartzite of clastic origin with iron oxide cement even though such rocks are sometimes grossly banded. It should only include rocks in which the quartz is megascopically recognizable as crystalline, in order to differentiate it from unmetamorphosed oxide-facies iron-formation. A certain amount of impurity in the form of a dolomite or calcite, clay, and the metamorphic minerals derived from these materials may be included, but these may never be dominant constituents over any notable thickness. Where they are, the rock term must be qualified by the use of appropriate mineral name as a qualifier (for example, dolomitic itabirite, a rock in which the dolomite largely takes the place of quartz). Rarely itabirite grades into ferruginous

> chert which, when recrystallized, may look like low-grade itabirite, although commonly it is finer grained and whiter. To prevent confusion, a cutoff point of about 25 percent iron should be established. This figure is a practical one, as few itabirites are so lean in iron and most ferruginous cherts do not contain so much iron. Itabirite may grade into pure hematite through enrichment in iron or removal of quartz. The cutoff point might well be set at 66 percent because at and above this grade quartz is rarely concentrated in regular laminae.

Fresh itabirites are gray to light brown but weather to shades of brown as a result of hydration of hematite to limonite.

Berge (1968) has recognized four types of laminae:

> One consists of almost entirely equidimensional or elongate grains of equigranular quartz (white). A second type of lamina consists of equal proportions of equigranular quartz and iron oxide (magnetite and/or hematite). A third type consists of coarse aggregates of highly strained quartz together with coarse grains of subhedral magnetite-hematite (black and white). Finally, a fourth type consists mainly of coarse elongated grains or subhedral masses of magnetite-hematite with fine quartz inclusions (black). Diffuse laminae range from 0.5 to 5 millimeters in thickness.

The Nimba itabirite consists of quartz, hematite and magnetite, with occasional amphibole and chlorite in silica-bearing laminae. Goethite is present not as a primary mineral, but results from chemical weathering of the iron formation. The itabirite has a dry Fe content of 40 percent, contains 40 percent iron oxides, and 60 percent quartz by volume.

The Nimba itabirite forms ridges and comprises the backbone of the Nimba, Gbahm, and South Nimba Ridges,

Figure 2.--Nimba Itabirite, hematite, goethite, magnetite and silica. White is granular quartz. 1X

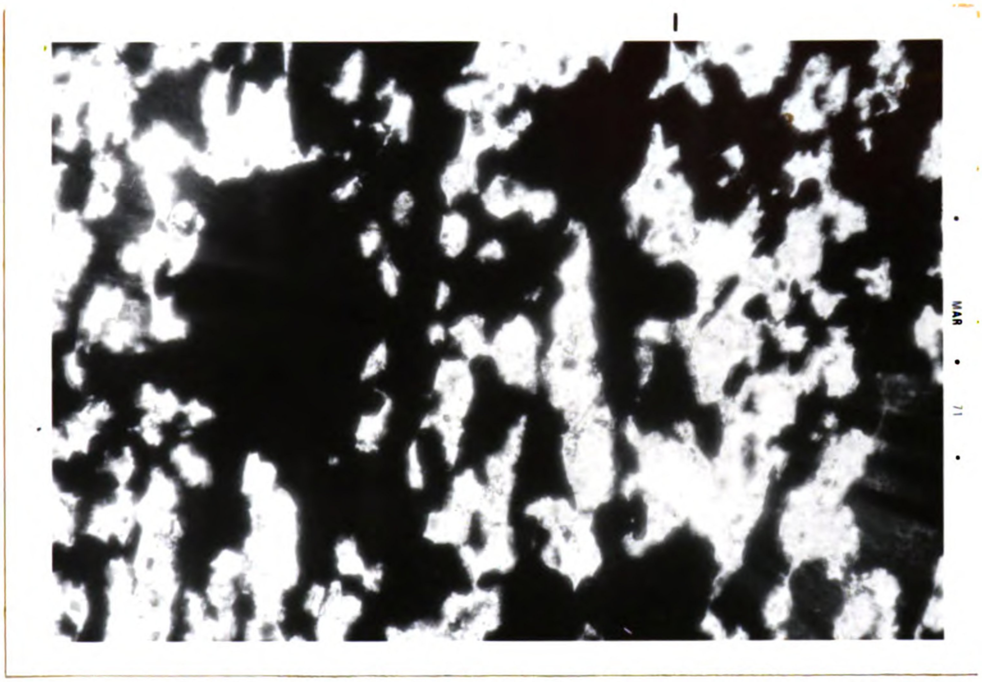


Figure 3.--Thin section of Nimba Itabirite showing quartz (white) and iron ore minerals (black)--hematite, magnetite and goethite. 175X

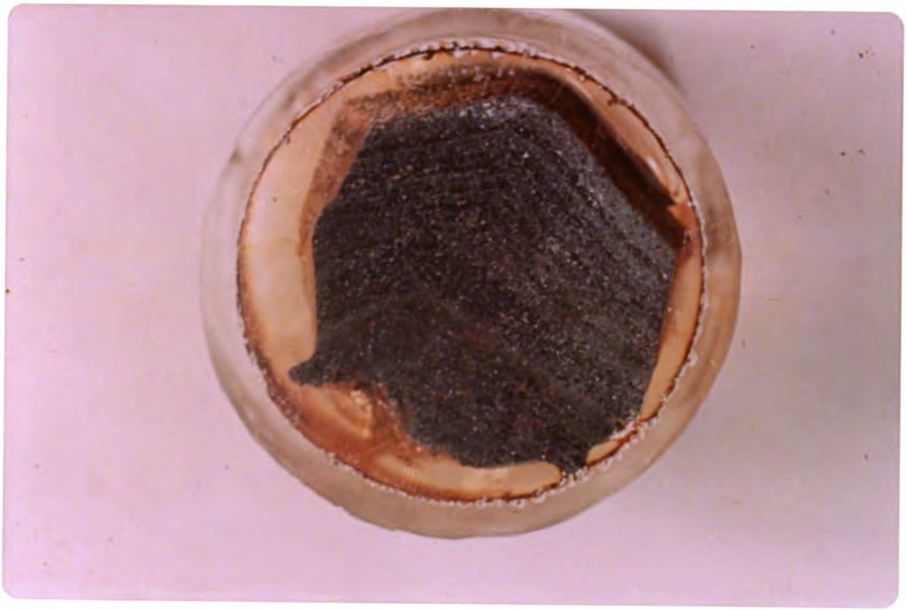


Figure 4.--Medium hard itabirite--well developed small scale folding. 2X

jutting up sharply from the Gbahm Ridge phyllite on the northwest slope of the Nimba Ridge (Plate 1).

Mount Alpha Phyllite

The Mount Alpha Phyllite is the youngest unit of the Nimba Series. It is so named because a complete section of the formation is exposed in the isoclinal Nimba syncline on Mt. Alpha, between the Mt. Alpha and Northeast Extension ore bodies. The thickness of this formation varies from 50 to 100 meters.

The Mt. Alpha Phyllite has a variable topography. At two locations it forms the summit along the range and in both cases the phyllite is covered by an iron capping. The Nimba itabirite is postulated as the source of the iron capping. Berge (1968) has observed that in both locations, the summits occur a few meters higher than hard cappings over small ore bodies on the southeast limb of the Nimba syncline.

Granitic Rocks

Granitic rocks (Precambrian granites, gneiss, schist) are known to occur to the southeast of the Nimba Ridge where they form straight contact with the Nimba itabirite. These rocks are coarse-grained and have gneissic foliation. Samples of rocks taken have been used mainly for age determination and no petrographic study has been made.

CHAPTER III

PETROGRAPHY

Metavolcanic Rocks

The Seka Valley amphibole schist (Figure 5), consists of hornblende and plagioclase (oligoclase) and accessory carbonate, quartz, garnet, biotite, apatite, and opaques. The average composition of the rock is as follows:

Mineral	% by volume
hornblende	45
oligoclase	30
quartz	10
opaques	6
biotite	5
carbonates	3

The hornblende is blue-green to olive-green. The crystals are prismatic with poorly developed terminations. The grains are anhedral to subhedral with symmetrical extinction. Hornblende prisms up to two millimeters in length are common. These laths are corroded and contain intergrowths of feldspar and quartz.

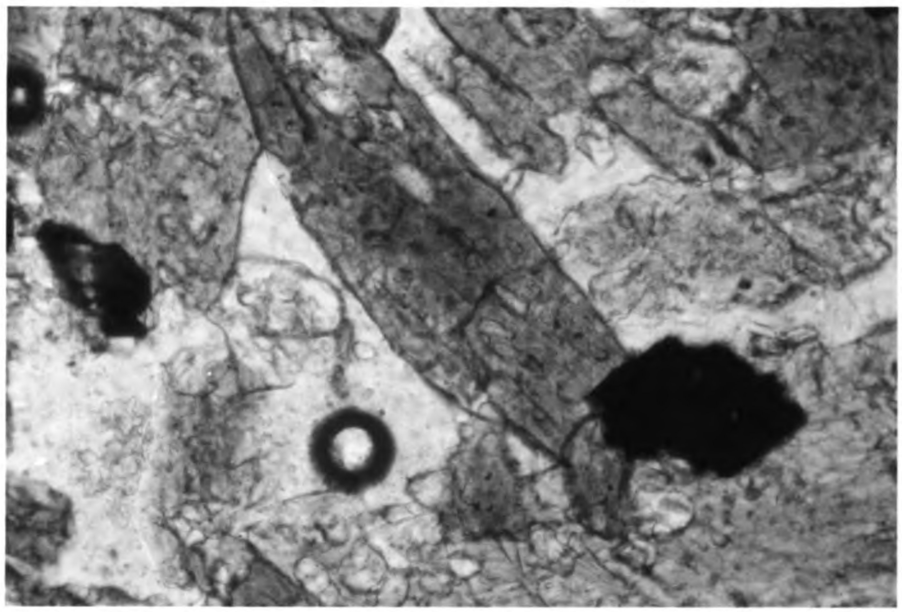


Figure 5.--Thin section of Amphibole schist showing prismatic grains of hornblende with poorly developed terminations. 350X

The plagioclase occurs in equal xenoblastic grains. Grains are generally subhedral and laths are rarely developed. Plagioclase grains normally exhibit zoned extinction. Inclusions of quartz, feldspar and biotite are common. Quartz with rotating extinction occurs and is associated with carbonates. Garnets are (usually) rare, subhedral, and are associated with carbonates and feldspar in the matrix. Feldspar occurs in the fine-grained amphibole schist. These feldspars show some zoning. The zoning of feldspars, uneven grain size, texture and composition indicate that these rocks were originally fine-grained igneous rocks that may have been extrusive.

Metasedimentary Rocks

Sedimentary members of the Seka Valley amphibole schist appear as relatively coarse-grained amphibole-garnet-quartz, or fine-grained quartz-biotite schists with carbonates, and garnets.

A garnet-amphibole rock occurring on the northwest slope of the Nimba Ridge consists of amphibole, garnet and quartz. Plagioclase is less abundant and quartz and biotite are usually more abundant than in metavolcanic rocks. The hornblende is blue-green and some non-pheochloric grains are present. Garnets are anhedral and are very much elongated parallel to foliation. Average composition shows:

Mineral	% by volume
hornblende	50
plagioclase	15
quartz	25
biotite	6
opaques	3
garnet	1

In another composition there is a weak alignment of amphiboles. The amphibole is deep green to olive, subhedral, and may be poikilitic but has a more distinctly prismatic shape than that in the schist. Carbonate is euhedral, frequently twined and grains are elongated parallel to foliation. Quartz grains are euhedral; but show undulatory extinction. The mineralogy and laminated structure clearly suggest a metamorphosed calcareous sediment.

Gbahm Range Phyllite

A sample of black phyllite from the Seka Valley slope of Gbahm Ridge consists of biotite, chlorite, muscovite, quartz amphibole and feldspar. Another sample consists of fine-grained graphite, quartz, pyrite, and muscovite and is cemented by a matrix of finer quartz and mica. This rock has a composition of:

Mineral	% by volume
quartz	85
sillimanite	6
iron ores	5
biotite	3
carbonates	1

The sillimanite forms slender prisms of fibrous radial aggregates, with a diagonal cleavage and parallel extinction, the grains are mostly euhedral. Biotite, only associated with sillimanite, has a deep red-brown color owing to staining with iron-ore minerals and is strongly pleochloric in shades of brown. The rock has a microscopic appearance of a quartzite (85% quartz). Two other samples 75 meters apart in tunnel 8 consist of fine-grained graphite, quartz, pyrite and muscovite (Berge, 1968).

Mt. Alpha Phyllite

The Mt. Alpha phyllite occurs as a lepidoblastic assemblage of fine-grained quartz, chlorite, biotite, garnet and pyrite, with sphene and apatite as accessories. Quartz grains are typically subhedral to euhedral with extinction mostly even. Chlorite is light green and has a blue interference color. Both tan and brown varieties of biotite are present. Pyrite occurs in subhedral elongate masses (Figure 8). Garnets are euhedral to subhedral but are cracked and corroded (Figures 6 and 7).

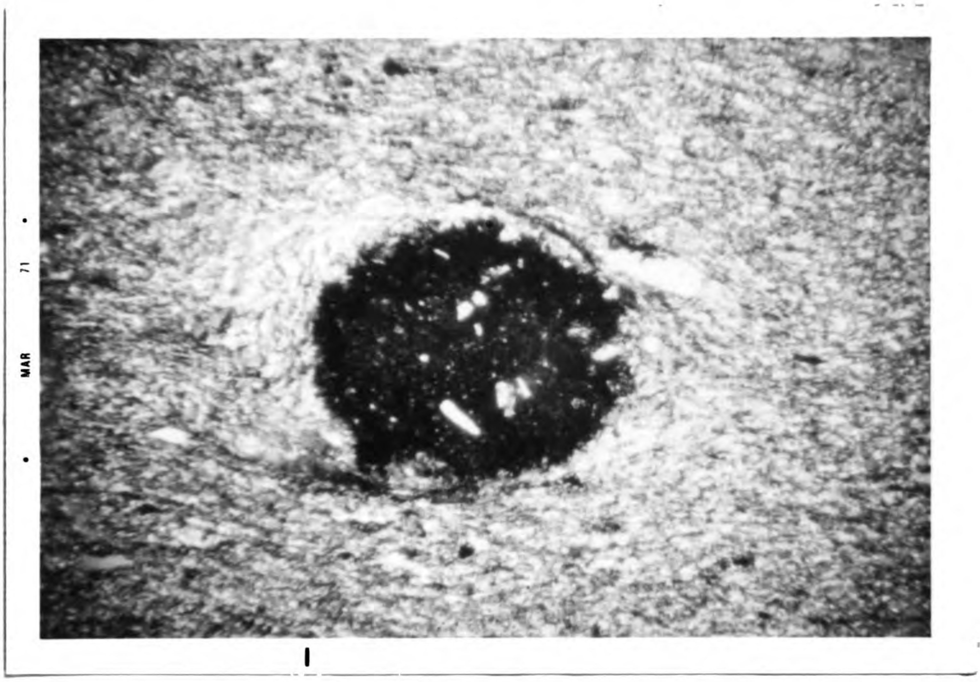


Figure 6.--Thin section of Mt. Alpha phyllite showing corroded and cracked grain of garnet. 175X

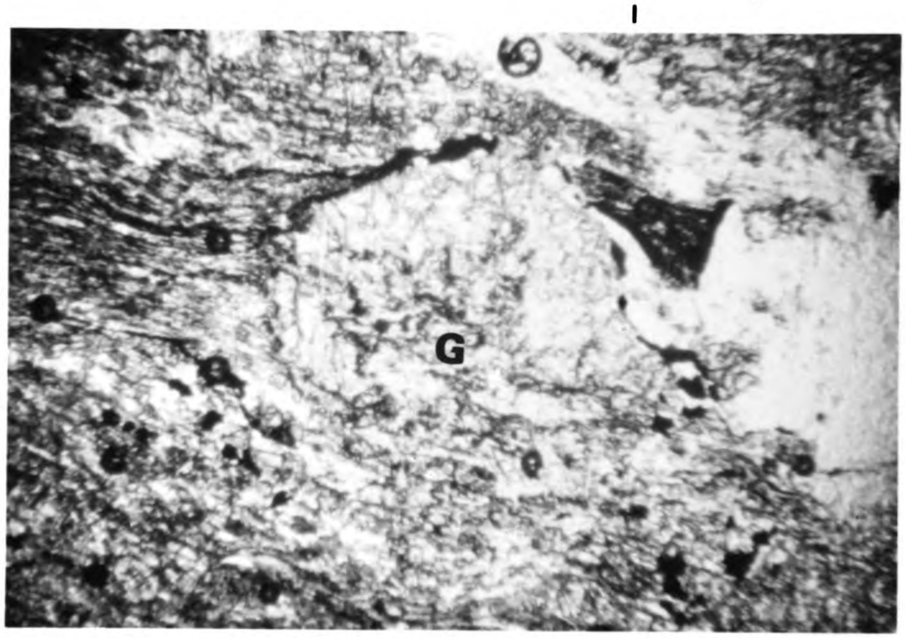


Figure 7.--Garnet in Mt. Alpha phyllite. 250X

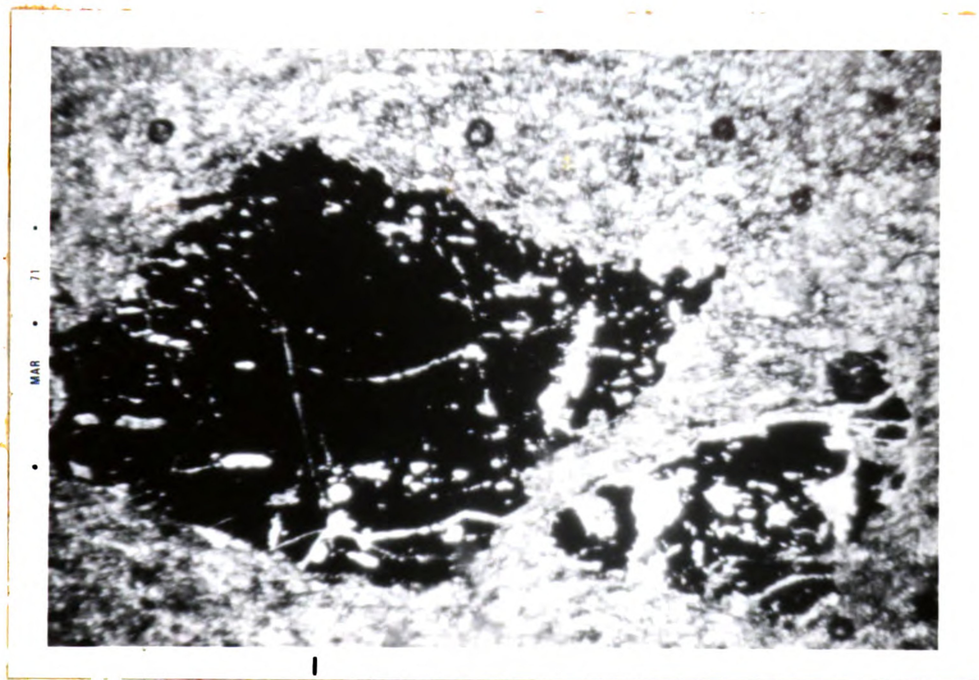


Figure 8.--Pyrites (black) occurring in Mt. Alpha phyllite. 350X

Carbonates are present in small amounts, usually in tiny grains. The characteristic mineralogy and texture of these phyllites indicate that they have been recrystallized from pelitic sediments.

The Nimba Series is a 1,500-meter thick sequence of schists, phyllites and iron formation. It comprises of a lower unit, called the Valley group which consists of metavolcanic rocks; and an upper unit, the Ridge group, which consists of sedimentary rocks which have been metamorphosed.

CHAPTER IV

STRUCTURE OF NIMBA MINE AREA

The main structural feature of the Nimba Range is a central anticline underlying the Seka Valley to the north, and central Gbahm to the south (Figure 9--profiles 5, 8 and 13). This anticline is flanked by two synclines underlying the North Gbahm Ridge to the north, and the Yiti Valley and west slope of Gbahm Ridge to the south. The whole syncline-anticline-syncline structure is plunging to the southwest at a low angle.

According to Berge (1968), the present structural interpretation stems from two lines of reasoning:

> Stratigraphic arguments are as follows: (1) Petrographic data indicate that the two large amphibole schist horizons are of similar composition. Hence, they are assumed to be of the same formation (Seka Valley amphibole schist). (2) Based on the similarity of contacts of the east and west itabirite horizons on the Nimba Ridge with the Mt. Alpha phyllite, it is assumed that these two itabirite horizons are parts of the same formation. The acceptance of these two assumptions leads to the conclusion that both ridges are underlain by cores of complete isoclinal folds, either anticlinal or synclinal.
>
> Structural arguments are as follows: (1) Observations on drag folds in phyllite near iron ore contacts on Mt. Alpha suggest that the fold core underlying the Nimba Ridge is synclinal and that the anticlinal fold is to the northwest or underlying Seka Valley. (2) Linear striations on ore and itabirite laminae plunge southwesterly.

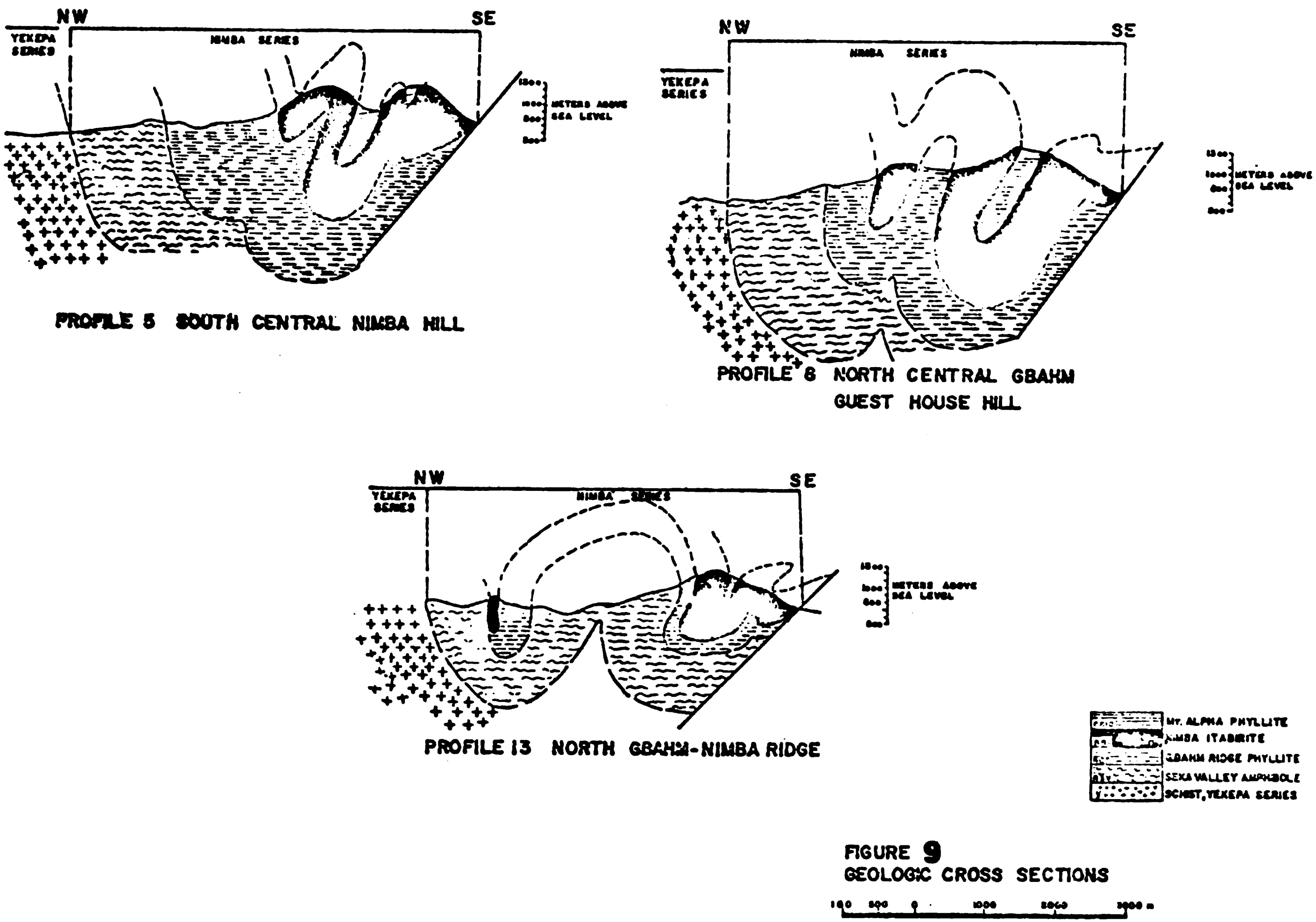


FIGURE 9
GEOLOGIC CROSS SECTIONS

Only one major fault has been observed in the area; this is to the southeast of the Nimba Ridge, where the structural relationship of the Nimba itabirites with the granites has been inferred as a fault. This stems from the rather straight baseline of the Nimba Ridge and geologically by the apparent contact of the Nimba itabirite with granitic rocks without the intervening Gbahm Ridge phyllite and Seka Valley amphibole schist, and by the observations of mylonitic rocks at the contact recorded by Lackshewitz and Tremaine (1962).

Due to inadequate geologic mapping of the area, geophysical (magnetic) correlation is not possible. However, some magnetic contours are considerably displaced along this "fault" line.

CHAPTER V

THE NIMBA IRON ORES

In general, the ore types in the Nimba area are divided into: (1) hard, intermediate and soft high grade blue hematite ores, (2) brown ore (mostly soft). This classification is based on the study of iron ores by Dorr and Barbosa (1963, p. C55) in Brazil and has since been applied to the Nimba Iron Ores--it is based on the estimated percentage of material that would, after mechanized mining, crushing and screening, be above one-half inch in minimum dimension:

Type of Ore (Physical)		Percentages Greater Than One-half Inch in Diameter
Hard ore		100-75
Medium hard	intermediate	75-50
Medium soft	intermediate	50-25
Soft		25- 0

Blue Hematite Ores

The blue hematite ores (Figure 10) in Nimba have an average of 67.8 percent iron. The blue ore is a steel-blue in color and has its hard, medium and soft varieties.

Figure 10.--Blue hard ore, mainly hematite and highly recemented. 1X

Within in the present mine area, the main ore body (estimated at 190 million tons) consists of blue ore.

The average composition of the blue ore is:

Fe_2O_3	97.0%
L.O.I.*	1.0%
SiO_2	1.5%
Al_2O_3	0.5%
P	0.4%

The hard ore (Figure 10) is compact, tough and resistant to both mechanical and chemical weathering. It is low in gangue materials, especially silica. Silica is the cementing material and its dark gray color is quite evident between white hematite grains in reflected light (Figure 11).

The medium (Figure 12) or intermediate varieties are composed of disaggregated and powdery hematite which is also resistant to weathering.

The soft ore (Figure 13) is the predominant type ore as regards physical quality. Most of this is called biscuit ore--the term referring to thin wafer-like laminae of iron ore minerals which occur uniformly throughout the zones of soft ore. These laminae vary in thickness from less than 1 mm to 5 mm. Their main characteristics are softness and friability and their laminated structures

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*Lost on ignition (amount of water).

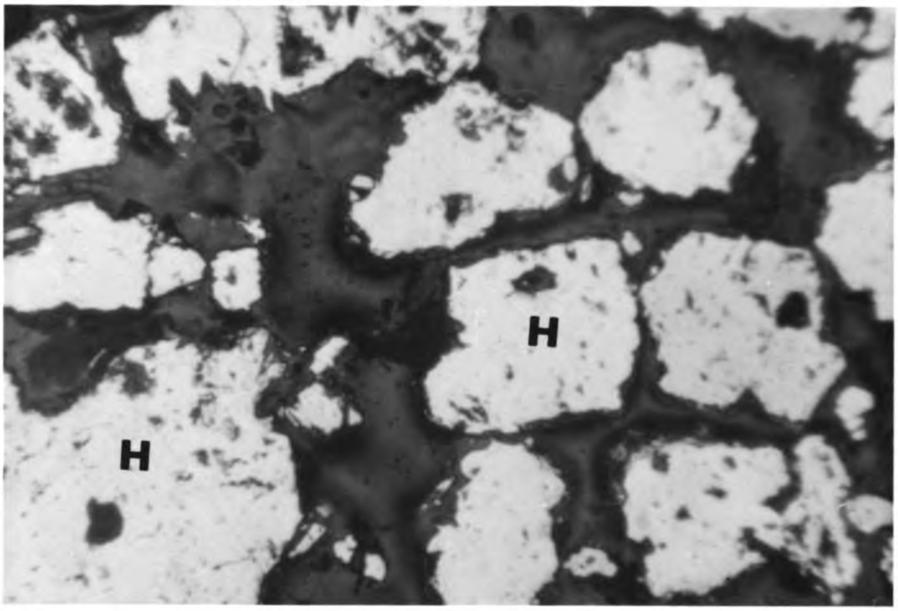

Figure 11.--Grains of hematite (white) cemented by quartz (dark gray) in recemented blue ore. (Polished Section, 350X)

Figure 12.--Siliceous blue medium hard ore, mainly hematite and silica. 1X

Figure 13.--Siliceous blue biscuit, mainly hematite and silica. 1X

have been retained from the original iron formation. Soft ores are known to grade vertically or horizontally into medium hard to hard varieties which usually retain the laminations present in the soft ores. This type of blue ore is more siliceous than medium and hard varieties (Figure 14).

The Brown Ores

The brown ore (Figures 15, 16, 17 and 18) is composed essentially of hydrated ferric oxides (Goethite-$Fe_2O_3 \cdot H_2O$) and feric oxides (hematite-Fe_2O_3) and has its hard, medium and soft varieties. It is found underlying flat topped flat ridges with a mean elevation of about 1300 meters above sea level. The flat topped ridges are preserved intact by the hardcapping. The brown ores have been estimated at 110 million tons and occupy the N-74, Mt. Alpha and Northeast Extension ore bodies (Plate I). The average composition is as follows:

	Brown Ore	Surface Brown Ore
Fe_2O_3	93.7%	90.0%
L.O.I.*	4.0%	5.5%
SiO_2	1.5%	0.8%
Al_2O_3	0.8%	2.8%
P	0.06%	0.07%

*Lost on ignition (amount of water).

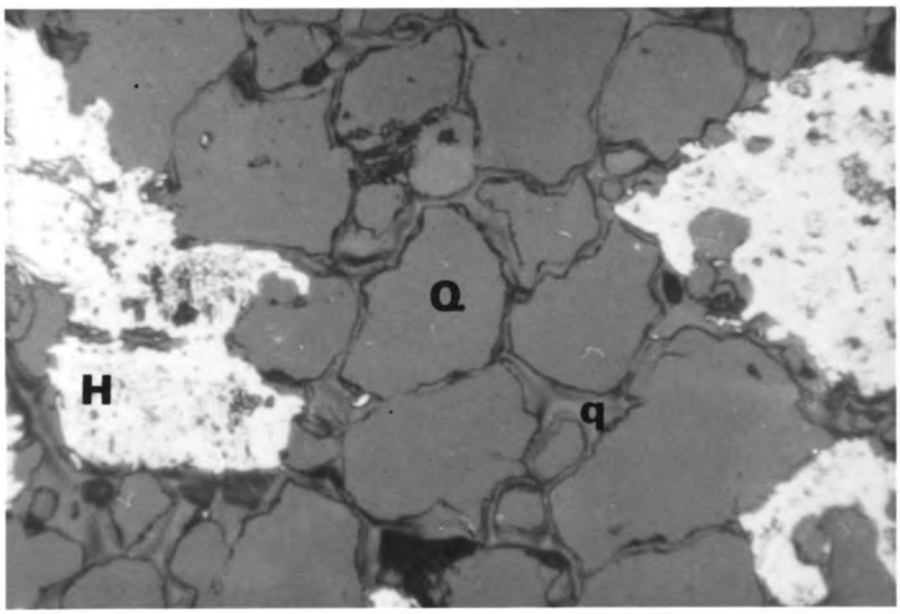

Figure 14.--Siliceous blue ore, mainly hematite (H) and quartz (Q). Note late quartz (q) crystallizing between earlier formed quartz; also islands of quartz in hematite (partial replacement of quartz by hematite). (Polished Section; 350X)

Figure 15.--Lateritic ironstone, mainly goethite, commonly interbedded with blue hard ore. 1X

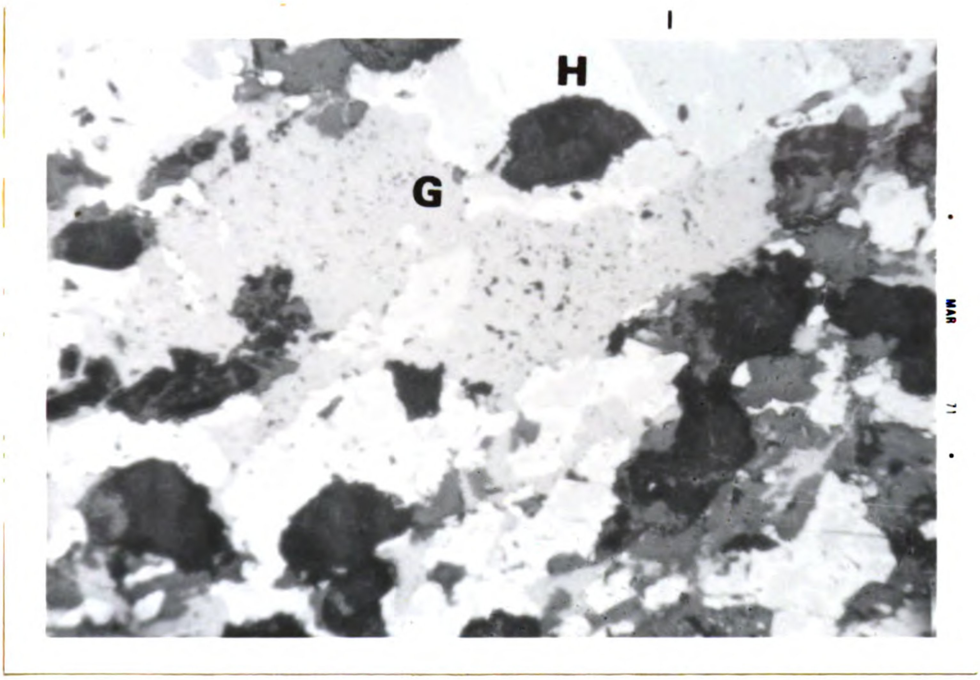

Figure 16.--Hydration of hematite (H) to goethite (gray) in brown ore. (Polished Section; 350X)

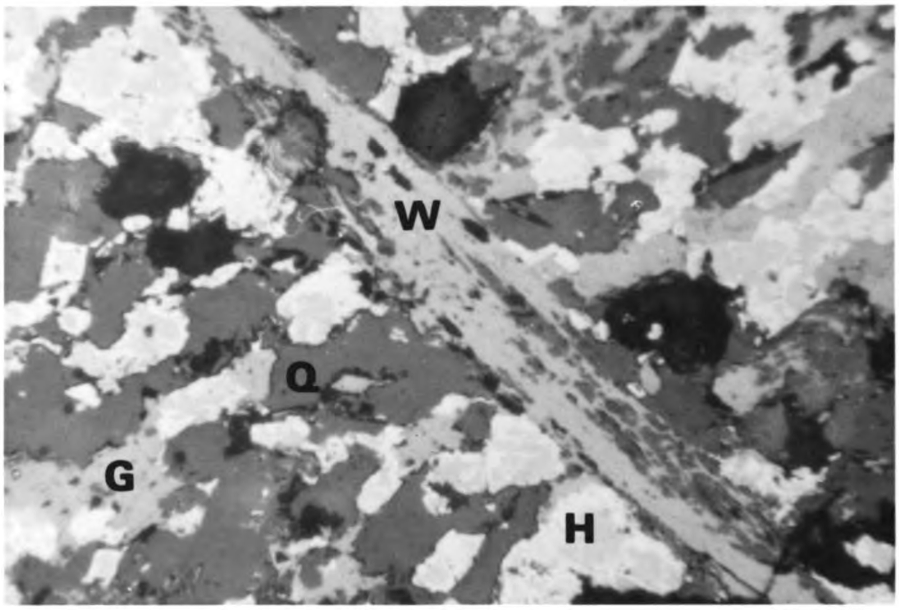

Figure 17.--Hydration of hematite (white) to goethite (light gray). Quartz is dark gray (w--probably micro fracture serving as pathway for water?). (Polished Section; 175X)

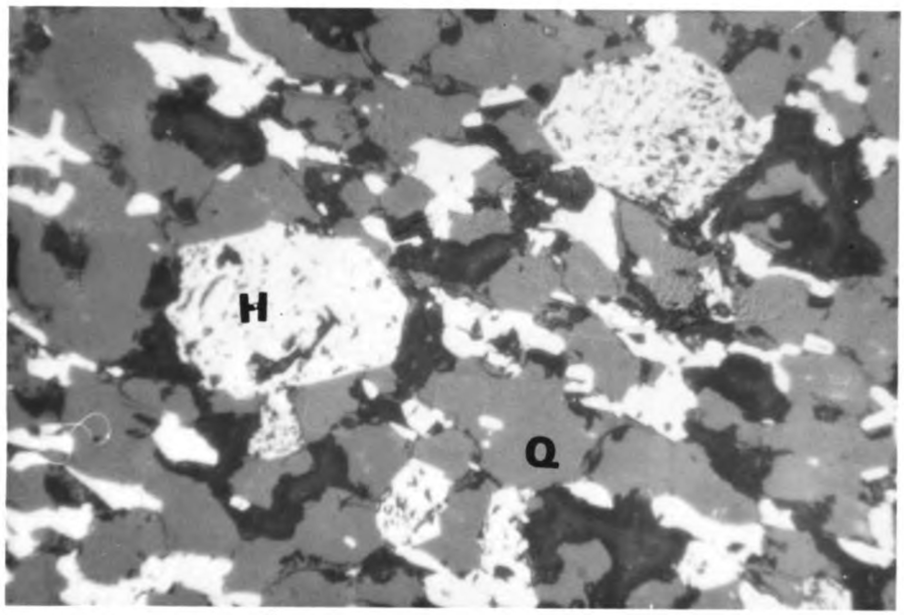

Figure 18.--Hematite (white) occurring together with quartz (dark gray). (Polished Section; 350X)

The brown ores are characterized by vertical zoning. In the surface zones (surface brown ore), the ores contain a higher percentage of goethite and alumina. Silica and alumina may combine to form clay minerals and with excess alumina, gibbsite forms. The brown ores are found under ridge crests and are capped by a hard completely recemented ironstone in which the laminated structure has been retained. Berge (1966) has estimated the depth of this hard capping at two to five meters. Clays are abundant in the surface zones and filling vugs and cavities which account for the increased alumina content in the surface zone. The silica content increases with depth, and the ore gradually becomes a soft itabirite at an average depth of 75 to 100 meters. The brown ore has an average Fe content of 65.5 percent at depth and 63.5 percent at the surface.

Ore Minerals

Magnetite

Magnetite occurs in grains ranging in size from 2 millimeters to about 10 microns. Average grains are 0.1 to 0.2 millimeters. Magnetite-bearing grains are commonly euhedral to anhedral, coarse grains are elongated and subhedral to anhedral.

Hematite

Hematite occurs in grains ranging in size from 2 millimeters to about 10 microns. Hematite and magnetite may occur together, the former replacing the latter without regard to magnetic grain shape (Figures 19, 20, 21 and 22). In a second type the hematite (martite) selectively replaces magnetite (Figure 23). Fine hematite grains are subhedral to anhedral while coarser grains are euhedral to subhedral. Elongate hematite grains range from 0.03 millimeter to 0.2 millimeter in dimension.

Goethite

Goethite, the third iron mineral, results from the hydration of hematite, and is associated with hematite rather than magnetite (Figure 23). Goethite tends to be anhedral. The grain sizes range from 0.1 millimeter to 2 millimeters. Goethite in the brown ore is not primary and has been formed by hydration of hematite during chemical weathering.

Quartz

Quartz grains range in size from 0.01 to 0.7 millimeters in equidimensional grains (Figure 14). Average grain size is 0.1 millimeters with elongation up to 0.2 millimeters the quartz grains developed anhedral faces with goethite. Quartz has an undulatory extinction. Quartz cements hematite grains (Figure 11) and also forms secondary growth rims around earlier quartz grains

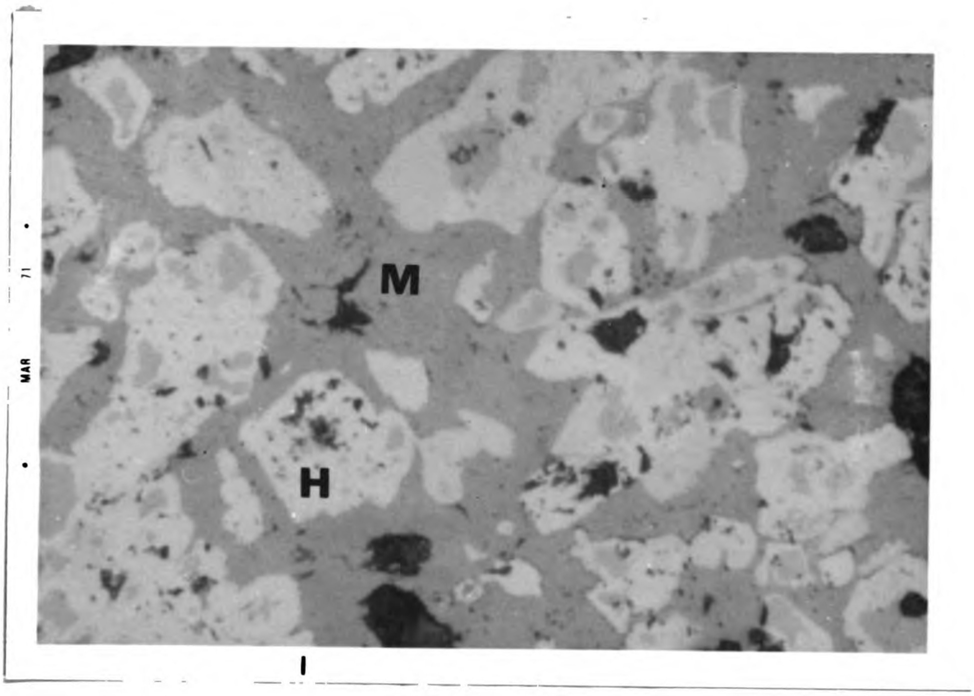

Figure 19.--Hematite (white) replacing magnetite (gray). (Polished Section; 175X)

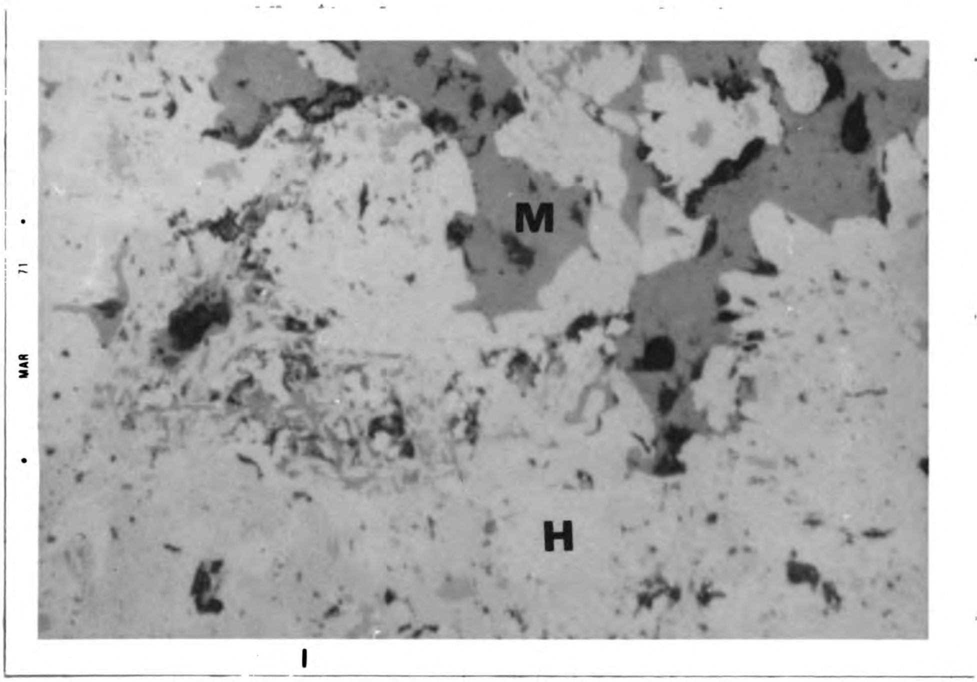

Figure 20.--Hematite (white) nearly completely replacing magnetite (dark gray). (Polished Section; 175X)

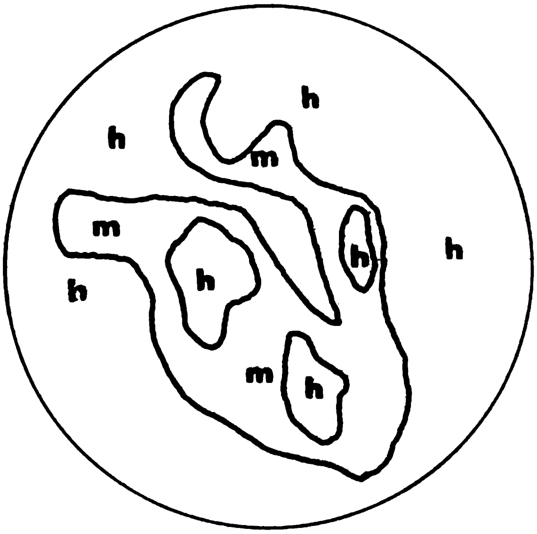

Figure 21. Freehand sketch showing hematite (h) replacing magnetite (m): magnification = 175 X.

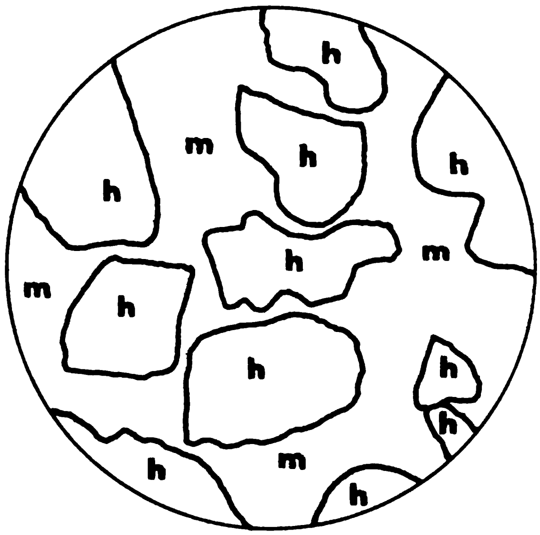

Figure 22. Freehand sketch of well-developed grains of hematite (h): magnification = 175 X.

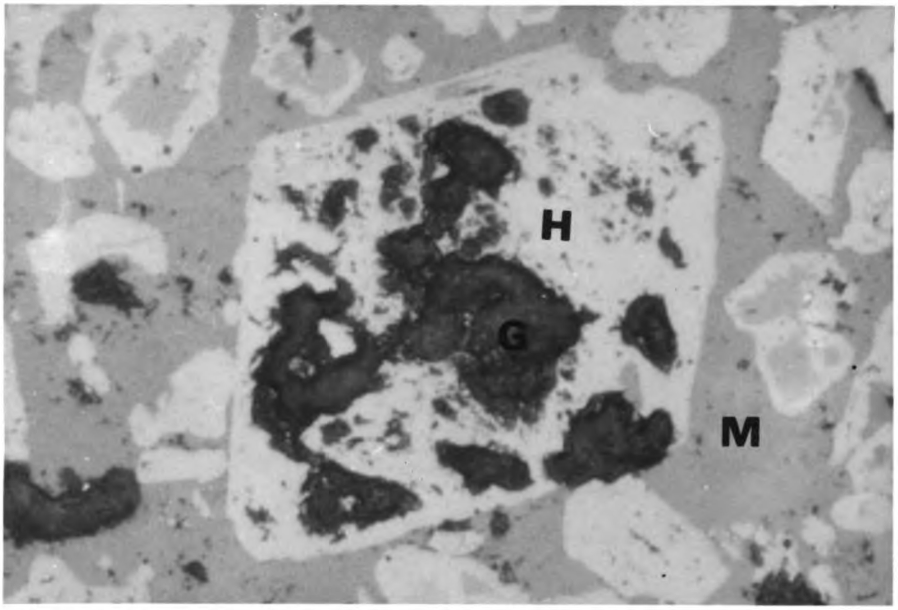

Figure 23.--Hematite (martite) grain (white) replaced magnetite (gray) and also in the process of being replaced by goethite (black). (Polished Section; 350X)

(Figure 14). In Figure 14, earlier formed quartz grains are surrounded by late quartz. This is suggestive of two periods of crystallization where late quartz has crystallized in open spaces between grains and also has corroded edges of earlier quartz grains. There are islands of quartz grains in hematite which may indicate partial replacement of quartz by hematite (Figure 14).

CHAPTER VI

ORIGIN OF THE NIMBA IRON ORES

The most important and controversial issue of the origin of iron ores and iron-bearing sediments is the source of the iron. The iron in iron bearing sediments has been considered to be derived either from weathering of the adjacent landmass or to have been contributed by volcanism or by hydrothermal waters.

Van Hise and Leith (1911) are responsible for relating the deposition of iron formation to volcanism. According to Pettijohn (1957, p. 458), the major factor which led these early workers to the concept of a volcanic source for the iron was the presumed inadequacy of ordinary weathering to supply solutions of the proper type for precipitation of iron in iron formation.

Shallow basins are postulated as the receptacles for the iron-silica sediments. Woolnough (1941), has suggested that iron formation is an epicontinental sediment formed as a chemical precipitate from river waters that entered saline lakes or other closed basins. The annual temperature cycle of fresh-water lakes, with its effects on water stratification and chemistry of the lake waters, under certain climatic conditions, provides a mechanism for rhythmic deposition of silica and iron (Hough, 1957). Sakamato (1950) attributed the iron and silica to mature weathering in the neighboring areas and noted that these materials must have been transported in different ways according to the seasons, in a manner similar to the development of distinct soil horizons in wet and dry climates. Sakamato (1950) further suggested that the iron was carried to lakes during the wet season when the waters were acidic; but in the dry season, precipitation of the iron and concomitant transportation of silica occurred due to a sharp rise in pH.

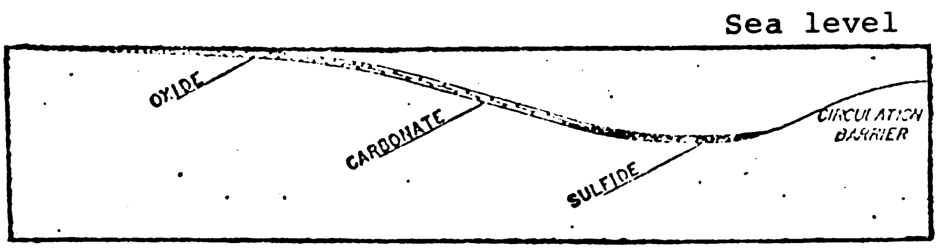

Figure 24.--Depositional zones in hypothetical basins in which iron compounds are being precipitated (after James, 1954).

Recent work by James (1954) has indicated that deposition of each iron facies is largely controlled by the Eh and pH conditions of the environment, especially the oxidation-reduction potential. High values of Eh and pH promote the oxide minerals. James (1954) tends to favor weathering and deposition in a restricted basin (Figure 24) as a more general mechanism of concentration; to account for the very abundant iron ores of the Precambrian when thick vegetation could not have aided the solution of iron from the lands, Krauskopf (1967) suggests that the atmosphere in Precambrian times may have contained more carbon dioxide than at present, making surface waters more acid and hence more effective in breaking down silicate minerals.

Krumbein and Garrels (1952) believe that the pH and Eh of the environment provide general controls on chemical sedimentation which include both inorganic and biochemical processes. They further emphasize that the amount of a particular mineral that will precipitate depends upon the amount of the constituents available but that a change in deposition from one mineral to another will not take place unless there is a change in the Eh or pH of the environment. Stability fields of iron oxides with respect to Eh and pH have been calculated by Garrels and Christ (1965). These indicate that hematite is stable under a strongly oxidizing environment while magnetite is stable under mildly reducing and mildly oxidizing conditions (Figure 25).

Polished sections of the blue ores indicate replacement of magnetite by hematite. Hematite can be seen along the grain borders and the cracks, working inward with a smooth front which shows no dependence on the

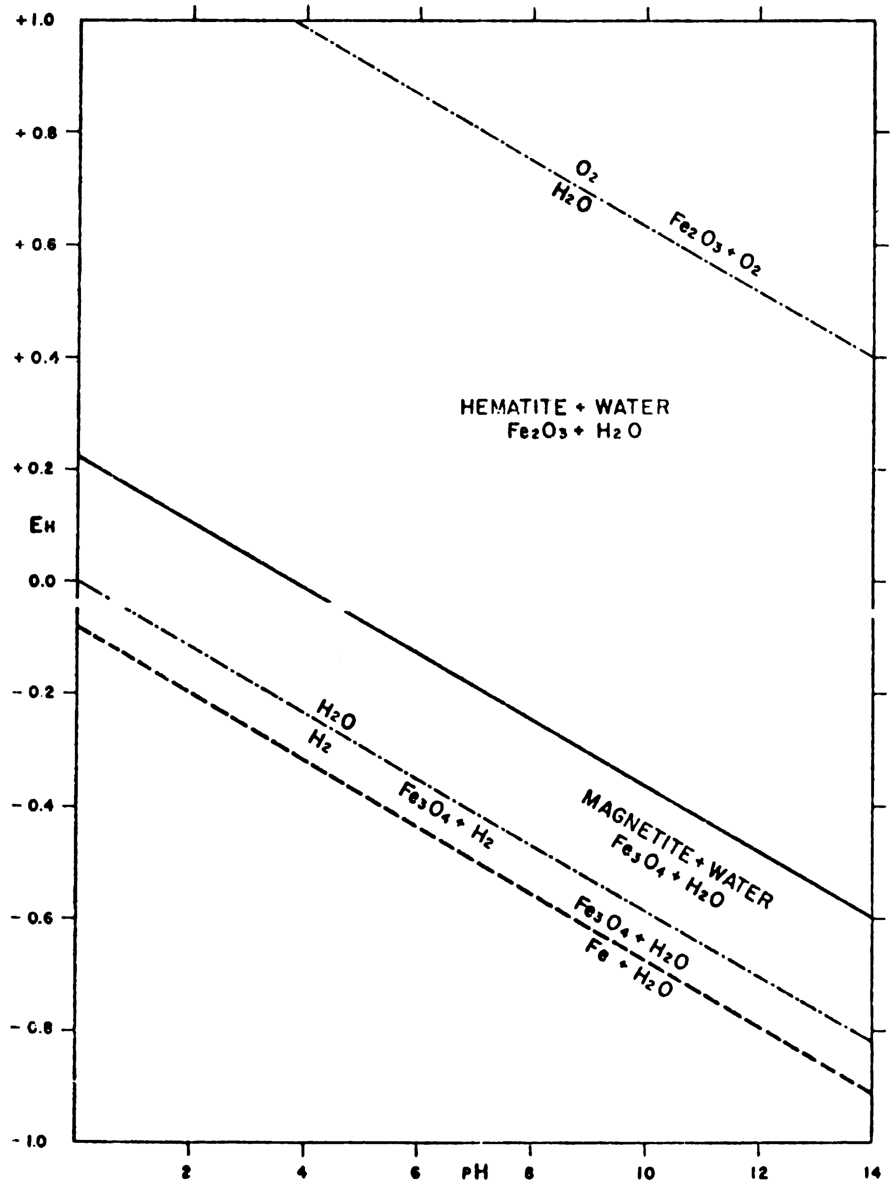

Figure 25.--Stability fields of iron oxides as functions of Eh and pH at 25 degrees C and 1 atmosphere total pressure. Dashed line indicates lower stability limit of magnetite in presence of metastable water (after Garrels and Christ, 1965).

crystal structure of the magnetite (Figures 19, 20, 21 and 22). When such relations are observed, there can be no reasonable doubt that the magnetite is the older and hematite replaces it. In another specimen (Figure 23), the replacement is dependent on the structure of the magnetite grain. In both types of replacement, it is evident that magnetite is the host.

CHAPTER VII

CONCLUSION

It has been noted earlier that deposition of the various iron minerals is largely controlled by the Eh and pH of the environment. In the environment of deposition, iron in the form of colloids, or of true solution is supplied to the basin in wet seasons from a nearby continental landmass. Ferrous ion is oxidized to ferric ion due to aeration. Then in the dry seasons when we have less water, the pH of the lake water rises to neutral and ferric hydroxide is precipitated. Then silica is supplied to the basin in colloidal solution and is deposited as chert interlaminated with the iron oxides. This process is repeated upon the return of the wet season when there is a supply of fresh surface water and there is a return from neutral to acid again, in this stage silica is precipitated again. When the pH approaches neutral or alkalinity (dry season) once more, silica and iron hydroxides precipitate together, thus forming layers of silica and iron hydroxides. This iron may have been derived from basic rocks, now metamorphosed to the Seka

Valley Amphibole Schist, exposed at the time of deposition.

Magnetite has been formed at or near the surface as a sedimentary iron formation (itabirite) and has been altered to hematite (martite) (Figures 12 and 13) and complete leaching or replacement of the chert and silicates from the itabirites have given rise to soft blue ores. Medium to hard blue ores result from chemical weathering and regional metamorphism of the soft blue ores.

All ores have been formed by the removal of silica from the itabirite by surface waters during the wet seasons. In the brown ores, goethite has resulted from the hydration of hematite. During this process, alumina from the surface has been added to the surface zones of the brown ore.

Based on field observations and microscopic study, the following conclusions can be made:

1. The Nimba Iron Ores of Liberia are of Precambrian age.
2. The ores had an original sedimentary origin.
3. That the original iron mineral was probably magnetite; this has been partially replaced by hematite and enriched by lateritic weathering.
4. The ores were highly metamorphosed--perhaps to the sillimanite grade.

5. The ores have been folded but less faulting has occurred.
6. Weathering, related to the present surface, has altered the hematite to goethite; near the surface an increase in Al_2O_3 and reduction in SiO_2 in the ore may result from intense laterization effects.
7. Because of similarities with other Precambrian iron ores, it may be assumed that the ores were formed from a lower grade iron formation by leaching of silica and/or enrichment of iron (Figures 3 and 4 strongly suggest this).
8. Finally, Precambrian sandstones in the Nimba area have been altered to quartzites; chemical sediments (iron formation) have been crystallized to form itabirites; sediments that were primarily argillaceous have changed to phyllite or schist and volcanic rocks are now gneiss and schist.

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