

BRAZILIAN IRON FORMATIONS AND THEIR GEOLOGICAL SETTING

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ABSTRACT In the Quadrilátero Ferrífero banded iron formations (BIFs) are metamorphic jaspilites named itabirites that occur in the Paleoproterozoic platformal sequence of the Minas Supergroup (2.6 - 2.12 Ga). Several types of itabirites can be defined according to primary (sedimentary) and secondary features, acquired under the influence of metamorphic, deformational and weathering processes. A complex interaction of primary and secondary processes was responsible for the anomalous concentration of iron in high-grade deposits. In the Carajás Range in the central north of Pará, BIF-related iron ores are weathered anchimetamorphic jaspilites with preserved primary textures and structures, making up approx. 18 billion tons of ore with 66 % Fe. The jaspilites are weakly deformed and extend over 2500 km² in the eastern portion of the region in the Archean Grão-Pará Group (2.7-2.6 Ga) between metavolcanic rocks. The Urucúm District in Mato Grosso do Sul, at the Brazilian - Bolivian border, displays the youngest Brazilian banded iron formation as flat-lying anchimetamorphic jaspilites of Proterozoic age (ca. 0.6 Ga). These are associated with fine glacial marine sediments and manganese layers that outcrop as inselbergs locally called Morrarias. Urucúm jaspilites belong to the group of Rapitan-Type iron formations and can be distinguished from the Carajás jaspilites by the presence of glacial-clastic components and nodules of uncertain origin. Tropical weathering as well as primary concentration are the principal processes responsible for the high grade iron ores with more than 63% Fe and reserves of approximately only 100 million tons, that are very appreciated for direct reduction plants.

Keywords: Banded iron formations, Quadrilátero Ferrífero, Carajás, Urucúm

INTRODUCTION The principal iron formations in the world were deposited during the Late Archean to the Paleoproterozoic and subordinately in the Neoproterozoic. Deposits of these different ages are represented in the Carajás, Quadrilátero Ferrífero and Urucúm Mining Districts in Brazil.

This paper represents a short review of the main characteristics; similarities and differences between the main sequences of Brazilian banded iron formations according to published data and recently acquired information. It emphasizes stratigraphy, structural, mineralogical, and textural features that are of great importance for the metallurgical characterization of iron ore.

THE QUADRILÁTERO FERRÍFERO The Quadrilátero Ferrífero (Dorr 1969), located on the southern portion of the São Francisco Craton (Almeida 1977), was affected by at least three orogenic cycles, the Archean Jequié (2.7-2.5Ga), the Paleoproterozoic Transamazonian (2.1-1.9 Ga) and the Neoproterozoic to Early Paleozoic Brasiliano (0.7-0.50 Ga). The Quadrilátero Ferrífero has a quadrangular shape due to the dome and basin structure of the Minas Supergroup (Fig 1a).

The basement of the Minas Supergroup consists of amphibolite facies metamorphic granite gneiss terrains and the Rio das Velhas greenstone belt. These Late Archean units were reworked during the Proterozoic (Machado *et al.* 1992. Machado and Carneiro 1992. Noce 1995) with the development of pegmatite and granite bodies.

The ca. 3,700-m thick platformal sediments of the Minas Supergroup were deposited between 2.6 and 2.12 Ga. (Renger *et al.* 1994. Noce 1995. Romano 1989. Babinski *et al.* 1995). Opening of the basin is first recorded by the development of a U-Au pyrite – bearing fluvial – deltaic system, which evolved to a shallow-water marine environment. The bottom of the sequence is represented by the clastic Caraça Group that contains psammites originated in a rift phase (alluvial to deltaic deposits) gradating upwards to shallow water carbonaceous phyllites and metapsammites. Widening of the basin allowed the deposition of the BIF-bearing sequence of the Itabira Group, with thick (ca. 250-300m) iron formations (itabirites and hematite bodies), hematite phyllites, dolomitic phyllites marbles and dolomites. Over the Itabira Group deposited the transgressive to regressive marine Piracicaba Group composed of psammitic to pelitic sediments, dolomitic, carbonaceous and ferruginous phyllites, dolomite, minor marble and banded iron formations with a complex lateral and vertical facies variation.

The Sabará Group is the uppermost sequence of the Minas Supergroup. It is younger than 2.12 Ga and is constituted of orogenic immature sediments with volcanic contribution formed during the Transamazonian (Paleoproterozoic) orogenesis (Renger *et al.* 1994).

Younger sequences are Paleo- to Mesoproterozoic rocks formed during the Espinhaço rift, and Neoproterozoic rocks of the São Francisco Basin. Paleo- to Mesoproterozoic rocks comprise metasediments of the Espinhaço Supergroup and 1.7 Ga sin-rift-related magmatic rocks such as alkaline to peralkaline Borrachudo granites (Chemale Jr.

et al. 1997) and tholeiitic mafic rocks. Espinhaço quartzites outcrop at the Serra das Cambotas in the northeastern Quadrilátero Ferrífero. The slates, metasilites and limestones of the Bambuí Group exposed in the northwestern portion of the region represent Neoproterozoic metasediments.

The evolution of the Quadrilátero Ferrífero and adjacent areas occurred during the Archean and Proterozoic ages. At the end of Archean started the rift-related faulting followed by further opening of the basin into a platformal environment. Widening of the basin was succeeded by the generation of a dome and basin structure with the nucleation of open interconnected megasynclines with different axial orientations due to the uplift of granite-gneiss blocks (Chemale Jr. *et al.* 1994). This architecture was probably developed as a response to the early stages of the Transamazonian Orogeny as already proposed by Chemale Jr. *et al.* (1994) and was superposed by structures related to compressive tectonic developed during one (the Brasiliano cycle - Chemale Jr. *et al.* 1994) or two orogenic events (the Transamazonian and Brasiliano cycles – Alkmim and Marshak 1998. Machado *et al.* 1992. Marshak and Alkmim 1989) with involvement of the Espinhaço Supergroup, Borrachudos-type granites and the Bambuí Group.

The most conspicuous compressive structures in the Quadrilátero Ferrífero are west verging major thrusts (e.g. Cambotas-Fundão Thrust System), transcurrent shear zones (e.g. Engenho shear-zone) and tight to isoclinal folds (e.g. Itabira Synclorium and the Monlevade syncline) (Fig 1a). At mesoscopic scale three main deformational phases are recognized, one ductile and two ductile-brittle. They are related to an eastward increasing metamorphic gradient from lower greenschist to amphibolite facies (Herz 1978. Hoefs *et al.* 1982). Contact metamorphism appears in the boundary between gneiss domes and supracrustal rocks (Herz 1978. Jordt-Evangelista *et al.* 1992). In addition, retrometamorphic reactions are heterogeneously observed in the rocks of the Minas Supergroup associated with late tectonic phases.

Itabira Group: Different types of metamorphic iron formations The Itabira Group is divided in the lower Cauê Formation (iron formations) and the upper Gandarela Formation (dolomites and marbles), both units gradating vertically as well as horizontally. Renger *et al.* (1994) propose for the upper limit of the Caraça Group the appearance of dolomitic phyllites that would represent the beginning of chemical sedimentation.

Lithostratigraphic, structural and textural studies enable us to recognize in the Quadrilátero Ferrífero Low Strain and High Strain Domains (Fig. 1b). In the first, primary features are present such as sedimentary parallel bedding, pisolitic structures and stromatolites that in high strain zones are partially or totally obliterated.

Chemical and mineralogical variation during deposition resulted in compositional BIF types. They are related to changes of facies in the basin, originating cherty jaspilites, clay-rich and carbonatic iron formations and lenses of hard banded iron rich bodies (high graded ores) (Fig 4a). Metamorphic overprint generated normal itabirites or quartz-itabirites (Fe-oxide rich and SiO₂-rich layers) carbonatic

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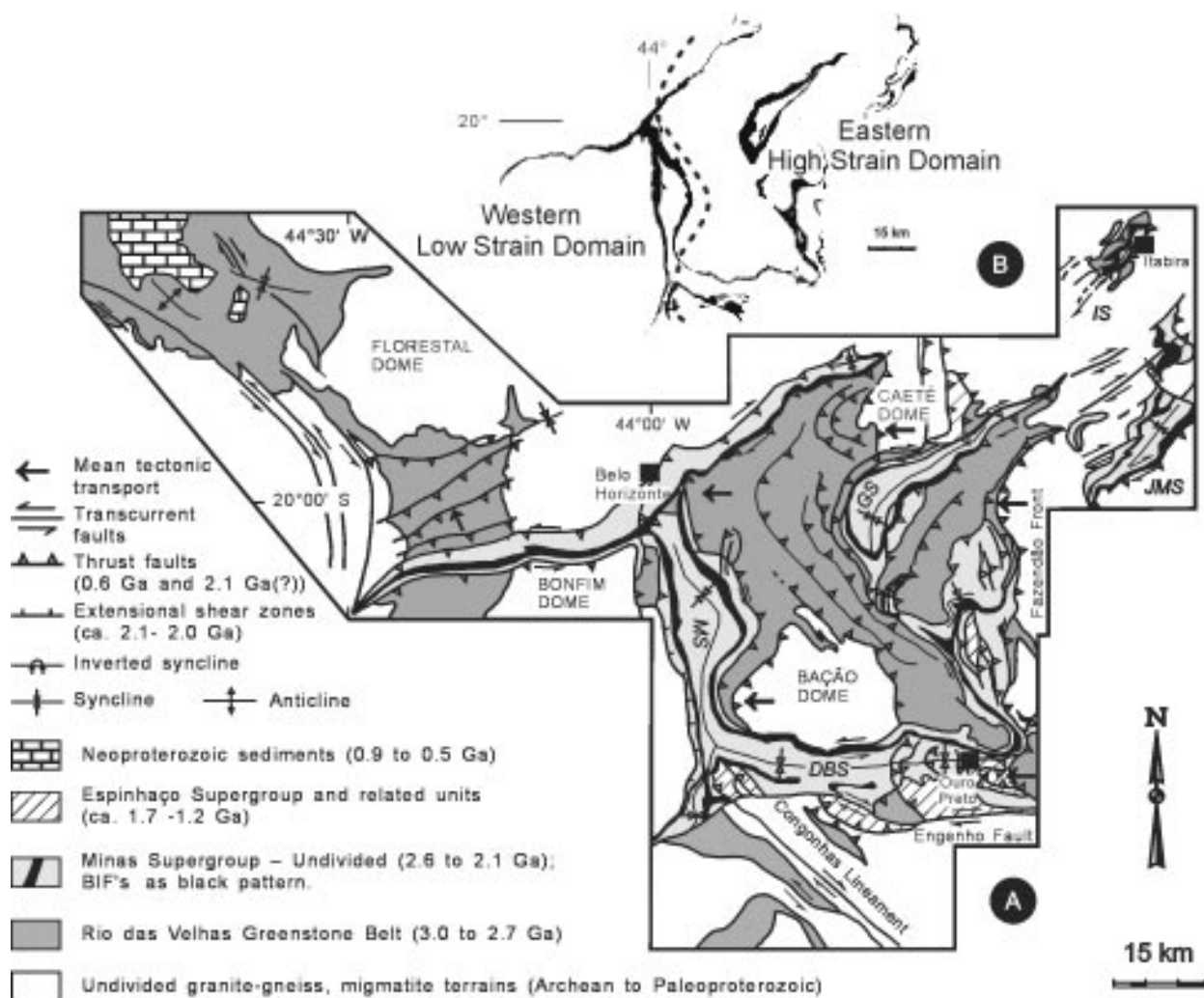


Figure 1—(a) Geologic Map of the Quadrilátero Ferrífero (modified after Baars and Rosière 1994). Major tectonic structures: DBS – Dom Bosco Syncline, MS – Moeda Syncline, GS – Gandarela Syncline, IS – Itabira Synclinorium, JMS – João Monlevade Synclinorium. (b) Location of metamorphic and structural domains in the Quadrilátero Ferrífero. Depicted is the distribution of the Cauê banded iron formation.

(dolomitic) itabirites, amphibolitic itabirites, hematite phyllites, Fe-sulfide phyllites and hematite-rich bodies (primary iron ore bodies). It is still possible to distinguish pre-deformational minerals such as magnetite I, martite I and hematite I (Rosière 1981; Rosière and Chemale Jr. 1991) formed during diagenesis, lithification, and pre-tectonic hydrothermal alteration.

Tectonic types are schistose itabirite and hematite rich ore bodies (tectonic iron ores), presenting oriented and syntectonic grown platy hematite called specularite (Fig. 4b), developed in sequential generations (Rosière 1981). Oriented amphiboles, sericite, kyanite and pyrophyllite may also be present. Tectonic breccia develops in faults and brittle shear zones. These tectonic breccias are composed by hard hematite or itabirite fragments in a quartz, carbonate or hematite matrix. Hematitic gouge is common and, when weathered, gives rise to the “blue dust” high-grade ore type.

The action of deep-reaching tropical weathering on the different types of iron formation produces soft and friable itabirites and hematite bodies (supergenic iron ores), “chapinha” ore and the blue dust. Weathering is one of the main processes responsible for the large volumes of iron rich ores in the Quadrilátero Ferrífero. Water percolation with pH ~ 5.5 or lower under conditions of tropical weathering induces leaching of carbonates, SiO_2 and Fe from the different itabirite types. Fe migrates as Fe^{2+} mainly from magnetite and precipitates under oxidizing conditions as hematite or goethite. Development of a hard

lateritic cap (“canga”) that protects the underlying iron formation from further oxidation may promote leaching of SiO_2 . (extensive discussions on supergene models of iron ores are found in Dorr 1964; Eichler 1967; Morris 1985).

THE CARAJÁS BASIN The Carajás Range in the central north of Pará is the main mineral province in Brazil. The Carajás BIF-related iron deposits make up ca. 18 billion tons of ore with 66 % Fe content. The dominating structure of the basin is the E-W trending Carajás Synclinorium, that is ca. 1000 km long and 100 km wide, situated in the eastern part of the Amazonas Craton and delineated by the BIFs of Carajás Formation. The BIFs, together with volcanic layers, constitute the Grão Pará Group (Beisiegel *et al.* 1973) with age of 2.8 Ga (Gibbs *et al.* 1986). In the core of the synclinorium, this sequence is overlain by the psamo-pelitic metasediments of the Rio Fresco Formation. The granite-gneissic terrains of the Xingú Complex represent the basement of the sequence and surround the entire structure. Strips of the Rio Maria Greenstone Belt (3.2. to 2.9 Ga) with important Au mineralizations occur to the south and to the east. The whole sequence is intruded by the Velho Guilherme alkali-granites (Silva *et al.* 1974) as the Serra dos Carajás batholith (Fig.2) with 1.8 Ga (Gibbs *et al.* 1986).

The jaspilites of the Carajás Formation lay between the volcanic rocks of the lower Parauapebas and the upper Cigarra Formations.

These are composed mainly of basalt to basalt-andesite flows. The top of the Parauapebas Formation displays amygdaloidal facies (Meireles *et al.* 1984) interbedded with BIFs and basic tuffs. In the basal portion, there are rhyolite layers and fluvial facies conglomerates and sandstones, deposited during the rift phase of the basin.

The basalts present the following mineralogy: relicts of augite, chlorite, actinolite and sodic plagioclase (albite to andesine). Plagioclase grains are partially replaced by sericite, calcite and epidote. Primary augite alters to chlorite and actinolite. Accessory minerals are leucoxene, quartz, K-feldspar, sphene, ilmenite and Ti-magnetite. Chlorite, actinolite, sodic plagioclase, quartz, carbonate, epidote, leucoxene and sericite as secondary minerals indicate hydrothermal alteration. Preserved igneous features such as intergranular (subophitic), quenching and glomeroporphyritic textures are also present. Meireles *et al.* (1984) uses relative immobile and rare earth elements to characterize a shoshonitic signature for the basic rocks of the Parauapebas Formation. They are considered as being extruded on a continental crust in a convergent setting suffering spilitization with addition of H_2O , CO_2 and MgO and leaching of CaO , Al_2O_3 , P_2O_5 , TiO_2 remained relative immobile.

The Carajás Synclinorium is intersected by E-W, and N70W-S70E lineaments that represent regional faults. The most important of them is the Carajás Fault, a left-lateral brittle to ductile-brittle shear zone that strikes NW-SE and crosscuts the synclinorium dividing it in two domains (Fig. 2):

(a) A northern domain with folded, tilted and rotated Fe-deposit bodies (N1 to N9). Several N-S-trending listric splays from the Carajás fault control the position of these bodies.

(b) A southern domain which includes north dipping deposits (S1 to S45) that form the relative continuous southern limb of the synclinorium without apparent secondary block tilting or rotation.

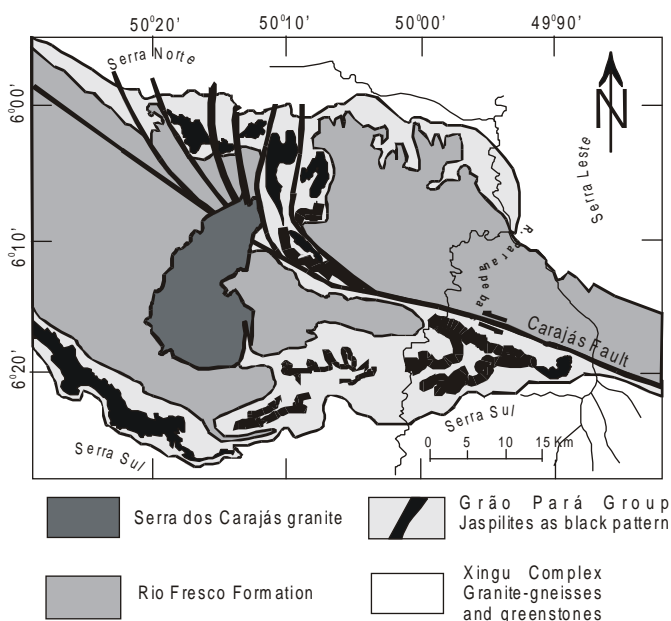


Figure 2—Geologic map of the Carajás District. Explanations in text. (modified after Rezende and Barbosa 1972).

Jaspilites of the Carajás Formation The Carajás Formation comprises a thick layer of jaspilites, lenses of hard hematite and some sills and dykes of basic rocks. Jaspilites represent the protore of the Carajás deposit, with 17.11 - 43.40 % Fe and 35.10 - 60.84 % SiO_2 (Tolbert *et al.* 1971. Beisiegel *et al.* 1973) and are characterized by irregular and discontinuous cm-thick mesobands and mm-thin microbands due to the intercalation of light and dark layers that represent primary structures. Light layers are white to pale red and composed of crypto- to microcrystalline quartz (grain size < 10 mm) with inclusions of cryptocrystalline hematite. Together with quartz are found hematite, martitized magnetite and occasionally sericite.

The dark layers are constituted of iron oxides with different fabrics. The dominant phases are fine-grained hematite (7 to 80mm diameter)

and martitized magnetite (7 to 250mm diameter) as idiomorphic blasts on the very fine matrix (Fig. 4c). Hematite is usually microcrystalline, microgranoblastic or occurs as fine plates randomly oriented. Hard iron ore (hematite hard ore) may appear as porous banded concordant lenses. Hard ore is constituted by martite with magnetite relicts and platy hematite. Some bodies may also appear oriented on brittle to brittle-ductile shear zones presenting fine to coarse-grained specularite (up to 1.5 cm long).

Jaspilites are folded, kinked and locally faulted, without the development of a pervasive schistosity. The structural inventory indicates a brittle to brittle-ductile behavior of the rocks under low temperature/shallow conditions.

Most of the mined ore in the Serra dos Carajás consists of soft jaspilites, soft hematite and some lenses of hard hematite. Soft jaspilites and hematite ores are product of progressive weathering and SiO_2 leaching that may reach a depth of 250m. (Tolbert *et al.* 1971) and represents the main source of the reserves of the district. The ore may show different degrees of contamination in Al, Mn, and P with the presence of limonite/goethite and kaolinite. Mn contamination occurs at the contact to the overlying volcanic sequence (Cigarra Formation).

THE URUCÚM BASIN The Urucúm Iron and Manganese District is located south of Corumbá, Mato Grosso do Sul State at the Brazilian-Bolivian border. The sediments of the Urucúm Basin constitute an epicontinental marine sequence beginning with the basal Jacadigo Group that comprises clastic sediments with carbonatic matrix, overlain by iron-rich arkoses and jaspilites with manganese layers (Band'Alta Formation), followed by the Corumbá Group with limestones, dolomites slates and siltites (Cerradinho Formation) overlain by dark dolomites and limestone breccia of the Araras Formation. This sequence developed in a slow sinking basin with upward gradation from clastic to chemical sedimentation without volcanic contribution. Deposition of widespread iron and manganese rich sediments is due to sharp variation in the Eh conditions most probably under the influence of marine currents in a restricted basin partially protected from atmosphere by large ice caps.

Contraposing Klein and Beukes (1989), that consider inevitable the existence of submarine volcanic-hydrothermal exhalations for the glacial iron formations (Rapitan type) Schneider (1984) uses the presence

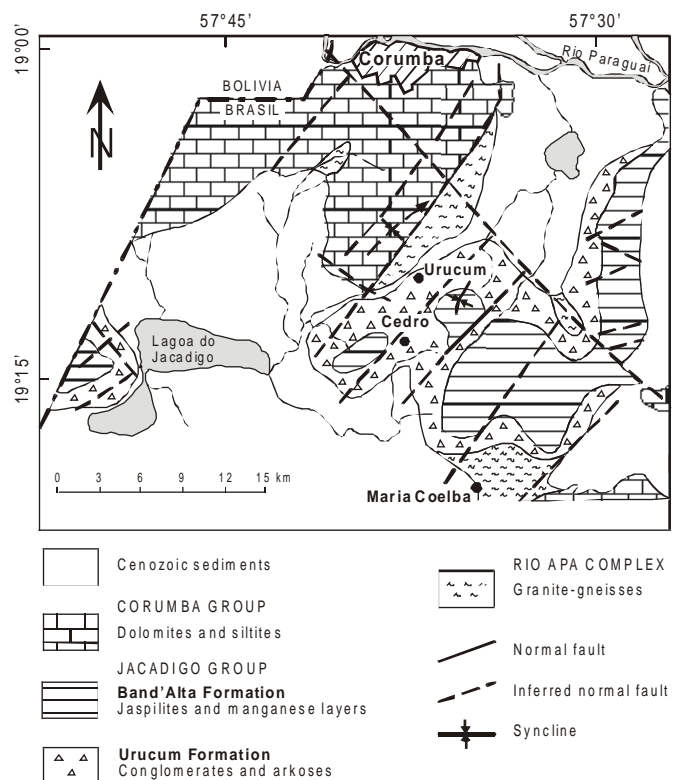


Figure 3—Geologic map of the Urucúm District. Explanations in text (after Padilha 1990).

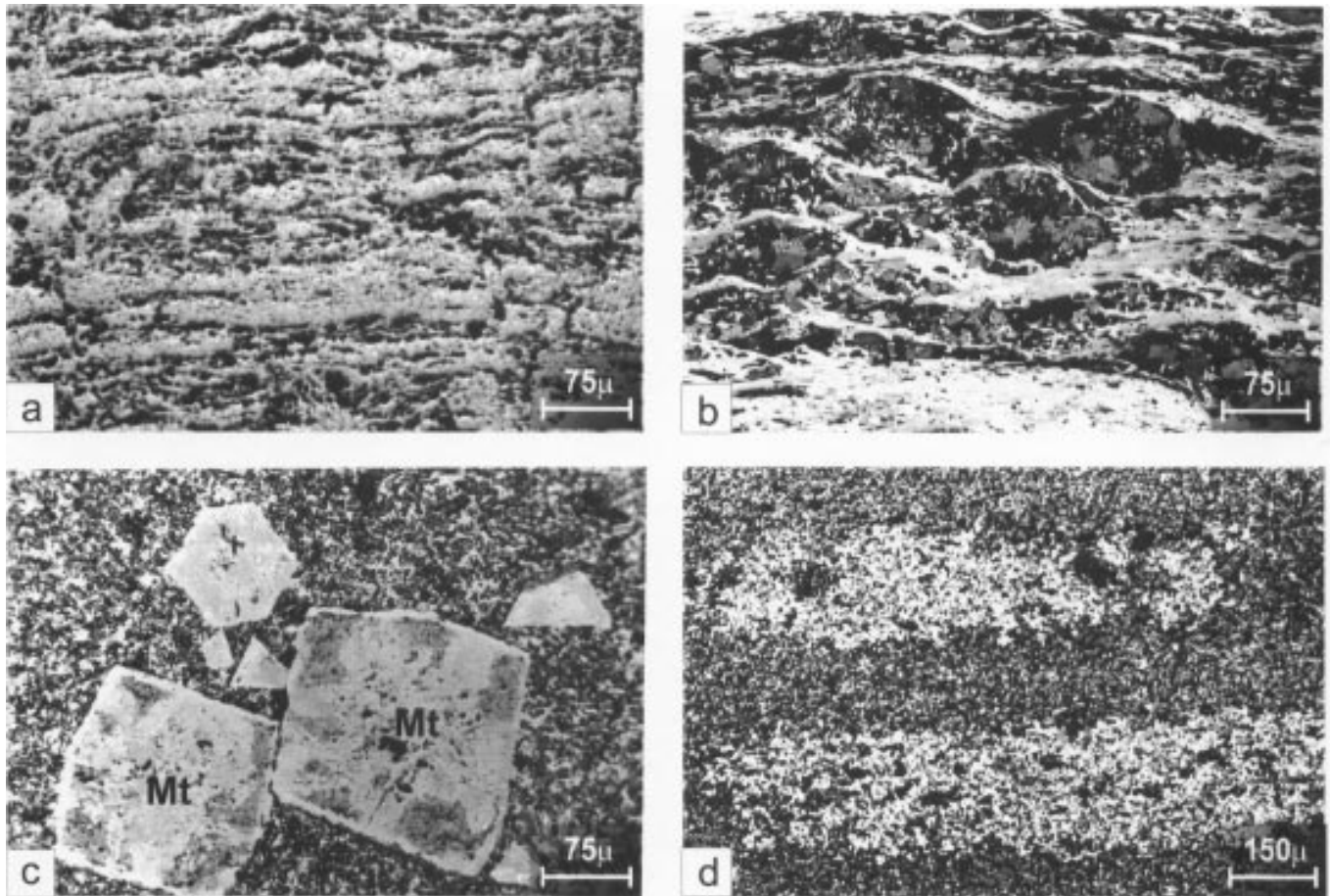


Figure 4—Photomicrographs of banded iron formations. a) Sedimentary banding in hard high-grade ore from low strain domain. Layering is defined by variation in porosity. The ore is composed of martitized magnetite and granoblastic hematite. Cauê Itabirite, Itabira Group, Casa de Pedra Mine. Reflected light, parallel polars. b) Schistose carbonatic itabirite. Platy hematite (specularite) envelopes carbonate aggregates and compose an anastomosed schistosity. Cauê Itabirite, Itabira Group, Alegria Mine. Reflected light, partially crossed polars. c) Martitized idiomorphic magnetite crystals (Mt) on a microcrystalline matrix constituted of both fine granoblastic and decussate hematite. Jaspilite of the Carajás Formation. Reflected light, parallel polars. d) Sedimentary banding in Urucúm jaspilite of the Band'Alta Formation. Layering is defined by variation in the porosity. Ore mineral is microcrystalline hematite in fine granoblastic fabric with very fine platy hematite in the interstices.

of large amounts of iron-rich detrital components and the absence of volcanic rocks as arguments to evoke the model suggested by Borchert (1952, 1964). According to this author, iron would be transported from the continent and deposited at first as solid mineral phases. Manganese and iron would be mobilized under reducing environment and precipitated in oxidized parts of the basin closer to open sea or due to melting of the ice cap. Additional fresh water increases Eh up to values high enough in order to permit Mn-precipitation.

The sediments of the Urucúm Basin are almost free of tectonic disturbances. The main macroscopic structures are straight lineaments that represent the trace of high angle joints and normal faults originated and repeatedly activated by a vertical block tectonic (Fig 3). The modern chessboard configuration seen in the geological map might represent inherited old basement faults that conditioned the original jagged morphology of the basin as postulated by Schneider (1984).

Band'Alta Formation: Urucúm jaspilites According to data published by Walde *et al.* (1981) the reserves of the Urucúm District reach about 40 billion tons of low-grade ore with average 54% Fe and 100 million tons of high grade ores with >63% Fe. The jaspilites of the Band'Alta Formation present a primary banding defined by planar layers and lenses of quartz and hematite, with variable thickness, from mm to cm. (Fig. 4d). Quartz is usually cryptocrystalline (chert) and hematite appears, similar to the Carajás jaspilites, as microcrystalline aggregates or as very fine platy crystals. Recrystallization of both hematite and quartz results in xenoblastic aggregates that occur discontinuously. Near to the contact with manganese layers hematite

may also appear intergrown with cryptomelane (Schneider 1984). Martite is also present in form of hypidiomorphic to idiomorphic crystals as individuals and aggregates. Fine clastic components are common at the base of the sequence but are also present as layers and lenses in the upper levels. Erratic blocks of glacial origin are quite frequent. The most puzzling feature is the presence of small hematite-chert ellipsoidal concretions with variable diameter (few mm to several cm), displaying a concentric structure similar to oolites. They are always aligned on the banding and own their shape to differential compaction. Thicker levels of primary high-grade ores occur in the whole sequence. In these layers, banding is less conspicuous, defined by slight variation in the proportions of quartz (chert) and hematite. Superficial leaching of the quartz leads to the development of a very high grade ore especially suitable to direct reduction plants.

DISCUSSION The itabirites of the Cauê Formation from the Quadrilátero Ferrífero (ca. 2.6-2.4 Ga) are metamorphic equivalents of jaspilites, coeval and similar to the BIF-bearing sequences in the Transvaal and Hamersley Basins (Trendall *et al.* 1990). The tectonic setting of the sedimentation is still a matter of discussion since they could have been deposited in intracratonic basins or in continental margin shelves. The depositional record fits well with the model of epicontinental sedimentation during a stable period, between two major orogenies, one Archean (2.7 to 2.8 Ga) and the other Late Paleoproterozoic (1.9–2.1 Ga). Similarly to the Australian and South-African basins, Transamazonian orogenesis (~2.10–2.0 Ga) affected the Minas Basin only 300 Ma after completion of the platform sedimentation.

Local characteristics of the sedimentary basin lead to compositional variations in BIF due to the influx of pelitic sediments, precipitation of

carbonates, development of oolitic structures, etc. In the Minas and Urucúm Basins, interlayered volcanic rocks in the BIF succession have not been recognized yet, but both in Hamersley (Trendall and Blockley 1970) and Carajás there is a close relationship between these rocks. A comparative analysis of these sequences suggests that both were associated with a volcanic source, which saturated the basin with silica and iron, but not always immediately close to the *locus* of deposition. Submarine currents would have accomplished transportation of iron further on, in the form of solution or precipitated colloids.

Metamorphism and deformation promoted quartz recrystallization, "cleaning off" hematite inclusions and enhanced or transposed sedimentary banding in dark gray (iron oxides) and white (iron free) layers sometimes accompanied by secondary (tectonic) enrichment of hematite. Deformation and metamorphism of the BIF led also to a wide variety of textures and fabrics but both itabirite and jaspilite present magnetite as an early phase, commonly relict in hematite aggregates, probably formed during diagenesis and lithification (Rosière 1981. Rosière and Chemale Jr. 1991). Magnetite appears in its kenotetrahedral variety (Kullerud *et al.* 1969) as idiomorphic to hypidiomorphic crystals with variable dimensions up to 3 mm of diameter, or as irregular and massive aggregates. It is usually partially or totally martitized. Oxidation to martite occurred at the onset of metamorphism or due to hydrothermal alteration. Progressive martitization, inversion to hematite and recrystallization resulted in xenoblastic to hypidioblastic hematite crystals. Syntectonic hematite grows as platy specularite that developed pervasively under ductile

conditions defining the regional schistosity or locally in shear zones (Rosière *et al.* 1999). While the presence of specularite is widespread in the Quadrilátero Ferrífero, it is only locally present in the Carajás jaspilites and very rare in the Band' Alta iron formation. This illustrates the direct relationship between the presence of specularite and deformation.

Comparison among the features of all iron ore provinces indicates that there is no simple model for the formation of high-grade ore deposits. The presence of lenticular, concordant hard hematite/magnetite lenses both in jaspilite and itabirite indicates a sedimentary origin. On the other hand, discordant, mostly specularite bodies are clearly product of syntectonic, secondary enrichment with weathering having played also a major role in the formation of large bodies of friable ore by leaching SiO₂ and carbonates. Most likely, the summation of processes is responsible for at least some of the remarkable giant high-grade deposits exploited not only in Brazil but also in all iron provinces in the world.

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