GEOCHEMISTRY AND GENESIS OF THE IRON ORE OF THE ÁGUAS CLARAS MINE, QUADRILÁTERO FERRÍFERO, BRAZIL

CARLOS ALBERTO SPIER (MBR - cbs@mbr.com.br), SONIA MARIA BARROS DE OLIVEIRA (Instituto de Geociências da USP- soniaoli@usp.br) & CARLOS ALBERTO ROSIÈRE (UFMG) (Instituto de Geociências da UFMG - crosiere@dedalus.lcc.ufmg.br)

The Águas Claras iron-ore mine is located in the Quadrilátero Ferrífero (QF), Southeastern Region of Brazil, state of Minas Gerais. Open-pit mining at Águas Claras commenced in 1973 and, by 2002, ca. 288 Mt of high-grade iron ore (average Fe>68%) have been mined. About 88 Mt of high-grade iron ore remained, but economic and environmental restrictions prevent mining from continuing (Spier et al., 2003).

The giant iron-ore deposits of the QF are hosted in metamorphosed Paleoproterozoic banded iron formations (locally called itabirite) of the Cauê Formation, Minas Supergroup. Itabirites of the Cauê Formation are entirely similar in lithology to most major oxide-facies BIFs of the Lake Superior type known worldwide (Dorr II, 1969). Based on their mineralogical composition, three major types of itabirite occurr in the QF: quartz, dolomitic and amphibolitic.

At Águas Claras dolomitic itabirite is much more common than quartz itabirite, which occurs only on the north wall of the mine. Banding of centimetric iron-rich and dolomite-rich bands is the most conspicuous macroscopic features of the dolomitic itabirite (Fig. 1a). The carbonate bands of thr dolomitic itabirite consist of very fine grained spary dolomite and hematite with grain size ranging from 5-30 μm (the average being 20 μm). The iron-rich bands contain hematite (>80%), interstitial carbonates and pores. The average hematite grain size is similar to that of the dolomite bands (~ 20 μm) ranging from 5-30 μm.

Unlike other mines in the QF, the Águas Claras mine contains mainly high-grade ores (Fe >64%), which are hosted within dolomitic itabirite. High- and low-grade ore formed from quartz itabirite are restricted to the western side of the pit, occurring close to the topographic surface, immediately below the canga cover. There are two distinct, main types of high-grade ores at the Águas Claras mine: soft and hard (Fig. 1b-c). The soft ore represents 85% of the overall resource, whereas the hard ore represents only 15% thereof. The orebody is a concordant, 2,500 m long, roughly tabular-shaped lens with a maximum thickness of 300 m and is formed essentially by soft ores. The hard ores generally occur within the soft ores as minor lenses concordant to the bedding. The depth of the ore is variable, extending to over 400 m below the surface at the center of the pit and then grading into the parental fresh dolomitic itabirite deeper down (Fig. 2). Dip and strike of the orebody are conformable with regional trends, i.e., strike is northeast-southwest, dip is 65° to 80° SE.

Soft ore is dark blue, friable and has a laminated appearance (Fig. 1b). It partially preserves the original structure of the protore, particularly meso- and microbanding. Field relations show that iron-rich bands of dolomitic itabirite grade into massive bands in the iron ore, while dolomite-rich bands grade into porous bands. The soft ore as a whole is highly porous, with intergranular porosity visually estimated in thin sections at 35 – 45%. Hematite is the major iron oxide in both bands, occurring as martite, anhedral to granular/tabular hematite and, locally, specularite. Magnetite is locally observed as relics within martite and granular hematite crystals, especially within thicker massive bands. Ferrihydrite is more frequent within the porous bands, where it occurs as an accessory mineral produced during the dissolution of dolomite. Gangue minerals are rare, increasing in amount close to the contacts with both the protore and the phyllite. They are also more frequent within the porous bands and consist of apatite, talc, chlorite and Mn-oxides.

Chemical analyses of the soft iron ore show that it consists almost entirely of Fe_2O_3 (average of 96.1%), with FeO representing less than 0.5% (average 0.1%). LOI (average of 1.1%), SiO_2 (average of 0.9%), MnO (average of 0.8%) and Al_2O_3 (average of 0.5%) complete the list of significant major elements. Na_2O and K_2O contents are below the detection limit of 0.01%. Most of the trace elements show concentrations of less than 10 ppm, except for Ba (32 ppm), V (57ppm), Zn (47 ppm), Cr (93 ppm), Y (15 ppm), Ni (26 ppm), Cu (10 ppm) and ∑REE (18 ppm). When compared to the average composition of the dolomitic itabirite, the soft ore is enriched in all trace elements, which are concentrated in the porous bands. The REEY patterns of the soft ore, normalized with respect to PAAS are characterized by a pronounced depletion in the light REE relative to heavy REE (average La/Yb=0.2). These patterns are remarkably similar to those of the dolomitic itabirite.

The hard ore is dense, tough, compact, dark bluish gray and has a dull to metallic luster (Fig. 1c). Three main subtypes of hard ore are found at Águas Claras mine: massive, banded and schistose. Massive hard ore has low porosity, does not exhibit any kind of structure and usually shows signs of conchoidal fracture. Banded hard ore is the major type of hard ore, being characterized by conspicuous banding and varied porosity. Schistose hard ore generally has low porosity, does not preserve the original structures and exhibits a conspicuous cataclastic foliation. This type of hard ore is associated with the shear zones which are mainly found on the north wall of the pit. Petrographic and SEM observations of the massive, banded and schistose hard iron ores have shown a very simple mineralogical composition consisting essentially of hematite and very subordinated magnetite. Hematite occurs as martite, anhedral to granular/tabular hematite and, locally, specularite. Magnetite occurs locally as relics within martite and granular/tabular hematite crystals. Gangue minerals are very rare, consisting of dolomite and, locally, apatite and talc.

*Figure 1 - Photographs of the protore and high-grade ores in the Águas Claras mine. **A** Hand specimen of dolomitic itabirite (protore) showing dolomite-rich (d) and hematite-rich (h) mesobands. **B** Soft Ore. **C** Outcrop of hard ore.*

The bulk geochemical composition of the hard ore is very simple, consisting almost entirely of Fe_2O_3 (avg. 97.4%), ranging from 95.0% to 99.1%. The average FeO content is 0.8% (ranging from 0.2% to 2.7%), whereas SiO_2 ranges from 0.2% to 1.3% (avg. of 0.6%). CaO and MgO contents present a similar distribution, ranging from 0.01% to 1.2% (avg. of 0.2%). LOI, CaO and MgO contents are higher in the hard ore hosted within the unweathered dolomitic itabirite. Al_2O_3 is the next most abundant component, ranging from 0.02% to 0.9% (avg. of 0.2%). Na_2O, K_2O and P_2O_5 contents are always below 0.5%, whereas TiO_2 averages 0.02%. The trace element composition of the hard ore is also remarkably simple, with only Cr (avg. of 65 ppm) and V (avg. of 35 ppm) showing average values higher than 30 ppm. The hard ore is depleted in REE, with an average content of 7 ppm. The REEY patterns of the hard ore are characterized by a strong depletion in light REE relative to heavy REE, negative Ce anomalies, marked positive Eu and Y anomalies, and by the depletion of the heavy REE relative to the middle REE (Dy/Yb >1). The different REE fractionation pattern of the soft ore in relation to the hard ore may be related to their genesis.

The genesis of the iron ores within the Cauê Formation has been the object of debate since the beginning of the 20th century and continues to be the focus of studies by several researchers (e.g. Cabral et al., 2003; Dorr II, 1964, 1965; Guild, 1953; Harder and Chamberlain, 1915; Park, 1959; Ramanaidou et al., 1996; Rosière and Rios, 2004). Two end-member genetic models have been proposed: supergene versus hypogene. The low-grade iron ores rich in goethite, such as the limonitic itabirite, are generally accepted to be the result of supergene enrichment of BIF, whereas the high-grade hard ores are considered as hypogene in origin. Most studies on the supergene ore refer to the ore originated from the siliceous itabirite, the most common type of itabirite in the QF. They attribute the genesis of this iron ore to the leaching of quartz from the protore by meteoric water, with consequent enrichment in iron and development of great porosity. In these supergene models, dissolution of quartz can be total or partial, generating iron ores of varied Fe contents. Hematite remains stable, and the resultant pores are not filled by other minerals such as goethite or gibbsite, except in the upper level of the weathering profile, close to the canga surface (Ramanaidou et al., 1996).

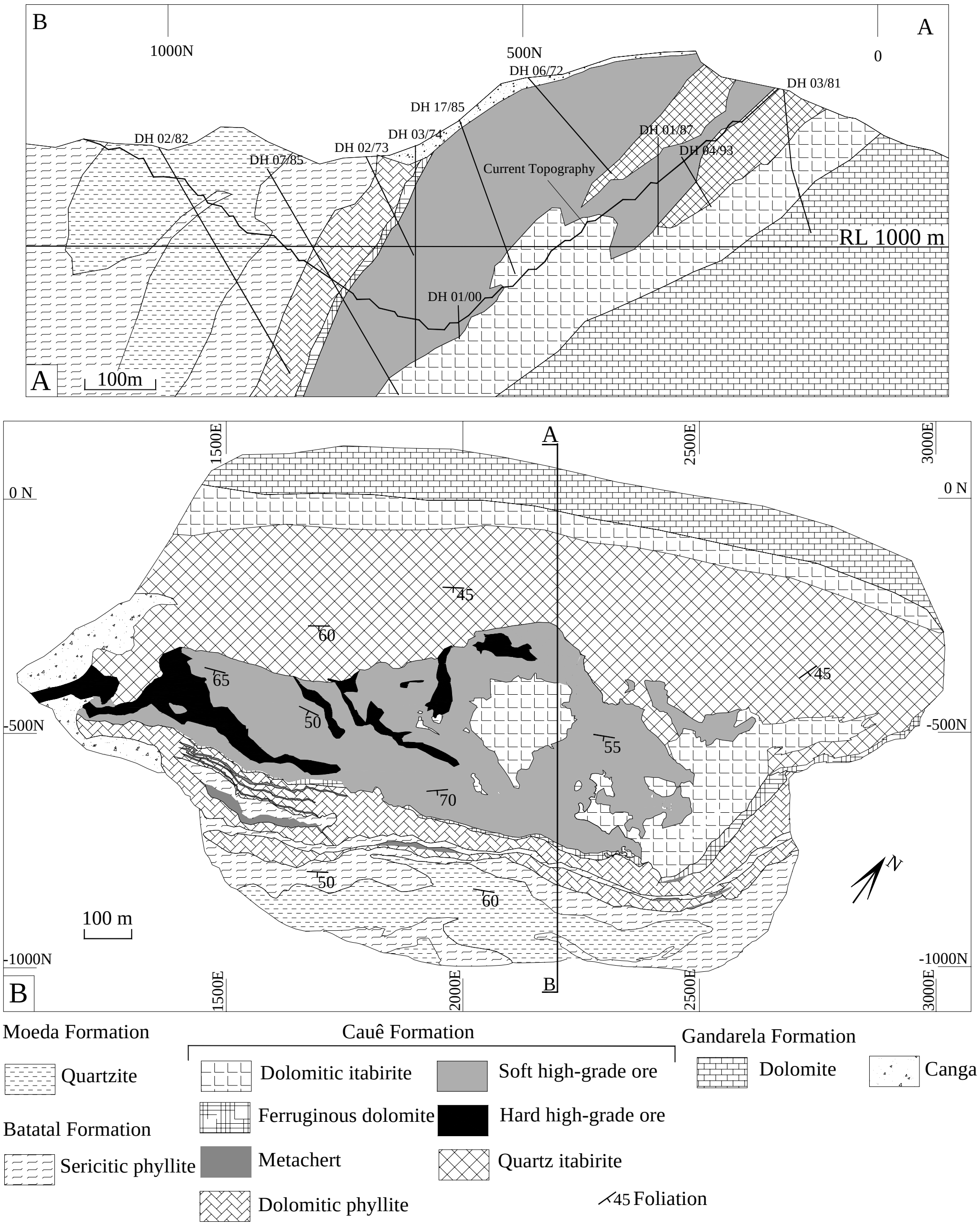

Figure 2 - Águas Claras mine. ***a*** *Cross section 2200E.* ***b*** *Geological sketch map.*

The hard ore at the Águas Claras mine occurs either within the soft ore as within the unweathered dolomitic itabirite, which clearly indicate its hypogene origin. The close spatial association between the hard and the soft ores and some features showed by the latter, such as the lack of goethite and the great depth of mineralisation, could indicate an hypogene origin for the soft ore. Otherwise, many features observed in the soft ore, such as: (1) clear transition from the dolomitic itabirite into the soft ore; (2) disappearance of the soft ore down dip, forming pinnacles; (3) pockets of dolomitic itabirite within the soft ore; (4) lack of hydrothermal aureoles around the hard ore hosted within the unweathered itabirite; (5) occurrence of slump folds in the soft ore, and Tertiary basins locally blanketing the orebody; (6) petrographic evidences of dolomite dissolution forming Mn-oxides and ferrihydrite (a metastable iron hydroxide that transforms into hematite at temperatures as low as 40 °C (Schwertmann et al., 1985), and (7) a similar REEY pattern for the dolomitic itabirite and the soft ore indicate that most of the Águas Claras orebody was formed by leaching of dolomite from the dolomitic itabirite by meteoric water.

Although quartz and dolomitic itabirite crop out at the Águas Claras mine, the soft iron ore was developed mainly within the latter. Therefore, the original composition of the BIF plays a major role in the genesis of the soft high-grade ore in the QF.

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