New ore types from the cauê banded iron formation, quadrilátero ferrífero, minas gerais, Brazil - Responses to the growing demand

Article · January 2011

Fernando Alkmim
Universidade Federal de Ouro Preto

New Ore Types from the Cauê Banded Iron-Formation, Quadrilátero Ferrífero, Minas Gerais, Brazil – Responses to the Growing Demand

L Q Amorim[1] and F F Alkmim[2]

ABSTRACT

The mining district of the Quadrilátero Ferrífero (QF) in southeastern Brazil contributes to 70 per cent of the Brazilian iron ore production, which reached 370 Mt in 2010. Traditionally, four iron ore types were mined in the QF region:

1. soft haematite,
2. hard haematite,
3. friable 'itabirite' (the Brazilian name for metamorphosed banded iron-formation), and
4. canga (an indurated iron-rich crust).

With the exception of the hard haematite, these categories derive from supergene enrichment of the Paleoproterozoic Cauê Itabirite. High current iron ore demand means that the QF high grade supergene ores will be depleted in a few decades. Consequently, several mining projects are being developed to exploit unenriched, fresh itabirite. Among them, the Mineração Usiminas Serra Azul project in northwestern QF is one of the most advanced. Four major itabirite types occur in the QF region:

1. siliceous (or standard),
2. dolomitic,
3. amphibolitic, and
4. magnetitic.

The dominant type in Serra Azul region is a fresh siliceous itabirite, composed essentially of haematite, martite and quartz that averages 36 per cent Fe (51.5 per cent Fe_2O_3) and 47 per cent SiO_2. The second type, the magnetitic itabirite, consisting of magnetite, martite, grunerite-cummingtonite, quartz, dolomite, stilpnomelane, and subordinate haematite, is typically a strongly magnetic greenish banded iron-formation with the iron grade varying between 25 and 35 per cent. Chemically, it differs from the siliceous itabirite due to the relatively high CaO, MgO and, consequently, high LOI contents. Together with supergene ores, fresh itabirites have been included in the ore reserves of the Serra Azul project. We anticipate that all the four types of fresh itabirite will be incorporated as ore in the QF region, causing a huge increase on the iron ore resources of the district, and representing enormous environmental and technological challenges for the local iron ore industry.

INTRODUCTION

Famous for its gold and high grade iron ores, the mining district of the southeastern Brazilian highlands known as Quadrilátero Ferrífero (QF) or Iron Quadrangle (Dorr, 1969) extends over an area of around 7500 km^2, highlighted by ridges of Paleoproterozoic banded iron-formation (Figure 1).

Large scale iron ore production started in the QF after the World War II in the mid-1950s and has experienced a continuous growth ever since. The QF mining industry is today responsible for ca 70 per cent of the Brazilian and ca ten per cent of world iron ore production.

The iron ores so far exploited in the QF were in general of higher grade (>55 per cent Fe) and, except for one category, the so-called hard haematite, derived from supergene enrichment of itabirites of the Paleoproterozoic Cauê Formation (Eichler, 1968; Dorr, 1964, 1965, 1969; Melfi *et al*, 1976; Ramanaidou *et al*, 1996; Spier, Oliveira and Rosière, 2003, 2007; Rosière *et al*, 2008; Ramanaidou and Morris, 2010). Fresh, unenriched itabirite, viewed as protore, was never incorporated in the beneficiation plants. However, the high current demand and consequent depletion of soft ores will cause a fast increment of

1. Superintendent of Geology, Mine Planning and Environment, Mineração Usiminas Ltda, Rua Professor José Vieira de Mendonça, 3011, bairro Engenho Nogueira, Belo Horizonte, Minas Gerais, CEP 31310-260 Brazil. Email: leandro.amorim@usiminas.com

2. Professor, Escola de Minas, Universidade Federal de Ouro Preto, Departamento de Geologia, Morro do Cruzeiro, Ouro Preto Minas Gerais 35.400-000, Brazil. Email: ffalkmim@gmail.com

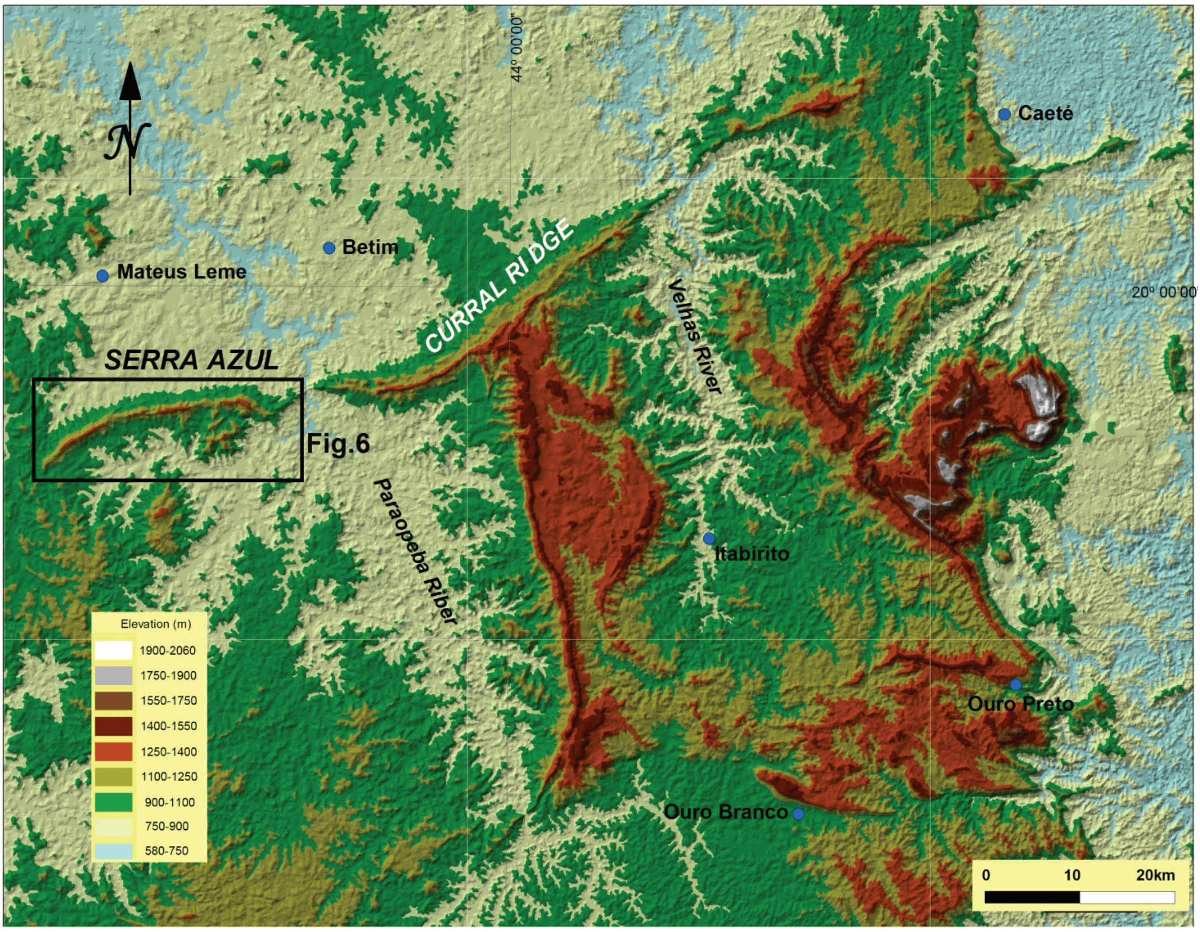

FIG 1 - Digital topography model of the QF region showing the locations of the Curral Ridge and Serra Azul.

iron ore production from fresh itabirite, which represents the new trend in the QF mining industry.

Since fresh BIF was so far considered to be waste in the QF region, the unweathered section of the Cauê Formation was not drilled and investigated on a routine basis in the exploration programs carried out in the QF. As a first in the region, Mineração Usiminas performed a comprehensive exploration program for hard itabirites in the locality named 'Serra Azul ', western QF (Figure 1), which included 67 km of drilling distributed in 542 boreholes. The new data obtained in this program forms the base for the descriptions and discussions presented in this paper.

THE GROWING DEMAND ON IRON ORES

The trend of the world's iron ore demand through time can be easiest visualised using crude steel production curves. Figure 2 shows the total crude steel production of the world in the last 100 years, plotted together with the sum of blast furnace iron (BFI) and directly reduced iron (DRI) productions. This sum represents the amount of steel produced from iron ore and the difference between the two curves corresponds to the amount of steel derived from scrap (Figure 2).

At first glance, the curves of Figure 2 record only the historical steel production growth based on iron ore consumption. This general tendency includes two major production increments, separated by a period relatively stability between the mid-1970s and the mid-1990s of the last century. A more careful examination of the plots reveals, however, that major events affecting the world in the last 100 years are reproduced by the curves. Critical periods – the 1929 crash, the World War II in the mid-1940s, the first and second oil

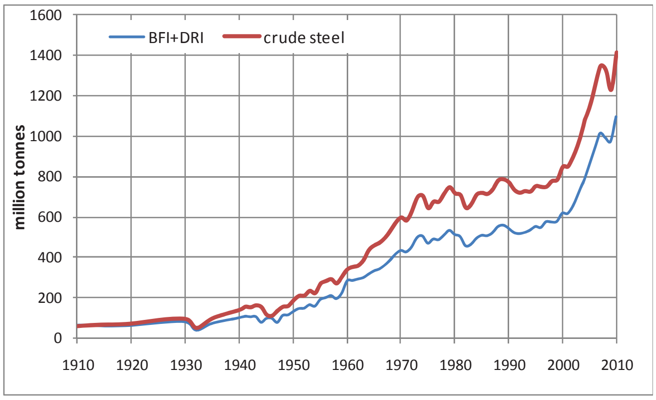

FIG 2 - World crude steel production in the last 100 years (data source: International Iron and Steel Institute – IISI; http://www.worldsteel.org).

crisis, respectively in the mid-1970s and 1980s, the end of the USRR in the beginning of the 1990s, as well as the very recent 2008 economic crisis – are represented by lows followed by recoveries in the years after.

In the aftermath of the World War II, the steel production experienced an enormous growth, rising from 200 Mt in 1950 to 600 Mt in 1970. This increment was a consequence of several developments, but mainly of the further industrialisation of the first world countries, the cold war, and reconstruction of Europe and Japan. In the following three decades, from 1970 - 2000, the steel production underwent only a vegetative growth, going from 600 - 800 Mt/a. Without any other historic equivalent, the second largest steel production increment, starting in the first decade or the 21st century and reaching the present day, represents the economic booming of China. The world steel production reached 1.4 Bt in 2010, a level that corresponds to the extraordinary increase of 600 Mt/a in ten years. From the 1.4 Bt of crude steel produced in 2010, around 1.1 Bt correspond to BFI plus DRI, which caused a consumption of 1.7 Bt of iron ore in one single year.

Brazilian iron ore production continuously increased after the mid-1950s, reaching 52 Mt in 1973 and the peak of 94 Mt in 1976 (Figure 3). Several iron ore projects were implemented in Brazil in the late 1960s and early 1970s, leading to a production of almost to 100 Mt in the mid-1980s (Figure 3). All of these projects were developed in the Quadrilátero Ferrífero, the only significant source of iron ore in Brazil until 1986, when Carajás, the second largest mining district of the country, start also to produce iron ores. During the 25 years period of the mid-1970s to the year 2000, the Brazilian iron ore production rose from near 100 Mt/a to approximately 200 Mt/a (150 Mt/a from the QF and 50 Mt/a from Carajás). From 2001 to 2008, the annual production of the QF grew from 150 Mt to 250 Mt. The production of other regions in the country (mostly from Carajás, northern Brazil) increased from 50 - 100 Mt/a,

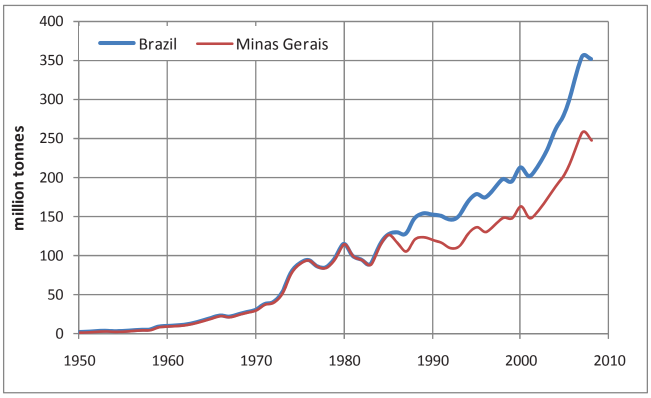

FIG 3 - Brazilian iron ore production 1950 - 2008 (data source: National Department of Mineral Production – DNPM; http://www.dnpm.gov.br/year).

leading a national production of 351 Mt in 2008 (Figure 3) as reported by the Brazilian National Department of Mineral Production (DNPM). According to United States Geological Survey statistics, the 2010 Brazilian iron ore production was 370 Mt.

The first iron ore concentration plant of Brazil was set in the town of Itabira, Minas Gerais (QF), in 1973. Up to that time, only high grade iron ores were exploited in the QF. Immediately after, the Brazilian iron ore industry underwent significant changes with the introduction of several other concentration plants, and the consequent incorporation of new iron types such as soft enriched BIF. Due to the enormous rise of the production in the last years, even the soft and rich BIF resources will be depleted in the QF in a few decades. Thus, as a response to present level of demand, new ore types, this time represented by former protores, ie fresh and hard itabirites, are to be introduced in the production system of the QF. The incorporation of these new ore types will result in an extraordinary increase of the QF iron ore resources, but also in new beneficiation process and considerable smaller mass recovery, implying in larger tailings dams, larger pits and consequently greater environmental impacts.

THE QUADRILÁTERO FERRÍFERO AND ITS IRON ORES

Geological setting of the Quadrilátero Ferrífero

Geologically, the Quadrilátero Ferrífero is located in the southeast border of the São Francisco Craton, an Archean/Paleoproterozoic stable block, surrounded by Neoproterozoic orogenic belts (Almeida, 1977; Alkmim and Marshak, 1998). The district is underlain by five major lithostratigraphic units:

1. the Archean basement,
2. the Archean Rio das Velhas Supergroup,
3. the Paleoproterozoic Minas Supergroup,
4. the Itacolomi Group, and
5. mafic intrusive (Figure 4).

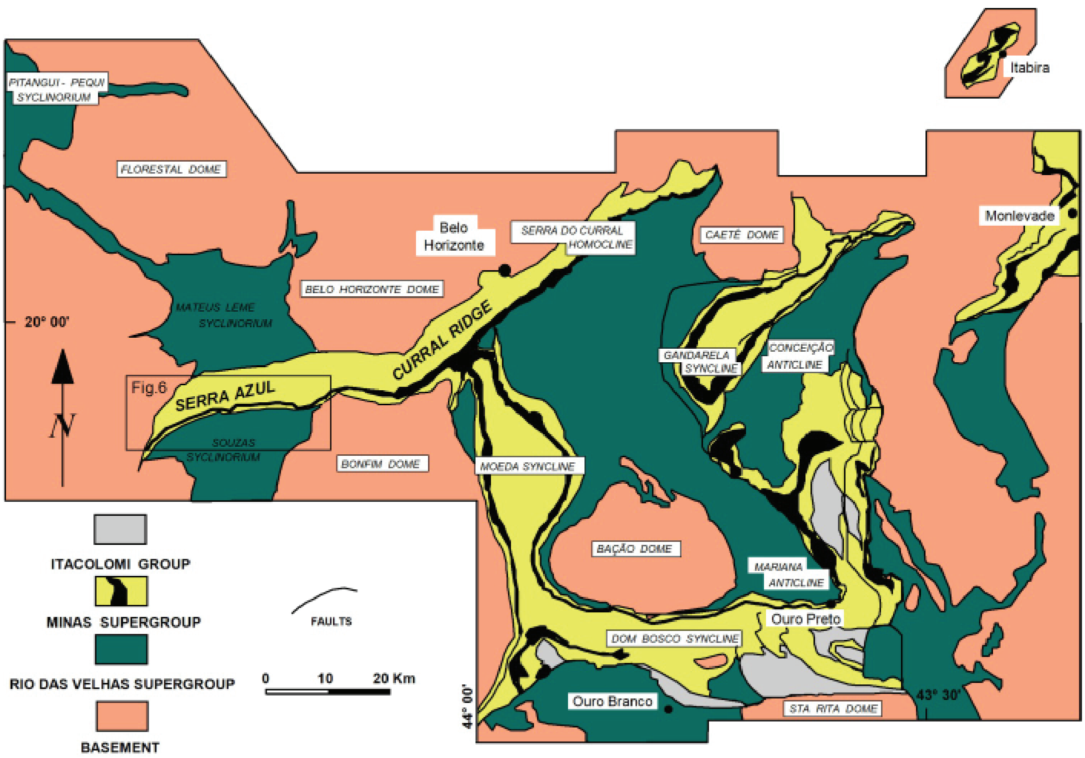

FIG 4 - Simplified geologic map of the QF, emphasising the distribution of the main lithostratigraphic units and structures (Based on Dorr, 1969; Romano, 1989).

The Archean basement is made up of 3.2 - 2.9 Ga old gneiss complexes and two generations of Late Archean granitoids (Machado *et al*, 1992; Carneiro, Teixeira and Machado, 1994; Noce, 1995). The 2.78 - 2.61 Ga old Rio das Velhas Supergroup, a classical greenstone belt succession, comprises a volcano-sedimentary package, mainly composed of komatiite, basalt and ryolitic lavas, intercalated and overlain by sedimentary units, including carbonate facies banded iron-formations (Dorr, 1969; Machado *et al*, 1992; Zucchetti, Baltazar and Raposo, 1998; Noce *et al*, 2005).

The Minas Supergroup, accumulated in a passive to convergent margin setting between 2.6 - 2.0 Ga, records the operation of a full Wilson cycle on the southern edge of the São Francisco craton (Alkmim and Marshak, 1998). Separated from the Rio das Velhas greenstone belt by a pronounced unconformity, the basal Caraça Group consists of alluvial conglomerates and sandstones that grade upwards into shallow marine pelites. Caraça sediments are overlain by the transgressive Itabira Group that contains the Cauê Banded Iron Formation, the marker bed of the QF that hosts all of its iron ore resources. The Cauê Formation grades upward into the shallow water carbonates of the Gandarela Formation, which is in turn overlain by a thick transgressive succession of sandstones and pelites of the Piracicaba Group. The youngest unit of the Minas Supergroup, the Sabará Group, made up of turbiditic conglomerates, sandstones and pelites, records the conversion of the Minas passive margin into a syn-orogenic (flysch) basin at ca 2.1 Ga (Dorr, 1969; Machado *et al*, 1996; Renger *et al*, 1995; Hartmann *et al,* 2006).

Probably representing an intermontane molassa, the quartzites and conglomerates of the Itacolomi Group unconformably overlie Minas Supergroup strata in the southern QF (Dorr, 1969) (Figure 4). Intrusions cutting the previous units include mainly mafic dykes, which dominantly trend N-S to NW-SE. One of these dykes was dated at 1.714 Ma (Silva *et al*, 1995).

The regional geologic map pattern of the QF defines a dome-and-keel architecture, in which the Archean basement occurs in form of domes surrounded by 'keels ' containing the metasedimentary units. Keels include first-order synclines, such as the Moeda and Dom Bosco synclines, as well as the large Serra do Curral homocline (Marshak *et al*, 1992; Alkmim and Marshak, 1998) (Figure 4). Rocks of the supracrustal sequence adjacent to the domes contain a distinct high-T/low-P metamorphic aureole (Herz, 1978; Jordt-Evangelista, Alkmim and Marshak, 1992; Marshak *et al*, 1992).

The rocks of the Rio das Velhas Supergroup have been strongly deformed prior to the deposition of the Minas Supergroup (Dorr, 1969). Furthermore, two sets of pronounced post-Minas structures that apparently do not show any relationship with the dominant dome-and-keel structure can be recognised in the region. One set trends NE-SW and comprises the Gandarela syncline, the Serra do Curral homocline, as well as the synclinoria of the Itabira and Monlevade regions (Figure 4). The second set includes a series of west-verging thrusts, which are particularly well developed in the eastern QF (Dorr, 1969; Chemale Jr, Rosière and Endo, 1994; Chauvet *et al*, 1994; Alkmim and Marshak, 1998).

Second-order mesoscopic folds associated to penetrative tectonic fabrics (ie schistosity, mylonitic foliation, stretching lineation) also occur throughout the region. The stretching lineation and the mesoscopic fold hinges plunge preferentially towards S80°E with 30° (Dorr, 1969; Chemale Jr, Rosière and Endo, 1994; Chauvet *et al*, 1994; Alkmim and Marshak, 1998).

A regional, syn-kinematic metamorphism affecting all units exposed in the QF region varies from lower greenschist to the west to upper amphibolite facies to the east (Dorr, 1969; Herz, 1978; Pires, 1995).

The Cauê banded iron-formation and associated ores

The Cauê Formation is composed of a variety of metamorphosed BIF currently referred to as 'itabirite', iron ores, and subordinated dolomites (Dorr, 1969; Pires, 1979; Pires, Aranha and Cabral, 2005; Rosière and Chemale Jr, 2006, Rosière *et al*, 2008; Spier, Oliveira and Rosière, 2003, Spier *et al*, 2007). The name itabirite (Eschwege, 1833) is used to designate:

> *...a laminated, metamorphosed oxide-facies iron formation in which the original chert or jasper bands have been recrystallised into granular quartz and the iron is present as haematite, magnetite or martite...* (Dorr, 1964).

According to their mineralogical composition, the QF itabirites, as fresh rock, are classified into four main types:

1. siliceous (or standard);
2. dolomitic;
3. amphibolitic; and
4. magnetitic itabirite (Dorr, 1969; Pires, Aranha and Cabral, 2005; Rosière and Chemale Jr, 2006; Rosière *et al*, 2008, Spier *et al*, 2007).

Their chemical and mineralogical compositions are presented on Table 1. The standard itabirite is the dominant type in the QF. The other types occur as beds or lenses within the Cauê Formation. Dolomitic itabirites are more frequent in the western part of the QF, whilst the amphibolitic itabirites are more common in the eastern part of the district. Magnetitic itabirites normally occur as a deeply weathered, ochreous, goethitic iron formation ('yellow magnetitic iron formation' according to Pires (1979). Fresh magnetitic itabirite, as recently found in the western portion of the QF, is a green banded iron-formation, containing magnetite, martite, grunerite-cummingtonite, quartz, dolomite, stilpnomelane, and subordinate haematite (Alkmim, 2009). According to Pires, Aranha and Cabral (2005), chemical composition and observed macroscopic structures point towards a volcanic origin for the magnetitic itabirite. The presence of stilpnomelane in this type of itabirite is indeed an indicator for contamination with volcanic material (eg Pickard, 2002, 2003).

The maximum original thickness of the Cauê Formation is estimated to be 350 m (Dorr, 1964). However, as emphasised by this author, due to the plastic behaviour of Cauê BIF in the deformation processes affecting the QF region, the final thickness of the unit exceeds 1500 m in many places.

The metamorphic conditions experienced by the Cauê Formation can be expressed by temperatures obtained in oxygen isotope studies. The metamorphic temperatures show a general increase from west to east, varying from a minimum of 394°C in the Moeda syncline to a maximum of 780°C in the Itabira synclinorium (Müller, Schuster and Hoefs, 1982) (Figure 4). These values are in agreement with the metamorphic facies zoning of the QF, as described by Herz (1978) and Pires (1995).

No direct age determinations are available for the Cauê Formation. Babinski, Chemale and Van Schmus (1995) obtained a Pb-Pb age of 2.42 Ga for the basal limestones of the overlaying Gandarela Formation. Considering that the maximum depositional age of the basal quartzites of the Minas Supergroup is 2.58 Ga (Hartmann *et al*, 2006), the accumulation of the Cauê BIF must be occurred between

TABLE 1

Chemical and mineralogical characteristics of the fresh itabirites.

		Siliceous itabirite		Dolomitic itabirite		Amphibolitic itabirite		Magnetitic itabirite	
		Major components	Accessories	Major components	Accessories	Major components	Accessories	Major components	Accessories
Mineralogy	Dark bands	haematite, martite	mt, se, qz, py, mnox	haematite, martite	mt, qz, dl, mnox	hornblend, grunerite	hm, ma, mt, qz, dl, af	magnetite, haematite, martite, grunerite	hm, ma, qz, af, ca, cl, bi, sp, tc
	Light bands	quartz	hm, ma, cl, se, dl, py, mnox	dolomite	hm, ma, qz, py, tc, mnox	tremolite, actinolite	hm, ma, mt, qz, dl	quartz, carbonate	mt, hm, ma, qz, af, ca, cl, bi, sp, tc
Typical chemical composition	Fe	30 - 40%		35%		35%		25 - 35%	
	SiO_2	40 - 60%		<1%		45%		35 - 55%	
	CaO	<0.1%		15%		<1%		2 - 10%	
	MgO	<0.1%		10%		<1%		2 - 10%	
	LOI	1 - 2%		>5%		1 - 2%		>5%	

af = amphibole, cl = chlorite, dl = dolomite, hm = haematite, mt = magnetite, ma = martite, Mnox = manganese oxide, py = pyrophyllite, qz = quartz, se = sericite, tc = talc, ca = carbonate, sp = stilpnomelane, bi = biotite.

2.58 and 2.42 Ga, a time interval that encompasses most of the Paleoproterozoic BIF deposition ages (Gole and Klein, 1981; Trendall, 2002).

The iron ores so far exploited in the QF belong to two genetic classes: hypogene and supergene. The first category, also referred to as hard or compact haematite, comprise very rich (Fe >66 per cent), massive, banded or foliated haematitic orebodies. Exhibiting linear or less frequent tabular shapes, the haematite bodies can vary from less than five to more than 50 Mt. Their origin is matter of a long standing debate among various authors (for discussion see Guild, 1953; Dorr 1965, 1969; Varajão *et al*, 1997; Rosière and Chemale Jr, 2006; Hagemann *et al*, 2006; Rosière *et al*, 2008; Rosière and Rios, 2004; Clout and Simonson, 2005). After the beneficiation, the hard ores produce a high proportion of lumps (more than 50 per cent), making it a quite valuable material.

The QF ores generated by supergene processes include soft haematite, enriched itabirites, and laterite crusts. Morphotectonic processes acting upon the QF region probably at the beginning of the Paleocene (Spier, Vasconcelos and Oliveira, 2006) created conditions for vertical and lateral water circulation within the Cauê Formation layers, causing the leaching of silica and dolomite from the itabirites and thus forming supergene ores (Dorr, 1964, 1965; Eichler, 1968; Melfi *et al*, 1976; Ramanaidou *et al*, 1996; Spier *et al*, 2003). This process generated bodies of almost pure soft haematite (Fe ≥ 64 per cent) and an enormous volume friable itabirites.

Two subtypes of laterite crusts, known as 'canga' in Brazil, occur in the QF region:

1. the *in situ;* and
2. the detrital canga (Dorr, 1969).

The *in situ* or structural canga occurs in form of up to 30 m hard caps on top of the Cauê itabirites and associated orebodies (Dorr, 1965, Ramanaidou *et al*, 1996, Ramanaidou and Morris, 2010), especially in high elevations (1200 m to 1600 m above the sea level) (Varajão, 1994). Covering the Cauê Formation and adjacent units along hill slopes and small basins, the detrital canga corresponds to breccias or less frequent to conglomerates containing hard haematite and BIF clasts. Usually associated with high alumina (four per cent Al_2O_3 or more) and phosphorous (0.12 per cent P or more), both types of canga are iron rich (usually Fe >50 per cent) and contain, besides haematite, goethite, and limonite (Dorr, 1969, Melfi *et al*, 1976; Varajão, 1994, Ramanaidou, 2009).

Due to the depletion of most of the high grade deposits, many projects considering the exploitation of the unenriched hard itabirites (former protores) are already launched in the QF, among them the Serra Azul project discussed in the next section. The new category of fresh rock ores (Figure 5) includes all types of previously mentioned itabirites that average around 36 per cent iron (approximately 50 per cent Fe_2O_3). In order to produce pellet feed fines, their main use, the fresh rock ores must be grinded before concentration.

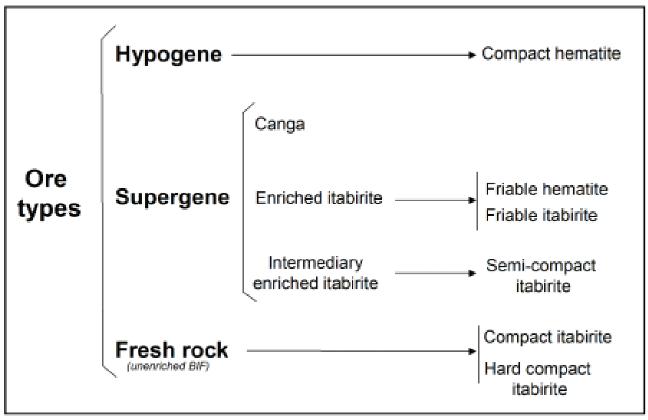

FIG 5 - Genetic classification of the Serra Azul iron ores, including the new category of fresh rock ores (unenriched BIF) (modified from Dorr, 1964).

THE SERRA AZUL PROJECT

Geologic outline of the Serra Azul

The Mineração Usiminas mineral claims are located along the western segment of Curral ridge, locally referred to as the Serra Azul (literally Blue Ridge) (Figures 3 and 6). The Serra Azul, extending for ca 30 km in the NE-SW, is underlain by a continuous outcrop belt of the Cauê Formation, which hosts several iron ore deposits (Simmons, 1968; Romano, 1989; Romano *et al*, 1991; Alkmim, 2009), including the Western, Central and Eastern mines, as well as the Camargos and Pau de Vinho deposits of the Mineração Usiminas (Figure 6). As part of the Curral ridge, the Serra Azul is the morphologic expression of an overturned, SE-dipping homocline that involves Rio das Velhas and Minas strata (Dorr, 1969). Along the Serra Azul, the basal units of the Minas supergroup are very thin and Gandarela Dolomite is absent for over almost its whole length (Simmons, 1968; Alkmim, 2009) (Figure 6).

The Serra Azul overturned homocline can be subdivided into three structural domains (Alkmim 2009) (Figure 6). Along the structural domain I, which encompasses the Western Mine and the major part of the Central Mine, the thickness of the overturned Cauê Iron Formation increases from west to east, varying from around 50 m, at the western end of the ridge, to 250 m at the Central Mine. The dips also increase from west to east, being 20° at Ponta da Serra and reaching 45° at Central Mine (Figures 6, 7 and 8). Standard itabirites and their weathering products are the more abundant ore types in this domain. The amount of fresh magnetitic itabirite is negligible. However, its weathering product, a magnetite-rich, ochreous itabirite occurs as a continuous layer on top (stratigraphic base) of the iron formation, especially in the Western Mine. A small lens of hard haematite was identified near to the base (stratigraphic top) of the Cauê Formation in the Western Mine (Figure 7).

The ca 15 km long domain II (Figure 6) encompasses the central portion of Serra Azul, including the Camargos deposit. Minas Supergroup strata strike ENE-WSW and dip 40° to 80° to SSE. NW-verging folds and faults give rise to local structural complexities. Magnetitic itabirites occur in form of layers or lenses intercalated with siliceous itabirite, which in turn grades laterally into dolomites. A clay-rich, deeply weathered itabirite (called by the miners AIF, for '*argillaceous iron formation*') is quite frequent close to the contact with the Cercadinho Formation, the basal unit of the Piracicaba Group (Figure 9).

Along the structural domain III, which hosts the Pau de Vinho deposit (Figure 6), layers of the Minas Supergroup describe a large curve with the concave side facing north. On the easternmost sector of the curve, the strata dip NW, a change probably caused by the uplift of the adjacent the Bação Dome (Figure 6). NW-trending sinistral to reverse-sinistral shear zones cut the homocline along its whole length. One of the largest sinistral faults runs along the border of a large dyke (~300 m wide) of gabbro that divided the domain (as well as the Pau de Vinho deposit) in two sectors (Figure 6). To the southwest of the dyke, layers of NW-striking fresh itabirites predominate along the ca 500 m-thick Cauê Formation. To southeast of the dyke, the Cauê Formation consists of a sequence of magnetitic itabirite, dolomite, friable ore and *argillaceous iron formation* (AIF) (Figures 6 and 10).

Serra Azul iron ores

During the Serra Azul exploration program, two basic criteria were used to classify the iron ores:

1. the iron grade; and
2. the 'W1' parameter, which represents the mass percentage above 6.35 mm after crushing the sample in 31.5 mm.

According to the second variable, the itabirite (or haematite) is classified as:

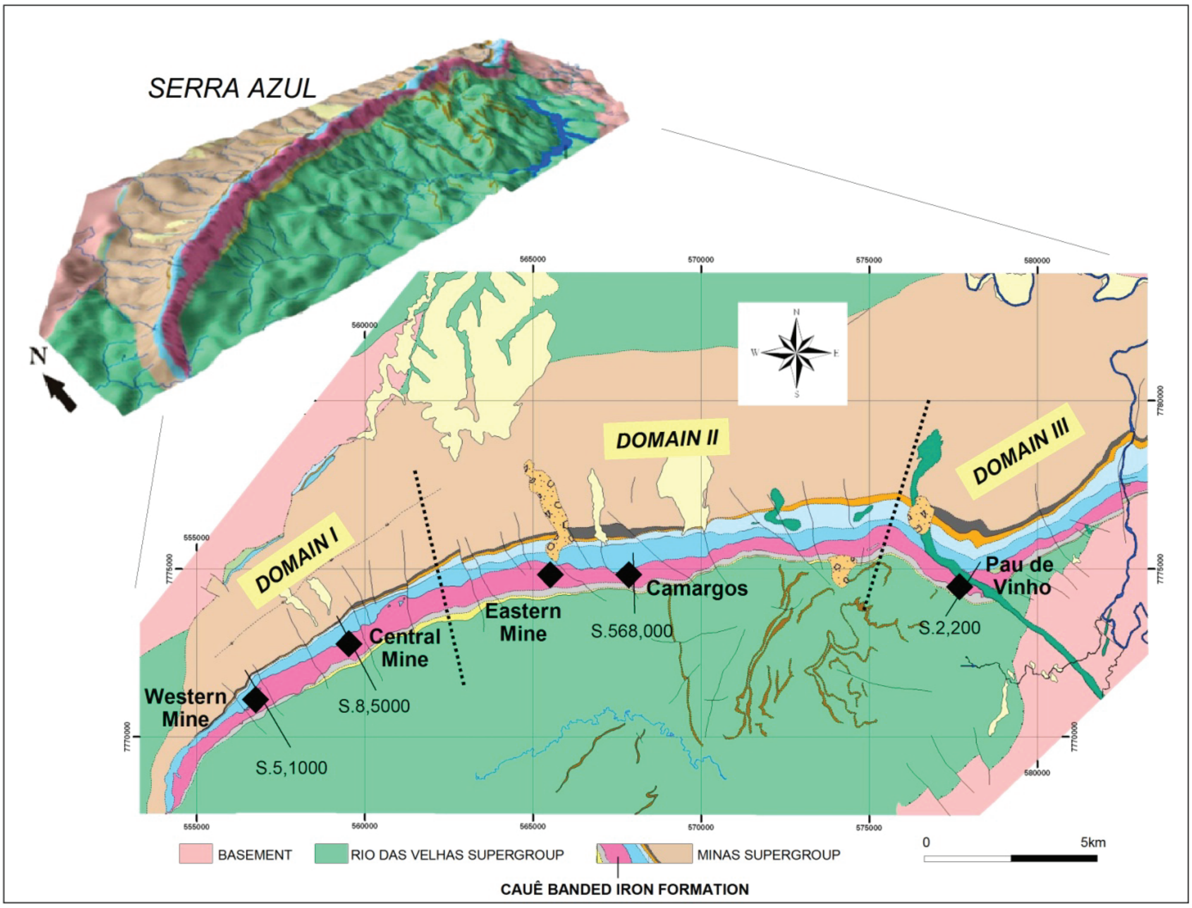

FIG 6 - Digital terrain model and geologic map of the Serra Azul region (based on Simmons, 1968; Romano, 1989; Alkmim, 2009).

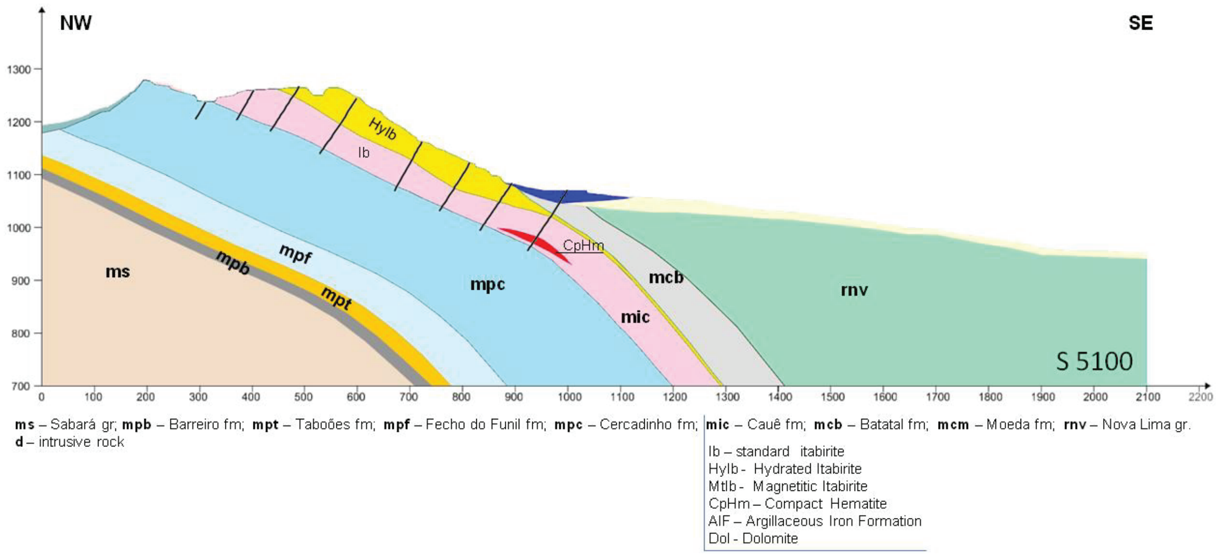

FIG 7 - Cross section 5100 – Western Mine (for location see Figure 6).

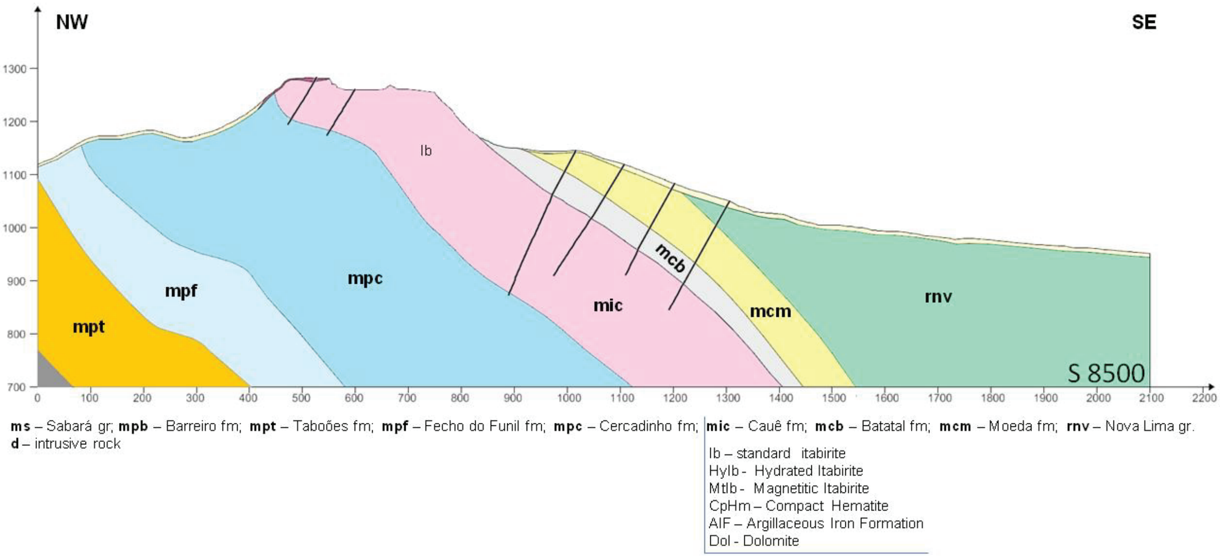

FIG 8 - Cross section 8500 – Central Mine (for location see Figure 6).

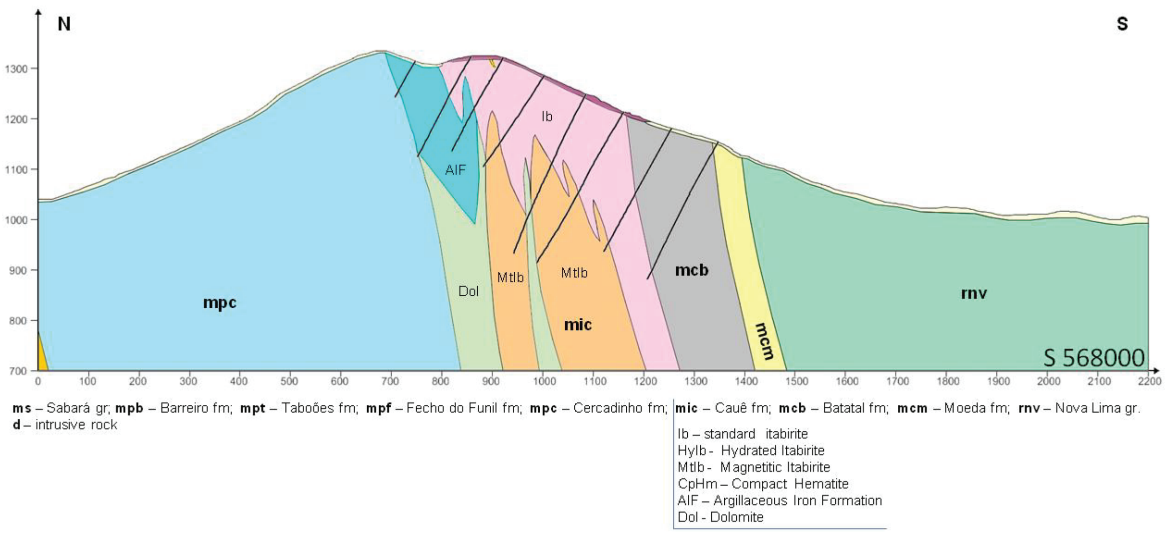

FIG 9 - Cross section 568 000 – Camargos Deposit (for location see Figure 6).

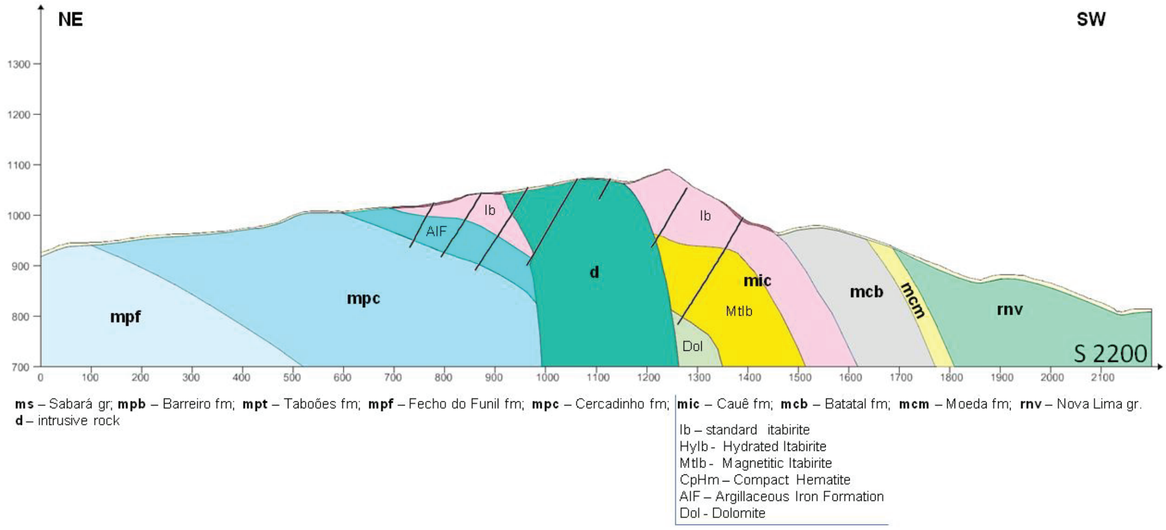

FIG 10 - Cross section 2200 – Pau de Vinho Deposit (for location see Figure 6).

- 'friable', for W1 minor or equal to 30 per cent;
- 'semi-compact' for W1 between 30 per cent and 55 per cent;
- 'compact' for W1 between 55 and 70 per cent; and
- 'hard compact' for W1 greater that 70 per cent.

According to these criteria, three major iron ore types have been discriminated in Serra Azul mineral claims:

1. haematite and standard itabirite,
2. magnetitic itabirite, and
3. argillaceous iron formation (AIF).

Haematites and standard itabirites

The iron grades and W1 values for 6385 itabirite and haematite core samples from Serra Azul are shown on the diagrams of Figure 11, which indicate a clear dominance of compact and hard compact ores in respect to other ore types. As consequence of the supergene enrichment process, the softer the material, the richer it is in average. Histograms of the iron grade for the different ore types as well as their statistics are shown on Figure 12 and Table 2. Under increasing degrees of weathering, the ore changes from hard compact, to compact, to semi-compact, and finally to friable. Accordingly, the iron grade increases and the ores become progressively heterogeneous.

The iron grade of hard compact itabirite (fresh itabirite) from Serra Azul typically varies between 30 and 40 per cent, averaging 36 per cent, which corresponds to a haematite/

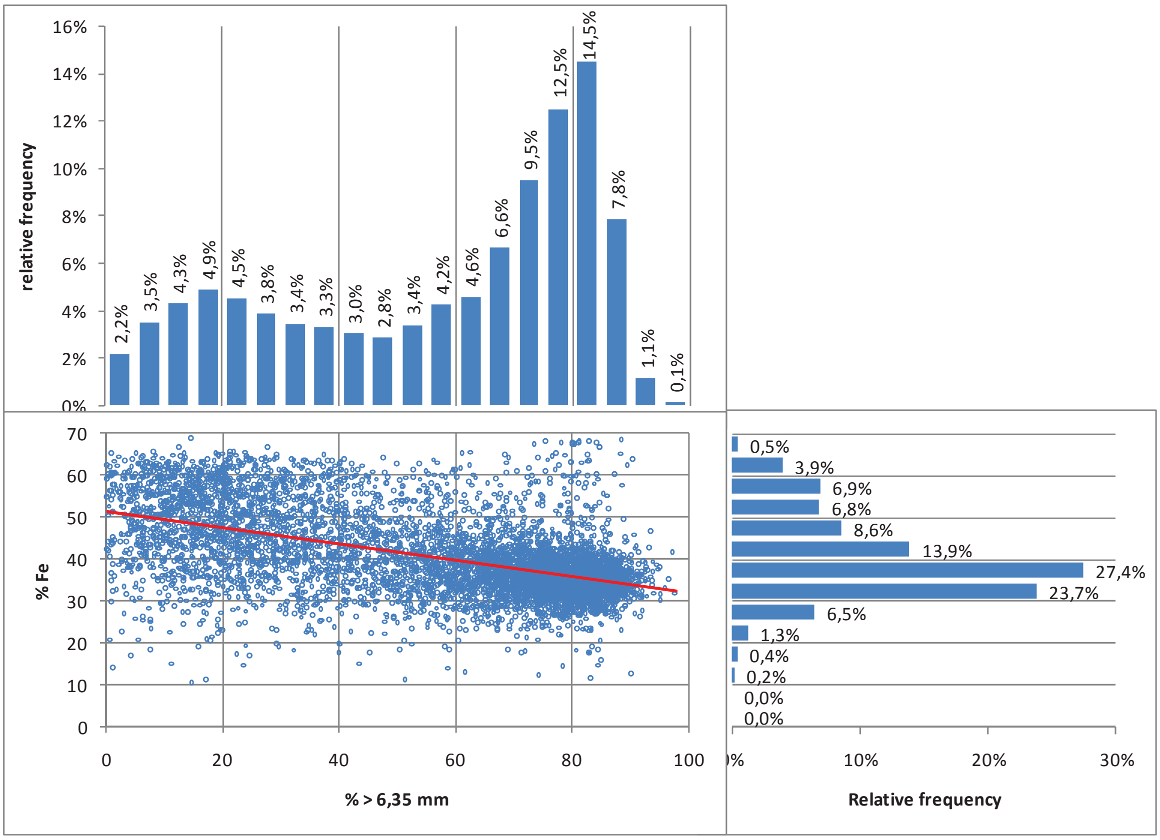

FIG 11 - Distribution of W1 and iron grade of the siliceous (standard) itabirites and haematites.

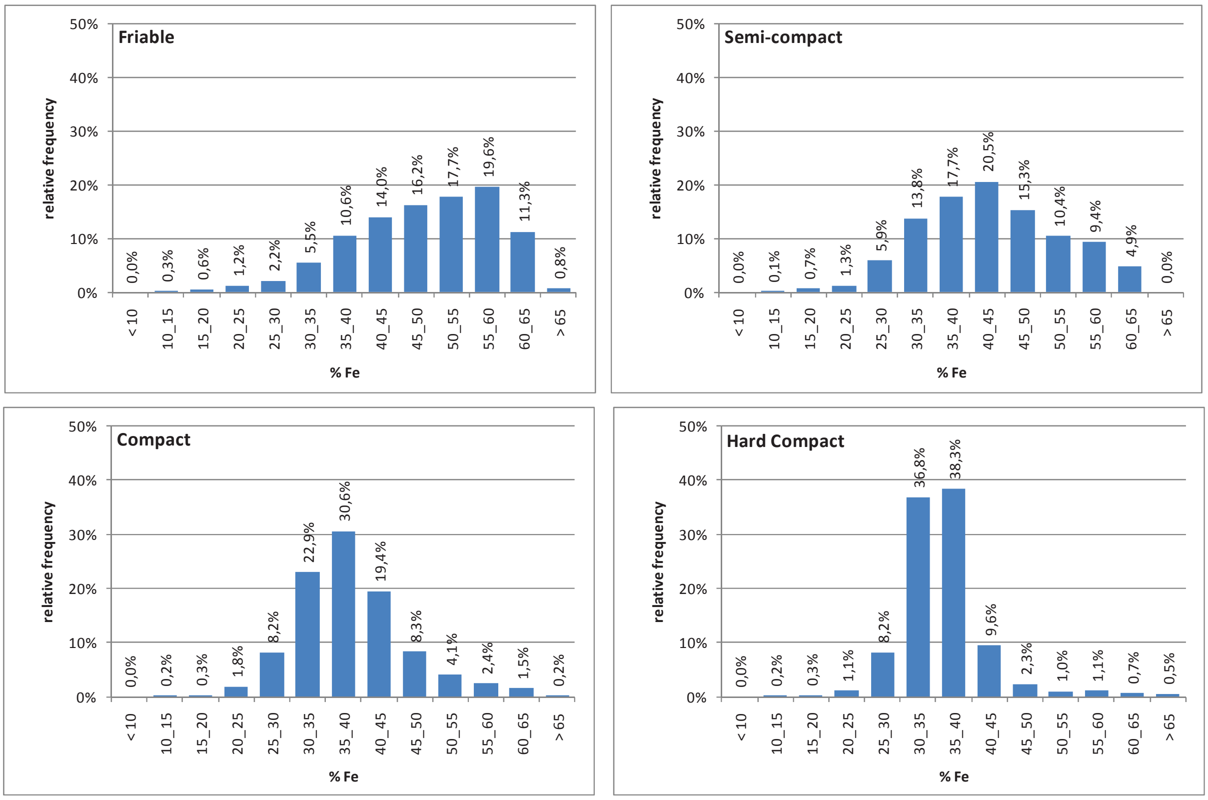

FIG 12 - Histograms of the iron grade for different ore types of the standard itabirites and haematites.

TABLE 2

Statistics of the iron grade for the different types of haematite and standard itabirites (in per cent).

	Friable	Semi-compact	Compact	Hard compact
n	1.478	1.018	984	2.905
Maximum	68.9	64.9	65.4	68.4
Percentile 95%	62.5	60.0	53.8	45.7
3rd quartile	56.6	49.9	42.3	38.3
Average	**48.6**	**43.2**	**38.5**	**36.0**
1st quartile	42.0	36.2	33.6	32.7
Percentile 5%	30.9	28.4	27.7	28.1
Minimum	10.6	11.3	13.2	11.7
sd dev	10.09	9.80	7.73	6.19
Variance	101.83	95.96	59.76	38.29

martite (Fe_2O_3) content of around 50 per cent. The average silica content is 47 per cent, meaning that the hard compact itabirite is a rock composed basically of haematite/martite and quartz, with very low amounts of other components, which may include phosphorous, alumina and loss on ignition (Table 3).

Magnetitic itabirite

Less frequent in the western half of Serra Azul (Western and Central Mines), the magnetitic itabirite occurs mainly in the Eastern Mine, Camargos and Pau de Vinho deposits (Figure 6).

The distribution of the iron grade and W1 for 375 core samples of the magnetitic itabirite is shown in the diagrams of Figure 13. Typically, the magnetitic itabirite it is a hard rock (W1 >80 per cent) with iron grade between 25 and 35 per cent. The iron bearing minerals are magnetite, haematite, goethite and grunerite. Calcite and dolomite are also present, as well as quartz. The presence of carbonates implies in relatively high contents of CaO and MgO and, consequently, high loss on ignition (LOI) (Table 4). The distribution of CaO, MgO and LOI is shown on Figure 14. The contents of these components tend to be similar, as indicated by the concentration of the plots in the centre of the diagram. Field and drill core observations indicate that the weathering product of the magnetitic itabirite is the goethitic, phosphorous-rich, ochreous (Dorr, 1969) or yellow iron formation (Pires, 1979, Pires, Aranha and Cabral, 2005) widely known in the QF region.

Argillaceous iron formation

A soft, iron bearing rock that looks like a phyllite occurs near to the stratigraphic top (close to the footwall, since the sequence is overturned) of the Cauê Formation in the eastern

TABLE 3

Statistics of the chemical characteristics of the hard compact itabirite (in per cent).

n = 2905	w1	Fe	SiO_2	P	Al_2O_3	LOI	CaO	MgO
Maximum	97.7	68.4	81.5	0.440	7.84	11.19	1.37	1.22
Percentile 95%	88.6	45.7	58.7	0.077	1.17	3.66	0.12	0.18
3rd quartile	84.3	38.3	52.3	0.036	0.42	0.99	0.03	0.05
Average	**80.2**	**36.0**	**47.0**	**0.030**	**0.37**	**0.87**	**0.03**	**0.07**
1st quartile	75.9	32.7	43.5	0.014	0.14	0.17	0.01	0.05
Percentile 5%	71.4	28.1	32.0	0.007	0.05	0.03	0.01	0.05
Minimum	70.1	11.7	1.1	0.003	0.05	0.00	0.01	0.05
sd dev	5.4	6.2	9.2	0.028	0.49	1.22	0.07	0.09
Variance	29.3	38.3	85.2	0.001	0.24	1.49	0.00	0.01

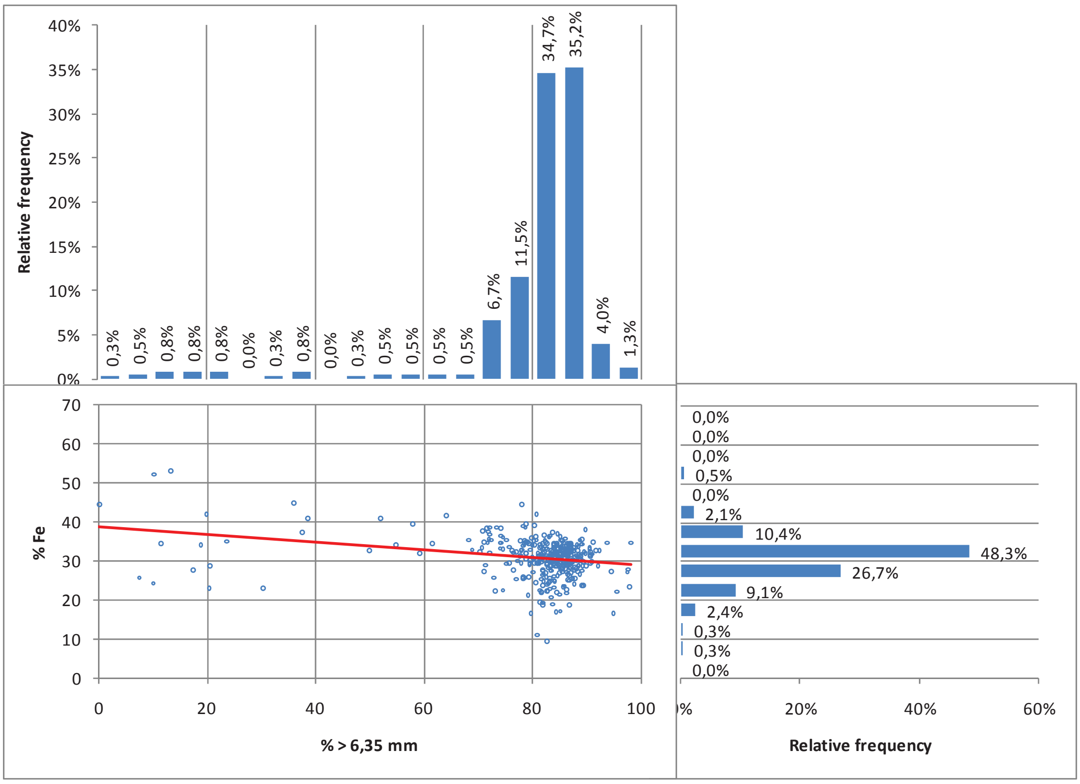

FIG 13 - Distribution of W1 and iron grade for the magnetitic itabirite.

TABLE 4

Statistics of the chemical characteristics of the magnetitic itabirite (in per cent).

n = 375	w1	Fe	SiO_2	P	Al_2O_3	LOI	CaO	MgO
Maximum	98.3	53.2	71.4	0.242	6.96	32.22	20.53	14.30
Percentile 95%	90.6	38.4	47.1	0.043	1.02	16.34	11.18	7.84
3rd quartile	86.6	33.5	40.7	0.029	0.24	10.19	7.13	5.23
Average	**80.4**	**30.7**	**38.2**	**0.028**	**0.30**	**7.70**	**5.11**	**4.34**
1st quartile	80.3	28.3	35.5	0.021	0.05	4.55	2.68	3.02
Percentile 5%	57.0	22.2	29.0	0.014	0.05	1.29	0.22	1.34
Minimum	0.0	9.4	16.6	0.003	0.05	0.16	0.01	0.05
sd dev	14.7	5.1	5.6	0.022	0.65	4.81	3.40	2.04
Variance	215.9	26.4	31.4	0.000	0.42	23.14	11.57	4.17

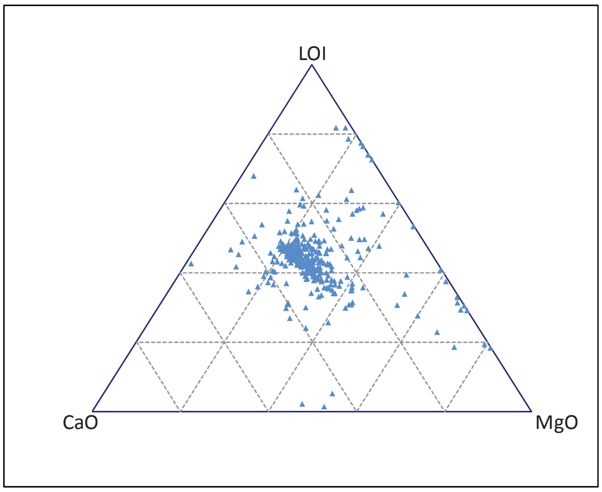

FIG 14 - Triangular diagram CaO-MgO-LOI for the magnetitic itabirite.

half of Serra Azul (Eastern Mine, Camargos and Pau de Vinho deposits).

The statistics of 441 core samples of this ore type is shown on Table 5 and the distribution of iron grade and W1 parameter on Figure 15. Differently from the hard itabirites, more than 50 per cent of the iron grades are smaller than 30 per cent, typically averaging 29 per cent Fe.

Comparison between the three major ore types

The SiO_2, Fe, and CaO+MgO contents of the hard compact itabirite, magnetitic itabirite and AIF are represented in the triangular diagram of Figure 16. Due to the absence of CaO and MgO in the hard compact itabirite and argillaceous iron formation, they plot along the Fe-SiO_2 axis. Thus, an increase in Fe in these rock types implies in a decrease in SiO_2 and vice versa. The magnetitic itabirite, on the other hand, containing CaO and MgO, plot in central sector of the diagram. Its distribution shows that an increase in the CaO+MgO content implies in an approximately equal decrease in both Fe and SiO_2.

TABLE 5

Statistics of the chemical characteristics of the argillaceous iron formation (in per cent).

n = 441	w1	Fe	SiO_2	P	Al_2O_3	LOI	CaO	MgO
Maximum	78.7	57.1	83.0	0.620	16.66	12.92	0.15	1.44
Percentile 95%	55.3	45.6	73.8	0.203	6.58	7.78	0.06	0.44
3rd quartile	24.7	36.0	58.2	0.125	3.38	5.30	0.03	0.21
Average	**17.5**	**28.6**	**48.5**	**0.097**	**2.81**	**4.21**	**0.03**	**0.18**
1st quartile	4.7	21.5	40.1	0.054	1.54	2.90	0.02	0.05
Percentile 5%	0.8	11.7	21.9	0.028	0.65	1.24	0.01	0.05
Minimum	0.0	7.5	5.7	0.011	0.33	0.60	0.01	0.05
sd dev	16.9	10.5	14.9	0.069	2.16	2.09	0.02	0.18
Variance	284.4	109.7	222.6	0.005	4.66	4.37	0.00	0.03

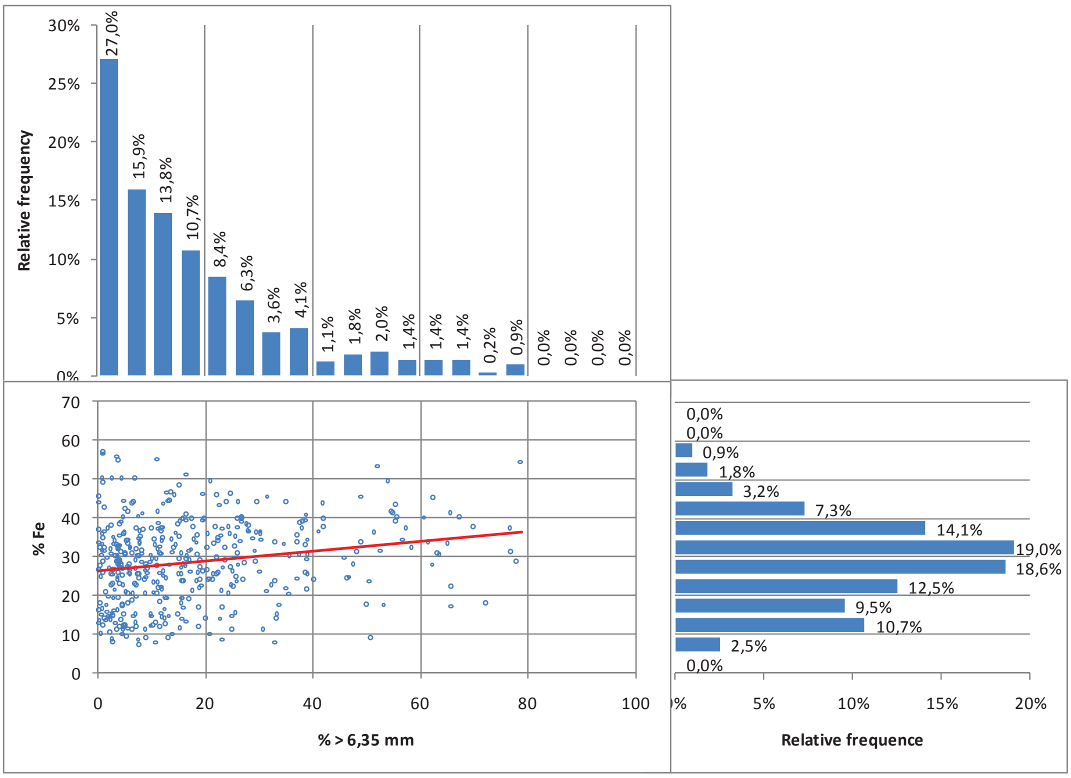

FIG 15 - Distribution of W1 and iron grade for the argillaceous iron formation.

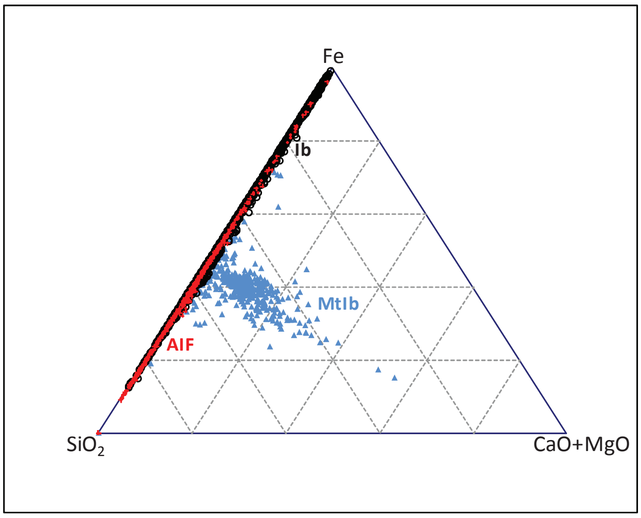

FIG 16 - Triangular diagram Fe - SiO_2 - CaO + MgO for standard itabirite (ib), magnetic itabirite (MtIb) and argillaceous iron formation.

CONCLUSIONS

The enormous demand for iron ore in the last ten years is causing a rapid depletion of the ores traditionally exploited in the QF. In order to maintain the present status of the QF as global iron ore producing area, exploitation of low grade and compact ores, so far considered waste, will be necessary. In this scenario, the Mineração Usiminas project conducted in Serra Azul is pioneer in increasing the knowledge on fresh itabirites and incorporating them in the category of ore. Three new types of lower grade ores (~36 per cent Fe), namely standard itabirite, magnetitic itabirite and argillaceous iron formation, have been include in the Serra Azul reserves. The project is being very successful, even considering all technological, economic and environmental challenges to be faced in the next years.

ACKNOWLEDGEMENTS

L Q Amorim is grateful to the Mineração Usiminas for permitting the publication of the Serra Azul project data. F F Alkmim benefited from the Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq research grant #307531/2009-0. The manuscript of this paper benefited from comments and constructive criticism by an anonymous reviewer.

REFERENCES

Alkmim, F F, 2009. Principais traços geológicos da Serra do Curral entre o vale do Paraopeba e Ponta da Serra. Mineração Usiminas, 54 p, unpublished technical report.

Alkmim, F F and Marshak, S, 1998. Transamazonian Orogeny in the southern São Francisco craton region, Brazil: Evidence for Paleoproterozoic collision and collapse in the Quadrilátero Ferrífero, *Precambrian Research*, 90:29-58.

Babinski, M, Chemale Jr, F and Van Schmus, W R, 1995. The Pb/Pb age of the Minas Supergroup carbonate rocks, Quadrilátero Ferrífero, Brazil, *Precambrian Research*, 72:235-245.

Carneiro, M A, Teixeira, W and Machado, N, 1994. Geological evolution of a sialic Archean crustal fragment from the Quadrilátero Ferrífero in eastern-central Brazil, based on U-Pb, Sm-Nd, Rb-Sr and K-Ar isotopic constrains, *Terra Nostra*, 2:12-13.

Chauvet, A, Faure, M, Dossin, I and Charvet, J, 1994. A three stage structural evolution of the Quadrilátero Ferrífero: Consequences for the Neoproterozoic age and the formation of gold concentrations of the Ouro Preto area, Minas Gerais, Brazil, *Precambrian Research*, 68:139-167.

Chemale Jr, F, Rosière, C A and Endo, I, 1994. The tectonic evolution of the Quadrilátero Ferrífero, Minas Gerais, Brazil, *Precambrian Research*, 65:25-54.

Clout, J M F and Simonson, B M, 2005. Precambrian iron formations and iron formation-hosted iron ore deposits, *Economic Geology and the Bulletin of the Society of Economic Geologists, One Hundredth Anniversary Volume 1905 - 2005*, pp 643-680.

Dorr, J and van, N II, 1964. Supergene iron ores of Minas Gerais, Brazil, *Economic Geology*, 59:1203-1240.

Dorr, J and van, N II, 1965. Nature and origin of the high-grade hematite ores of Minas Gerais, Brazil, *Economic Geology*, 60(1):1-46.

Dorr, J and van, N II, 1969. Physiographic, stratigraphic and structural development of the Quadrilátero Ferrífero, Minas Gerais, Brazil, US Geological Survey Professional Paper, 641-A:1-110.

Eichler, J, 1968. O enriquecimento residual e supergênico dos itabiritos através do intemperismo, *Geologia (UFRJ)*, 1:29-40.

Eschwege, W L v, 1833. *Pluto Brasiliensis*, 375p (Reimer).

Gole, M J and Klein, C, 1981. Banded iron-formations through much of Precambrian time, *Journal of Geology*, 89:169-183.

Guild, P, 1953. Iron deposits of the Congonhas District, Minas Gerais, Brazil, *Economic Geology*, 48:639-676.

Hagemann, S, Rosière, C A, Lobato, L M, Baars, F J, Zuchetti, M and Silva, R C F, 2006. Controversy in genetic models for Proterozoic high-grade, banded iron formation (BIF)-related iron deposits – Unifying or discrete model(s)? *Transactions Institution of Mining and Metallurgy, Section B, Applied Earth Science*, 115(4):147-151.

Hartmann, L A, Endo, I, Suita, M T F, Santos, J O S, Frantz, J C, Carneiro, M A, Naughton, N J and Barley, M E, 2006. Provenance and age delimitation of Quadrilátero Ferrífero sandstones based on zircon U-Pb isotopes, *Journal of South American Earth Sciences*, 20:273-285.

Herz, N, 1978. Metamorphic rocks of the Quadrilátero Ferrífero, Minas Gerais, Brazil, *US Geological Survey Professional Paper*, 641-C:1-81.

Jordt-Evangelista, H, Alkmim, F F and Marshak, S, 1992. Metamorfismo progressivo e a ocorrência dos 3 polimorfos Al2O3SiO5 (cianita, andaluzita e sillimanita) na Formação Sabará em Ibirité, Quadrilátero Ferrífero, MG, *Revista da Escola de Minas*, 45(1/2):157-160.

Machado, N, Noce, C M, Ladeira, E A and Belo de Oliveira, O, 1992. U-Pb Geochronology of Archean magmatism and Proterozoic metamorphism in the Quadrilátero Ferrífero, southern São Francisco craton, Brazil, *Geological Society of America Bulletin*, 104:1221-1227.

Machado, N, Schrank, A, Noce, C M and Gauthier, G, 1996. Ages of detrital zircons from Archean-Paleoproterozoic sequences: Implications for Greestone Belt setting and evolution of Transamazonian foreland basin in Quadrilátero Ferrífero, southeast Brazil, *Earth and Planetary Science Letters*, 141:259-276.

Marshak, S, Alkmim, F F and Jordt-Evangelista, H, 1992. Proterozoic crustal extension and the generation of dome-and-keel structure in an Archean granite-greenstone terrane, *Nature*, 357:491-493.

Melfi, A J, Pédro, G, Nalovic, L, Queiroz Neto, J P, 1976. Étude sur l'altération géochimique des Itabirites du Brésil, Cahiers ORSTOM, *Série Pédologie*, XIV(3):179-192.

Müller, G, Schuster, A and Hoefs, J 1982. Oxygen isotope variations in polymetamorphic iron ores from the Quadrilátero Ferrífero, Brazil, *Revista Brasileira de Geociências*, 12(1-3):248-355.

Noce, C M, Zucchetti, M, Armstrong, R, Dantas, E L, Baltazar, O F, Renger, F E, Lobato, L M, 2005. Age of felsic volcanism and the role of ancient continental crust in the evolution of the Neoarchean Rio das Velhas Greenstone belt (Quadrilátero Ferrífero, Brazil): U-Pb zircon dating of volcaniclastic graywackes, *Precambrian Research*, 141:67-82.

Pickard, A L, 2002. SHRIMP U-Pb zircon ages of tuffaceous mudrocks in the Brockman Iron Formation of the Hamersley Range, Western Australia, *Australian Journal of Earth Sciences*, 49:491-507.

Pickard, A L, 2003, SHRIMP U-Pb zircon ages for the Palaeoproterozoic Kuruman Iron Formation, Northern Cape province, South Africa: Evidence for simultaneous BIF deposition on Kaapvaal and Pilbara cratons, *Precambrian Research*, 125:275-315.

Pires, F R M, 1979. Structural geology and stratigraphy at the junction of the Curral anticline and the Moeda syncline, Quadrilátero Ferrífero, Minas Gerais, Brazil, PhD thesis, 220 p, Michigan Technological University.

Pires, F R M, 1995. Textural and mineralogical variations during metamorphism of the Proterozoic Itabira Iron Formation in the Quadrilátero Ferrífero, Minas Gerais, Brazil, *Anais da Academia Brasileira de Ciência*s, 67(1):77-105.

Pires, F R M, Aranha, D M and Cabral, A R, 2005. Volcanic Origin of the Proterozoic Itabira Iron Formation, Quadrilátero Ferrífero, Minas Gerais, Brazil, in *Proceedings Iron Ore 2005*, pp 119-121 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Ramanaidou, E R, 2009. Genesis of lateritic iron ore from banded iron-formation in the Capanema mine (Minas Gerais, Brazil), *Australian Journal of Science*, 56(4):603-618.

Ramanaidou, E R and Morris, R C, 2010. Comparison of supergene mimetic and supergene lateritic iron ore deposits, *Applied Earth Science (Trans. Inst. Min. Metall.B)*, 119(1):35-37.

Ramanaidou, E R, Nahon, D, Decarreau, A and Melfi, A J, 1996. Hematite and Goethite from duricrusts developed by lateritic chemical weathering of Precambrian banded iron formations, Minas Gerais, Brazil, *Clays and Clay Minerals*, 44(1):22-31.

Renger, F E, Noce, C M, Romano, A W and Machado, N, 1995. Evolução sedimentar do Supergrupo Minas: 500 Ma. de registro geológico no Quadrilátero Ferrífero, Minas Gerais, Brasil, *Geonomos*, 2(1):1-11.

Romano, A W, 1989. Evolution tectonique de la region nord-ouest du Quadrilatère Ferrifère – Minas Gerais – Brésil, PhD Thesis (unpublished), Université de Nancy I, Nancy, France.

Romano, A W, Bertrand, J-M, Michard, A and Zimmermann, J-L, 1991. Tectonique tangentielle et décrochements d'âge Proterozoïque inférieur (orogénèse transamazonienne, environ 2000 Ma) au Nord du 'Quadrilatère Ferrifère' (Minas Gerais, Brésil), *Comptes Rendus Academie de Science de Paris, t.313, Série II*, p 1195-1200.

Rosière, C A and Chemale Jr, F, 2006. Itabiritos e minérios de ferro de alto teor do Quadrilátero Ferrífero – Uma visão geral e discussão, *Geonomos*, 8:27-43.

Rosière, C A and Rios, F J, 2004. The origin of hematite in high-grade iron ores based on infrared microscopy and fluid inclusion studies: The example of the Conceição mine, Quadrilátero Ferrífero, Brazil, *Economic Geology*, 99:611-624.

Rosière, C A, Spier, C A, Rios, F J and Suckau, V E, 2008. The itabirite from the Quadrilátero Ferrífero and related high-grade ores: An overview, *Reviews in Economic Geology*, 15:223-254.

Silva, A M, Chemale Jr, F, Kuyjimian, R and Heaman, L, 1995. Mafic dyke swams of the Qaudrilátero Ferrífero and Espinhaço range, MG, Brazil, *Revista Brasileira de Geociências*, 25:124-137.

Simmons, G C, 1968. Geology and Iron Deposits of the Western Serra do Curral, Minas Gerais, Brazil, *US Geological Survey Professional Paper*, 341C, 57 p.

Spier, C A, Oliveira, S M and Rosière, C A, 2003. Geology and geochemistry of the Águas Claras and Pico mines, Quadrilátero Ferrífero, Minas Gerais, Brazil, *Mineralium Deposita*, 38:751-754.

Spier, C A, Oliveira, S M, Sial, A N and Rios, F J, 2007. Geochemistry and genesis of the banded iron formations of the Cauê Formation, Quadrilátero Ferrífero, Minas Gerais, Brazil, *Precambrian Research*, 152:170-206.

Spier, C A, Vasconcelos, P M and Oliveira, S M B, 2006. $^{40}Ar/^{39}Ar$ geochronological constraints on the evolution of lateritic iron deposits in the Quadrilátero Ferrífero, Minas Gerais, Brazil, *Chemical Geology*, 234:79-104.

Trendall, A F, 2002. The significance of iron-formation in the Precambrian stratigraphic record, *International Association of Sedimentologists Special Publication*, 33:33-66.

Varajão, C A C, 1994. Évolution Supergène de L'or Rich en Palladium de la Mine de Maquiné, Quadrilatère Ferrifère, Minas Gerais, Brèsil, Thèse Doctorat, Université de Marseille, 215 p.

Varajão, C A C, Ramanaidou, E R, Colin, F and Nahon, D, 1997. Gênese dos corpos de hematita compacta (Hard hematite ores): Metasomatismo, sedimentação ou alteração supergênica? *Revista da Escola Minas*, 50:40-43.

Zucchetti, M, Baltazar, O F, Raposo, F O, (eds), 1998. Projeto Rio das Velhas – Texto Explicativo do Mapa Geológico Integrado, Escala 1:100.000. DNPM/CPRM Serviço Geológico do Brasil, 157 p.