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THE METAMORPHOSED IRON ORE OF EL PAO, VENEZUELA

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ABSTRACT

The Pao iron deposit in Venezuela occurs as a thirty-meter, intricately folded layer in a sequence of high-grade Precambrian paragneisses of the Imataca Complex. Most of the ore is direct-shipping, high-grade, hard, coarse-grained, hematite-magnetite, but some is of the soft variety. The hard ore exhibits many mineralogical, textural, and structural features that demonstrate it to have undergone a period of dynamothermal metamorphism. Most conspicuous among these features are: the presence of exsolved plates of corundum in hematite; the conversion of magnetite to coarse-grained hematite during the waning stages of the thermal history; the deformational features in both coarse-grained hematite and magnetite; a gneissic, oriented fabric in hard hematite ore; the presence of gneissic folds in the hard one. The writer favors the hypothesis that the hard ore has been derived by metamorphism from a primary, silica-poor ore, rather than that it is the result of concentration during metamorphism.

INTRODUCTION

THE Pao Mine is situated south of the Orinoco River, on the Precambrian Shield in Venezuela (Fig. 1). At the mine much of the iron ore is of the hard variety, occurring as a thirty-meter, intricately folded layer of direct-shipping, massive, coarse-grained hematite-magnetite (Figs. 2, 3), in a sequence of highly metamorphosed Precambrian gneisses of the Imataca Complex (5, 16). Similar coarse-grained material is known in non-commercial quantities from the forested area between El Pao and the delta of the Orinoco River (14). The hard El Pao ore differs from that which is mined 60 to 100 km to the southwest at Cerros Rondon, Altamira, and Bolivar, and known from Cerros San Isidro, Toribio, and Arimagua, in that in the southwest the ore is the common, fine-grained, soft, Lake Superior type, derived from iron formation by weathering (15).

The general features of the Pao deposit and problems regarding the origin of the hard ore were discussed by Burchard in 1930 (2) and by Zuloaga in 1930 and 1935 (21, 22). Burchard weighed the evidence pointing to concentration of iron during metamorphism, following the ideas of Harder (10), against evidence that the ore was of magmatic origin, and concluded that the iron ores were developed in quartzose, ferruginous sedimentary rocks by a concentrating action of magmatic solutions during a period of metamorphism (2, p. 364). Also Zuloaga believed that magmatic solutions concentrated the iron, but he did not stress the metamorphic aspects of the ore (22, p. 332).

Since the time that these papers were written, sufficient mining has been done by the Iron Mines Company of Venezuela, a subsidiary of Bethlehem

Steel Company, that many benches now extend through the zone of canga into less disturbed material below, and some into bedrock. Thus, it is now feasible to expand on, and modify significantly, some of the observations of the earlier workers. The writer had opportunities for field study, especially during a week in July 1963, while working on the Guayana Shield Project, an undertaking sponsored jointly by the Ministerio de Minas e Hidrocarburos of Venezuela and the Department of Geology, Princeton University. The laboratory work was done subsequently at Princeton.

The writer wishes to express his appreciation to R. Phillips for stimulating discussions on iron oxide mineralogy, to R. N. Clayton for oxygen isotope analyses of some El Pao mineral pairs, to E. Lyden for X-ray diffraction determinations, and to IMCOV and its parent company for various courtesies extended during the course of this work.

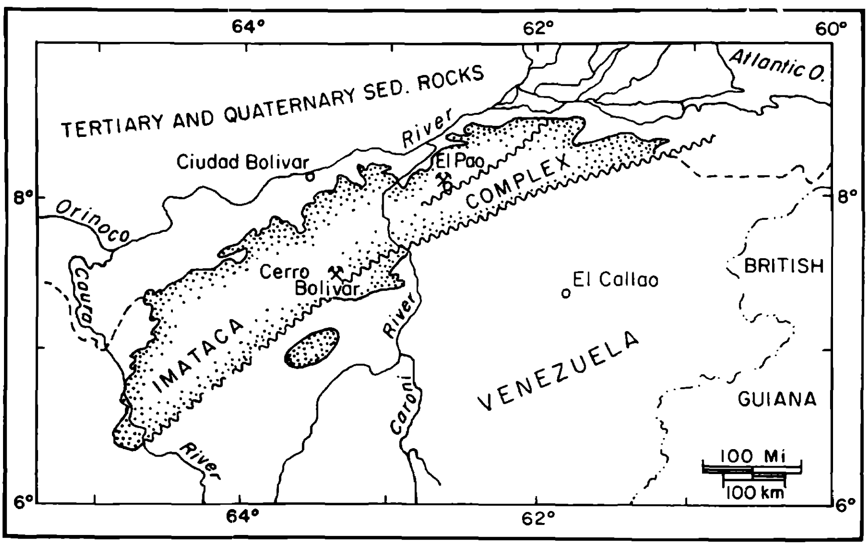


FIG. 1. Location of El Pao Iron Mine.

The purpose of this paper is to present new information on the geological setting of the deposit, and especially to demonstrate that the hard ore at El Pao shows very clearly the effects of a metamorphic episode. The subject matter bears directly on a discussion of the origin of hard ores by Park (12) and Dorr and Barbosa (4), on a brief mention of the subject by Gross and Strangway (8), and perhaps on a paper on Bomi Hill ores by Fitzhugh (7).

STRATIGRAPHY

In the westernmost part of South Basin, the lowest unit, originally a quartz-feldspar gneiss, now consists of scattered quartz grains in gibbsite, and northeast of South Basin the gneiss has weathered to quartz and white kaolinite.

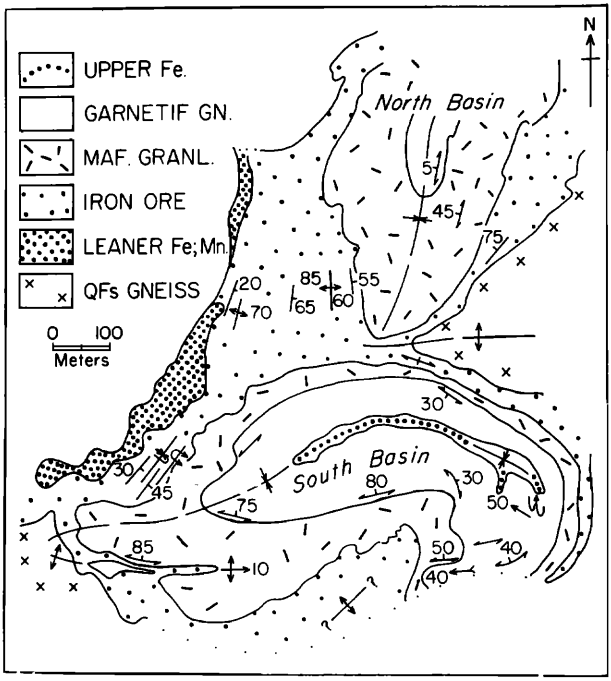


FIG. 2. Geology of El Pao Iron Mine.

The main ferruginous sequence is the next stratigraphic unit, about 10 m thick where considered to be relatively simple in structure, but attaining several times that figure where thickened by folding. In many places on the outcrop and in drill holes the basal part of the ferruginous sequence is a banded iron formation, consisting of 15 or 20 percent iron oxides in a quartz matrix. The

TABLE 1
FORMATIONS RECOGNIZED AT EL PAO

Recent and (?)Tertiary
Weathered products: clays, iron and manganese oxides
Unconformity
Precambrian, Imataca Complex
Period of dynamothermal metamorphism
Uppermost soft iron ore
Garnetiferous gneisses
Mafic granulite
Main iron ore bed
Iron formation
Quartz-bearing gneiss
Base unknown

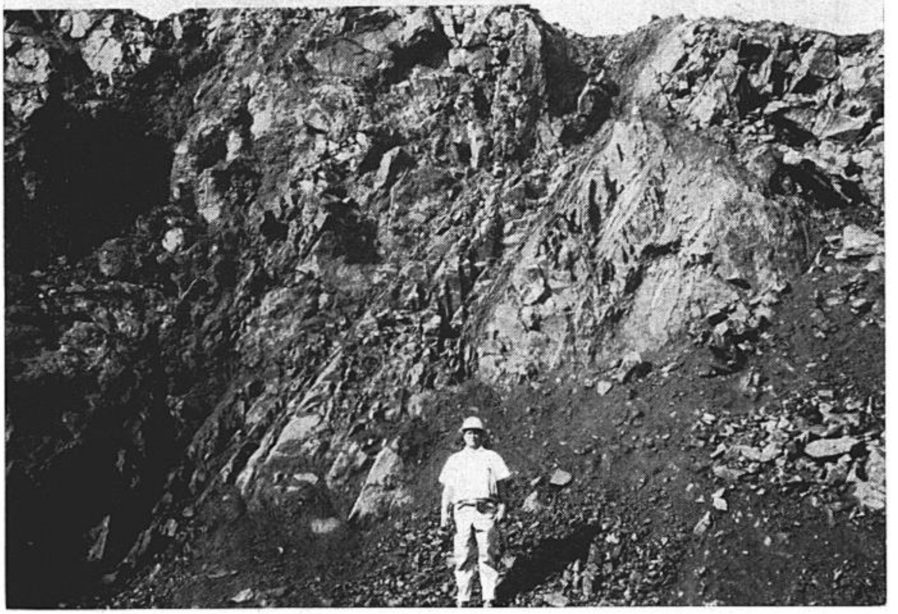
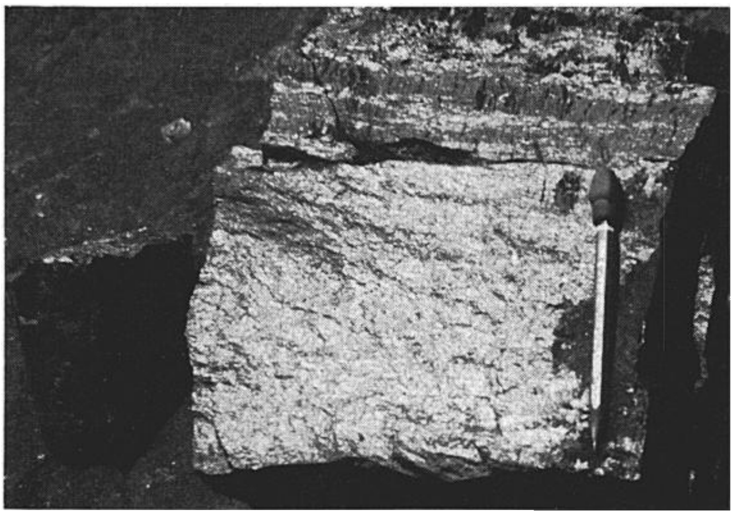


FIG. 3. (Upper) Coarse-grained El Pao iron ore. Bedding shown by lines of pits.

FIG. 4. (Lower) Hard iron ore. Bedding, inclined to the left, is cut by a vertical fracture set.

grain size is somewhat variable, those of the oxides ranging from about 0.01 to 0.1 mm and those of quartz being much finer, the small oxide grains in addition forming 1 mm clusters. Quartz is characteristically highly sheared and strained as noted by Zuloaga (22, p. 328). On the basis of an O_{16}/O_{18} analysis of a quartz-magnetite pair from fine-grained iron formation in drill core, the iron formation has been subjected to a temperature of at least 645° C. An isotopic analysis of a quartz-hematite pair from the very coarse-grained iron formation exposed at the west end of South Basin also gives a temperature of equilibration near 645° C.

Processes of supergene oxidation have converted iron formation locally to siliceous and fine-grained, soft ores. No iron silicates have been found in



Fɪɢ. 5. Hematite-martite ore. The lower $\frac{2}{3}$ is well-foliated hematite; at the top are martite bands with pronounced vertical fracturing, the fracture surfaces inclined to the right.

thin sections of the iron formation, but Burchard reports the occurrence of some iron carbonate in them (2, p. 358).

The upper part of the ferruginous unit, in some places perhaps constituting the entire thickness, is a coarse-grained, hard, foliated, jointed, magnetite-hematite ore, with a very low quartz content, as indicated by the typical analyses compiled by Burchard (2, p. 361). Burchard also mentions the occurrence of megascopically visible corundum in the ore (2, p. 358).

Bedding in the hard ore is shown in places by lines of pits from which some mineral has been removed by weathering (Fig. 3). On some faces of ore this layering parallels one-meter-thick sheets which in turn are cut by joints (Fig. 4), perhaps a kind of fracture cleavage. Locally the oxides show a mineralogical banding, consisting of alternate layers of hematite and magnetite. In the hematite layers the crystals are elongate and parallel the banding, whereas in

TABLE 2

MODAL ANALYSES OF MAFIC GRANULITE

Plagioclase	60% An_{74}	55% An_{40}
Hypersthene	19	15
Clinopyroxene	19	1
Hornblende	—	28
Opaques	2	1

those consisting essentially of magnetite or martite, the banding is cut by a close-spaced perpendicular set of parallel joints (Fig. 5). The pronounced gneissic structure in the ore was remarked upon by Zuloaga (22, p. 324).

A sheet of mafic granulite, 5 to 50 m thick, overlies the ferruginous units and represents a metamorphosed basic lava or gabbro intrusion. The contact between granulite and hard iron ore was seen in 1961 on freshly blasted blocks, but the geometric relationships are inconclusive, and certainly do not suggest simple intrusion by the mafic granulite.

In thin section the mafic granulite is a granoblastic, medium-grained, unfoliated rock with plagioclase, two pyroxenes, and locally with hornblende (Table 2). In the hornblende-free granulite the oxides are magnetite and ilmenite, either as magnetite grains with a single, broad ilmenite lamella or, where exsolution has been more complete, as discrete, adjoining grains. Among the opaques are also a few 0.02 mm grains of chalcopyrite. In the hornblende-bearing variety the oxides are represented by rare 0.02 mm grains of spinel, but the main opaque constituents are small chalcopyrite-pyrrhotite intergrowths in which the pyrrhotite consists of two phases. In some of these the pyrrhotite component is rimmed by pyrite, probably indicating a decrease in temperature (1). The fact that in the hornblende-bearing granulite iron is

TABLE 3

MODAL ANALYSES AND MINERAL PARAGENESES OF QUARTZ–FELDSPAR GNEISSES

Quartz	20	x	x	x	x
Perthite	40	tr	x	non-perth	
Plagioclase Anti-perth	25	x	non-perth	tr	x
Garnet	x			x	x
Biotite	x		x	x	x
Muscovite					x
Hypersthene	x				
Hercynite	x				x
Sillimanite	x			x	
Apatite	x				
Chlorite	x	x	x		
Epidote	x				
Opaques	x				x
Pyrrhotite	x			x	
Hemo-ilmenite	x	x	x	x	
Ilmenomagnetite	x				
Chalcopyrite				x	
Pyrite				x	

in the form of sulfide rather than oxide may be related to a higher sulfur pressure.

The succeeding unit, a variable quartz-feldspar gneiss, is conformable with the mafic granulite. The most conspicuous variety is garnetiferous (Fig. 6) but various parageneses are listed in Table 3. The assemblages containing perthite, antiperthite, garnet, hypersthene, and sillimanite are appropriate for the pyroxene-granulite subfacies of the granulite facies (19, p. 554).

FIG. 6. Weathered, garnetiferous gneiss showing compositional layering.

Petrographic relationships indicate that minerals in the garnetiferous gneisses have undergone a series of metamorphic retrograde changes. For example, in one specimen a box-work structure consisting of laminae of granular garnet with an axial zone of opaque minerals, is related obviously to the cleavage of some preexisting mineral. Around this garnet is a corona structure, comprising successive layers, first 0.3 mm of plagioclase, then 0.1 mm perthite, and followed by 0.2 mm of iron-rich hypersthene, slightly altered to chlorite, and by scattered 0.05 mm grains of a green spinel, perhaps hercynite. In other slides the feldspar zone is followed by a 0.5 mm zone of cloudy, weakly anisotropic chlorite. In these rocks biotite is a late mineral phase, characteristically occurring with a non-perthitic plagioclase, near An_{20} in composition. In some garnetiferous gneisses biotite veins all components, but in one it replaces an aggregate of plagioclase and opaque minerals which in turn have been derived from garnet.

Clay pseudomorphs of sillimanite were noted as a conspicuous component in graphitic gneisses.

The uppermost stratigraphic unit is represented by an elongate body of soft iron ore, derived from an isoclinally folded layer of iron formation.

STRUCTURE

The southern limit of the El Pao deposit is within a kilometer of the northern boundary of the El Pao fault-zone, a four kilometer-wide zone of mylonite and flaser gneiss, demarking a major tectonic break (5).

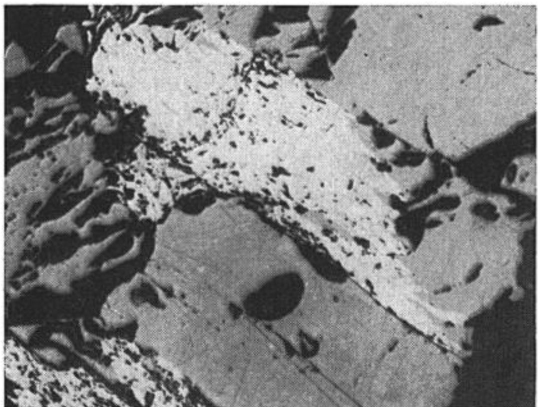
The major structural features at the mine have been determined by drilling to comprise two deep structural basins, their long axes at right angles to one another, and joined by a tight cross-anticline. Differences in outcrop-width of limbs is due to subsidiary folds. According to drill information, the iron ore layer is missing from the southeastern part of the South Basin, probably due to the penetrative folding of adjoining, less competent strata.

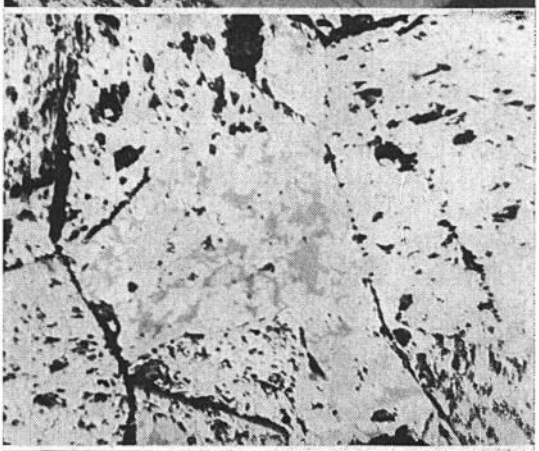
MINERALOGY AND PARAGENESIS OF THE IRON OXIDES

The sequence of stages in the development of iron oxides can be followed especially well in the quartz-bearing iron formation because the presence of accessory iron and copper sulfides can be used as a criterion to establish lack of supergene weathering. The observations made on the iron formation are in accordance with those made on the hard ore, the only difference being that in ore, minerals other than iron oxides are very rare.

In normal unweathered iron formation, that is, in polished surfaces showing also pyrite, the earliest oxides consist of magnetite, or of magnetite and hematite, in individual grains or elongate clusters ranging from 0.01 to 4 mm in size. Where magnetite occurs with hematite, the magnetite is commonly replaced by the hematite, the replacement controlled in general but not in fine detail by a magnetite cleavage (Fig. 7). In Figure 7 this cleavage extends through oxides into the quartzite matrix in the manner of a fracture cleavage. In the replacement type hematite, unreplaced residuals of magnetite do not show any geometric pattern (Fig. 8). Locally magnetite octahedra occur with hematite, suggesting that at some stage the direction of oxidation may have been the reverse of what it was later on (Fig. 9). All of these changes took place during regional metamorphism, obliterating any possible preexisting primary structures.

These recrystallization textures were modified by two processes: by deformation of grains during the period of folding probably accompanying the





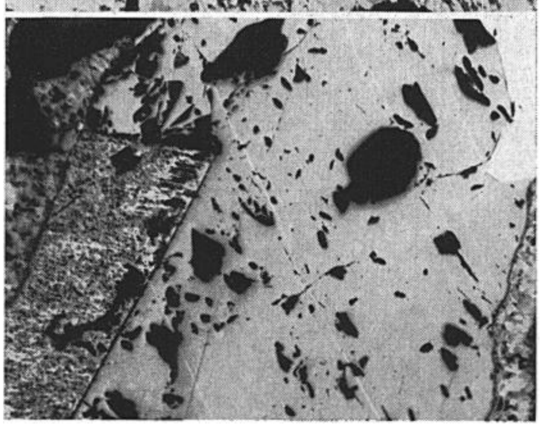


FIG. 7. (Upper) Parallel lamellae of hematite replacing magnetite along a cleavage direction. × 100.

FIG. 8. (Center) Unreplaced residuals of magnetite in hematite. Note the polygonal structure inherited from magnetite. × 270.

FIG. 9. (Lower) Magnetite metacryst in hematite. Note curved and disrupted twin-lamellae in hematite. Magnetite oxidized to martite, showing cloth-texture. At top and bottom oxides cut by supergene hematite. X-nicols. × 50.

metamorphism (Fig. 10), and by later supergene weathering. Only the latter will be discussed at this point.

Textures produced during supergene weathering show characteristically a rather close dependence on mineral cleavage and grain boundaries. For example, in some grains the distribution of goethite is controlled by the cleavage in metamorphic hematite, the hematite orientation in turn reflecting an inheritance from magnetite (cf. Fig. 11 with 7 and 8). It is possible, of course, that some of this goethite may have formed during the waning stages of metamorphism when temperatures were still elevated (17).

During supergene oxidation magnetite develops the well-known "cloth texture" (Fig. 9, 10, 12), quite distinct from the texture related to metamorphic recrystallization in these rocks (Fig. 8).

The process of weathering caused iron oxides to migrate and to produce some intricate relationships. For example, in Figure 12 hematite and martite are rimmed by crystalline supergene hematite and by a later ocherous hematite layer. In Figure 13 martite is replaced by light bluish-gray hematite (the clear areas), also by ocherous hematite (the diffuse spots), and cut by cleavage-controlled veinlets of probably quartz. Martitized magnetite can be replaced entirely by supergene hematite.

At the stage of magnetite martitization all sulfides disappear due to their oxidation, but even at the stage at which all large magnetite grains have been altered to martite, the iron formation may still contain a few scattered, completely fresh magnetite grains, 0.01 to 0.05 mm in diameter.

Turning to the hard iron ore, the individual magnetite and hematite grains are about 1 to 10 mm in greatest dimension, locally finer, but in some places up to 2 or 3 cm in size. Some of the coarse hematite contains tiny, oriented blades of a non-metallic component identified tentatively as exsolved blades of corundum (Fig. 14).[1]

In the coarse ore, similar to the relationships found in iron formation, metamorphic, twinned hematite grew at the expense of magnetite, with microscopic relationships similar to those shown in Figure 8 for cases in which the alteration has not been complete. A megascopic structural relationship between magnetite and hematite is that shown in Figure 15, an irregular veining of magnetite by metamorphically foliated hematite. At the peak of metamorphism more of the oxide must have been magnetite than what is presently apparent, the partial conversion to hematite occurring during conditions of decreasing temperature (6, Fig. 2) and the magnitude of this conversion being dependent on the availability of oxygen.

Subsequently, magnetite in the ore was oxidized to dark martite, and all were replaced and veined to varying degrees near the surface by supergene goethite and powdery hematite.

SUPERGENE EFFECTS

In addition to the effects noted above, weathering processes have concentrated manganese oxides on the west limb of North Basin. Two manganese

[1] An electron-probe study of this material by Bethlehem Steel Company for the writer indicates these blades to contain appreciable aluminum.

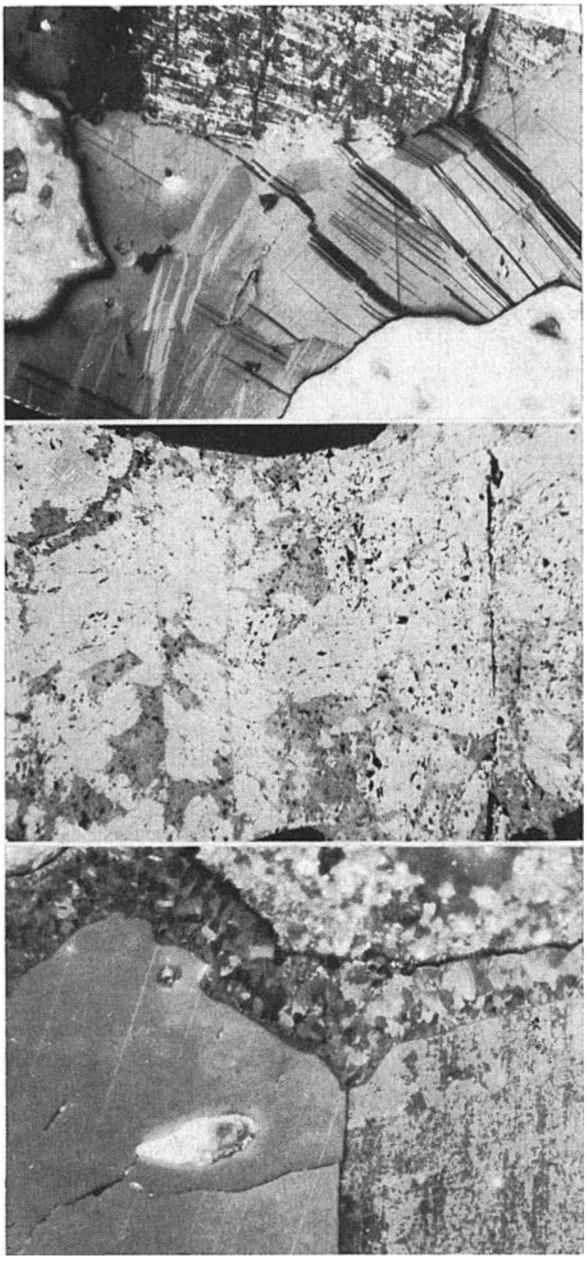


FIG. 10. (Upper) Deformed hematite and magnetite. Note bent cleavage in magnetite. The magnetite was oxidized to martite subsequently. ×-nicols. × 100.

FIG. 11. (Middle) Magnetite entirely altered to metamorphic hematite, but showing magnetite cleavage. Hematite subsequently altered to goethite. × 70.

FIG. 12. (Lower) Twinned hematite and martitized magnetite rimmed by supergene, crystalline hematite and ocherous hematite. × 130.

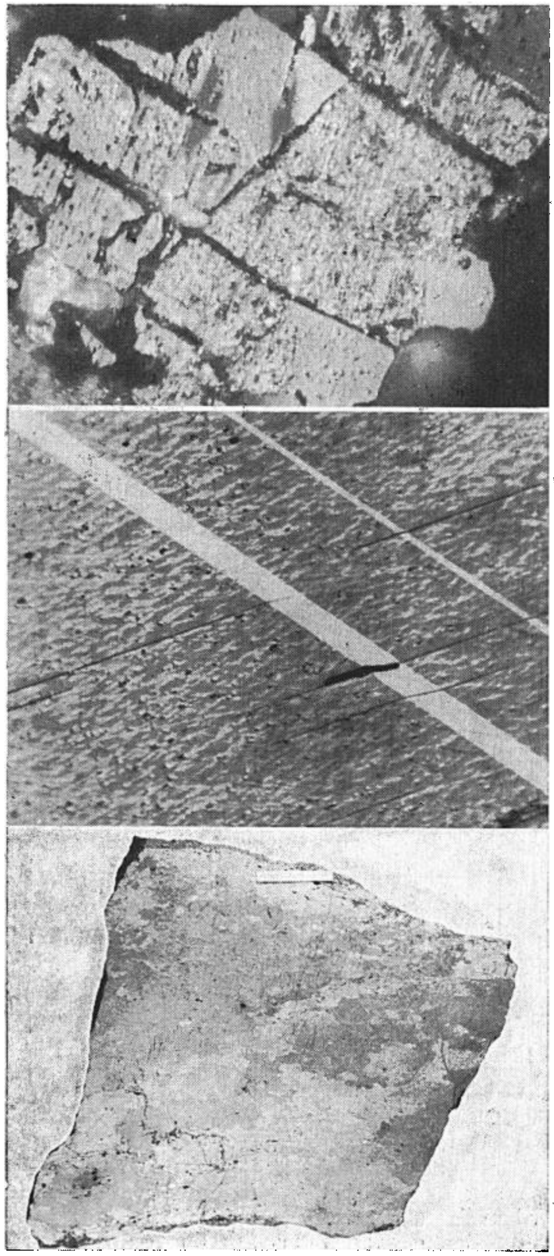


FIG. 13. (Upper) Magnetite replaced locally by hematite, then martitized, and later cut by veinlets of supergene material. X-nicols. × 300.

FIG. 14. (Middle) Twinned hematite with exsolved plates of probable corundum. Note the perthite-like structure in the hematite. Crossed nicols; oil immersion. × 650.

FIG. 15. (Lower) Dynamothermally metamorphosed magnetite-hematite ore. Magnetite (darker) is now martite. Scale bar is one inch.

oxides were identified by X-rays: pyrolusite, and Nsuta MnO_2, type 1.64 (18, p. 305).

Some of the residual soil in the basins consisted of bauxite according to Burchard (2, p. 355), and the writer found some hard, pisolitic material in one of the dumps, which gave a good gibbsite pattern.

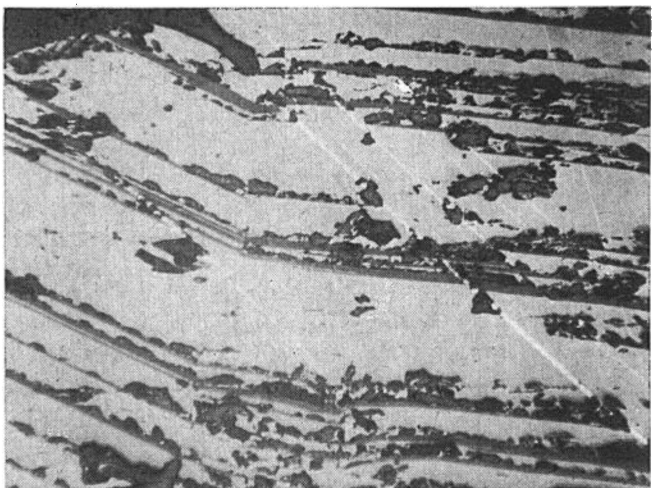


FIG. 16. (Upper) Bent twin lamellae in hematite, cut by straight and cross-twinned, narrower lamellae (light). Cross nicols. × 60.

FIG. 17. (Lower) Bent cleavage in martitized magnetite. × 70.

A deposit of white, quartzose kaolinite has developed along the northwest limb of South Basin, whereas near the western nose of that basin the same formation has gone to gibbsite.

DYNAMOTHERMAL METAMORPHISM OF THE MASSIVE ORE

Evidence for the dynamothermal metamorphism of the iron oxides, presented in part in earlier sections, consists of the following facts:

1. The hard, coarse-grained iron ores and iron formation occur as layers in paragneisses metamorphosed to the pyroxene-granulite facies of regional metamorphism.

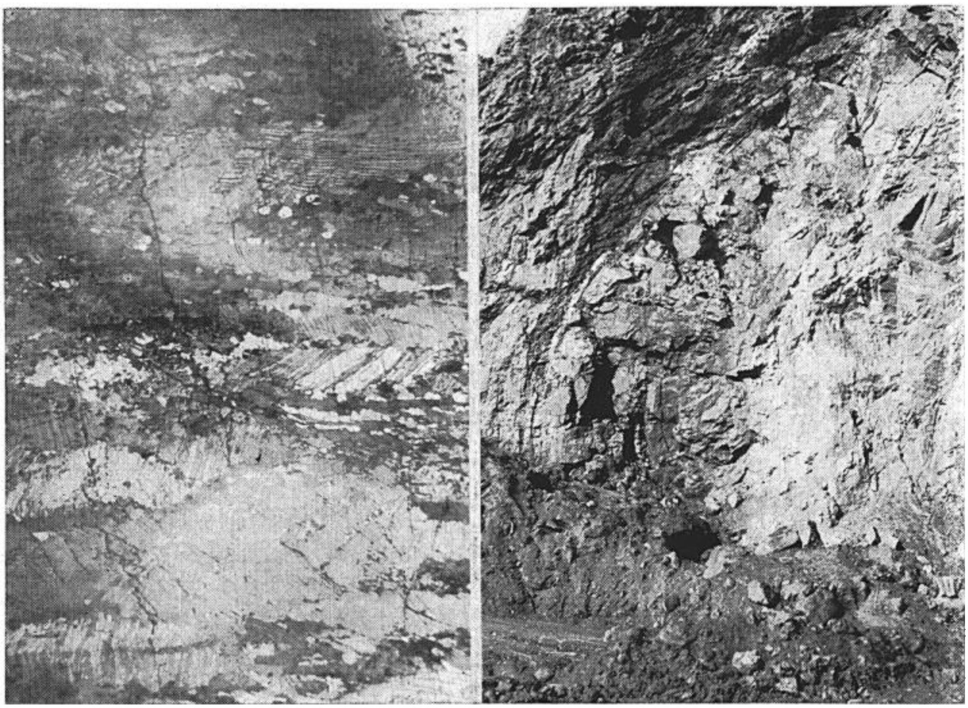


FIG. 18. (Left) Strongly deformed hematite. Note irregularity of twin lamellation. Polarized light. × 10.

FIG. 19. (Right) Isoclinal fold in hard iron ore. Nose occurs just above the black feature. Bench is 17 meters high.

2. The iron formation has been exposed to temperatures near 645° C on the basis of oxygen isotope analyses.

3. Temperatures in excess of 100 or 200° C are proved by the presence of probable exsolved plates of corundum in coarse-grained hematite (20, Fig. 7).

4. The coarse grain size of the iron ore in itself suggests an environment conducive to substantial recrystallization.

5. Lamellar hematite, that is, hematite with a perthite-like structure in polished section (Fig. 14) is known also from Yampa Sound iron ore, which is demonstratably a dynamothermally metamorphosed iron ore (3). Curiously, and perhaps significantly, lamellar hematite is also recorded from Bomi Hills, Liberia (13, p. 887–889, Fig. 558).[2]

6. Physical deformation of the iron ore can be seen in microscopic textures:

a. Twin lamellae in hematite crystals are bent (Fig. 16), or both bent and offset on fractures (Fig. 10). Many hematite grains also show undulatory extinction, or slight polygonization, produced by strain. A few martite crystals have bent cleavage planes (Fig. 17). The fact that supergene hematite that replaces magnetite along such slightly curved cleavage planes does not show similar strain bending or glide-twinning, may be used with caution as a criterion for supergene hematite.

b. Locally in massive magnetite-hematite ore, as well as in hematite ore, hematite crystals occur as parallel, oriented plates, with strongly deformed twin-lamellation (Fig. 18), producing megascopically the foliated, gneissic texture remarked upon by Zuloaga.

7. Megascopic evidence of dynamothermal metamorphism of the ore is fairly convincing:

a. The wide-spread gneissic structure in hard hematite ore is related to a preferred hematite orientation, permitting deformation by gliding. In the adjoining magnetite layers such deformation is represented by a system of cross-fractures (Fig. 5).

b. Hard iron ore is folded isoclinally (Fig. 19). Although folds are common in slumped Lake Superior-type ores (9, Plate 18, Fig. 6; 15, p. 23), in this instance the folds were produced not by slumping, but gneissic flow of crystalline hematite, as demonstrated by the curving of the mineral gneissosity around the nose of the fold. A study of the direction of remanent magnetism around the curve of this nose unfortunately produced no confirmatory data.

CONCLUSION

El Pao hard iron ore shows the effects of dynamothermal metamorphism. There is no evidence at present to indicate whether the metamorphosed ore was derived:

a. from a preexisting Lake Superior-type ore.

b. from a primary, chemically precipitated, silica-poor or silica-free, iron deposit.

c. from iron formation, by some concentration mechanism operating during regional metamorphism (4).

d. from iron formation, by some concentration mechanism, by pre-metamorphic or syntectonic intrusion of some postulated igneous rock, such as the present mafic granulite.

[2] The lamellar hematite from El Pao has now been studied by R. Phillips.

Although in Venezuela a small quantity of hard ore is known from Cerro Bolivar (15, p. 233), most of it occurs in the area between El Pao, the Orinoco River, and the delta. This distribution could be interpreted to reflect some stratigraphic limitation on the occurrence of massive ore, but likewise it could be interpreted to reflect merely the influence of the (dryer) granulite facies metamorphism characteristic of the El Pao region.

For the time being the writer favors the hypothesis that the hard ore was derived by metamorphism from a primary silica-poor ore, rather than that it is the result of concentration during metamorphism. The thickness of the ore may be related to tectonic processes, because under stress, hard, hematite ore probably will flow in a manner analogous to marble. This may be the explanation why some of the hard ore in the Itabira district occurs in what appear to be recumbent isoclinal, refolded folds (4, Plate 8, Sections 8 to 12). When mining at El Pao exposes larger quantities of fresh rocks, it may be possible then to re-evaluate the hypothesis of the ultimate origin of the El Pao hard ore by a careful study of ore-country rock relationships.

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May 21, 1964

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