# MINERALOGYCAL AND MICROSTRUCTURAL CHARACTERIZATION OF LUMP ORES USED IN USIMINAS[1]

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**Abstract**
Studies on geometallurgical characteristics of iron ores used in Usiminas' sinter plants and blast furnaces are underway. As a first step a mineralogical characterization of both the lump ores and the sinter feed has been done. This paper describes the mineralogical characterization of five lump ores from the Quadrilátero Ferrífero of Minas Gerais state that are used in Usiminas' blast furnaces. Chemical analyses, X-ray diffraction and optical microscopy using partially polarized and reflected light techniques were used. As main mineral all investigated lump ores presented hematite, together with martite and goethite in some of them. As secondary mineral all of them presented quartz and magnetite. Based on the present results and on literature reports, an attempt classification of the studied iron lumps was proposed.
**Key-words**: Iron Ore; Lump Ore; Characterization; Geometallurgy.

# CARACTERIZAÇÃO MINERALÓGICA E MICROESTRUTURAL DOS MINÉRIOS GRANULADOS USADOS NA USIMINAS

**Resumo**
Estão sendo desenvolvidos estudos na Usiminas sobre as características geometalúrgicas dos minérios de ferro usados nas sinterizações e nos altos-fornos. Num primeiro estágio foi feita uma caracterização mineralógica dos minérios granulados e dos *sinter feed*. Este trabalho descreve a caracterização mineralógica de cinco minérios oriundos do Quadrilátero Ferrífero no estado de Minas Gerais, usados nos altos-fornos da Usiminas. A caracterização foi realizada por meio de análise química, de difração de raios-X, e por microscopia óptica com luz refletida e parcialmente polarizada. Como mineral principal, todos os minérios apresentaram hematita, além de martita e goethita em alguns deles. Como minerais secundários todos eles apresentaram quartzo e magnetita. Baseando-se nos resultados e na literatura, foi proposta uma classificação dos minérios estudados.
**Palavras-chave**: Minério de Ferro; Minério Granulado; Caracterização; Geometalurgia.

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## 1 INTRODUCTION

Traditionally chemical and grain size characterization of iron ores have been enough to describe them. However, it has occasionally been noted that similar iron ores exhibit different performances in sinter machine or in blast furnace. The geometallurgical approach links the geology, mineralogy and microstructural aspects of iron ores to their metallurgical characteristics trying to explain those differences.

According to Rosière et alii(1) and Takehara(2) the behavior of iron ores in the metallurgical reactor is strongly dependent on their structural attributes, like the mineralogical constitution, morphology and sizes of crystals and pores, grade of anisotropy, fabric and texture, nature and characteristics of crystals contact, etc.

Rosière et alii(3) say that the mineralogical characteristics, the grains arrangement (fabric) and texture of iron ores are variables dependent on the ore beds. For example, the ore beds in the Quadrilátero Ferrífero present a complex sequence of crystallization from the total or partial martitization of primary magnetite (kenomagnetite), until the recrystallization to xenoblastic or idioblastic hematites.

Rosière et alii(4) show the sequence of iron oxide generation found in the entire iron deposit that they have analyzed, the predominance of each one being dependent on the structural position and the grade of metamorphism undergone by the rocks:

1. Magnetite I → Martite I → Hematite I;
2. Hematite I → Hematite II → Hematite III → Hematite IV;
3. Magnetite II → Martite II;
4. Magnetite III → Martite III.

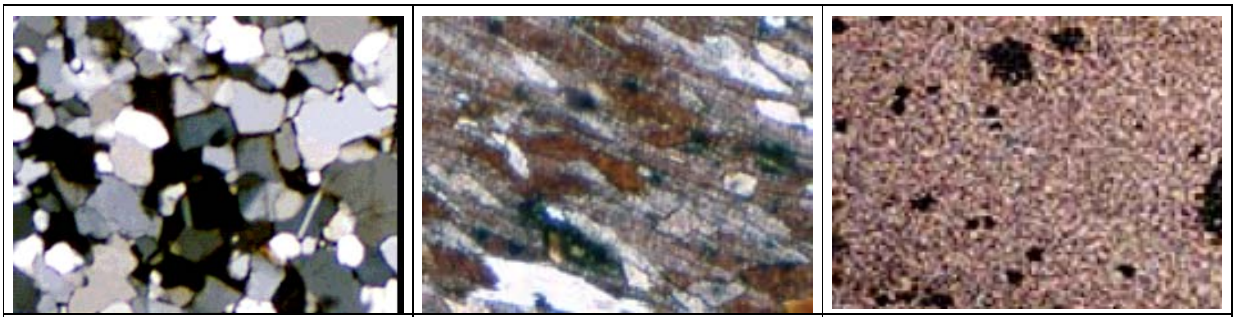
They show the mineralogical composition of different ores from the Quadrilátero Ferrífero (table 1) too.

**Table 1**. Mineralogical composition of different ores from the Quadrilátero Ferrífero(4).

| Type of ore | Main components | | Secondary** |
|---|---|---|---|
| Common Itabirite | light bands | quartz | hematite, clorite, sericite, dolomite, pirofilite, Mn* oxides, |
| | dark bands | Fe* oxides | sericite, quartz, pirofilite |
| Dolomitic Itabirite | light bands | dolomite | quartz, Fe* oxides, pirofilite, talc, Mn* oxides |
| | dark bands | Fe* oxides | quartz, dolomite, Mn* oxides |
| Anfibolitic Itabirite | light bands | Tremolite/actinolite, hornblende, grunerite | quartz, dolomite, Fe* oxides |
| | dark bands | Fe* oxides | quartz, dolomite, Amphiboles |
| Iron rich ore | hematite | | magnetite, quartz, pirofilite |

* Hematite is the main mineral-ore.
** Iron phosphates can occur in all types. Sulfides are occasionally present.

Vieira(5) has investigated the geometallurgical performance of lump ores from the Quadrilátero Ferrífero and concluded the following: the main minerals in all lumps are hematite and martite; lumps with lepidoblastic fabric have low values of reducibility index (RI) and high crepitation and reduction degradation (RDI) indexes; lumps with granoblastic fabric (see figure 1) exhibit low values of crepitation and RDI and generally better reducibility than those with lepidoblastic fabric; lumps with microgranullar fabric present good reducibility and values of crepitation and RDI higher than granoblastic and lower than lepidoblastic ores; the measured softening and melting parameters have showed that lepidoblastic lump ores possess lower softening start temperature ($T_S$) than granoblastic and martitic ores; the softening and melting temperature interval ($\Delta T_{SM}$) of lepidoblastic ores is wider than for martitic with granoblastic fabric ore. It must be noted that a large $\Delta T_{SM}$ is bad to the blast furnace permeability. Figure 1 shows examples of granoblastic, lepidoblastic and microgranular fabrics, as observed by Vieira(5).



| Granoblastic fabric | Lepidoblastic fabric | Microgranular fabric |
| --- | --- | --- |

**Figure 1**. Fabrics as described by Vieira(5).

Studies are underway in Usiminas in a first step to determine the mineralogical and microstructural characteristics of the lump ores used in its blast furnaces. In the next step the results will be used to perform a geometallurgical study of these iron ores.

## 2 MATERIAL AND METHODS

To perform the mineralogical and microstructural characterization of five lump ores used in Usiminas' blast furnaces, an optical microscope with partially polarized light was used for mineralogical quantitative analyses by counting the points. The X-ray diffraction technique was also used to identify the mineralogical and gangue phases. The amount of contaminants in each lump ore was determined by chemical analysis. Usiminas uses lump ores from five different mines in the Quadrilátero Ferrífero, here named from A to E.

## 3 RESULTS

Table 2 shows the mineralogical phases obtained by X-ray diffraction.

**Table 2**. Mineralogical phases obtained by X-ray diffraction (cps).

| | Lump A | Lump B | Lump C | Lump D | Lump E |
| --- | --- | --- | --- | --- | --- |
| Hematite – $Fe_2O_3$ | 1630 | 2831 | 2005 | 2924 | 1969 |
| Magnetite – $Fe_3O_4$ | 241 | 0 | 155 | 0 | 463 |
| Goethite – FeO(OH) | 616 | 180 | 162 | 0 | 37 |
| Quartz – $SiO_2$ | 133 | 61 | 301 | 5 | 134 |
| Biotite – $KMg_3(Si_3Al)O_{10}(OH)_2$ | 17 | 0 | 0 | 0 | 0 |
| Talc – $Mg_3Si_4O_{10}(OH)_2$ | 0 | 70 | 0 | 0 | 0 |
| Gibbsite – $Al(OH)_3$ | 0 | 0 | 0 | 438 | 0 |
| Greenalite – $Fe_3Si_2O_5(OH)_4$ | 0 | 0 | 0 | 0 | 21 |

Table 3 shows the mineralogical phases obtained by optical microscopy.

**Table 3**. Mineralogical phases obtained by optical microscopy (V/V%).

| | Lump A | Lump B | Lump C | Lump D | Lump E |
|---|---|---|---|---|---|
| Microgranular Hematite (Hm) | 0.00 | 0.00 | 0.00 | 26.67 | 14.80 |
| Granular Hematite (Hr) | 18.33 | 35.04 | 40.89 | 29.43 | 20.37 |
| Lamelar Hematite (Hl) | 11.93 | 17.14 | 7.21 | 17.58 | 8.26 |
| Hematite type II (HII) | 0.03 | 0.39 | 1.25 | 0.00 | 0.07 |
| Hematite type III (HIII) | 0.00 | 0.01 | 0.09 | 0.00 | 0.00 |
| Hematite type Ib (HIb) | 1.80 | 2.15 | 1.62 | 0.00 | 6.85 |
| Total Hematite | 32.09 | 54.73 | 51.07 | 73.68 | 50.34 |
| Martite (Mt) | 9.32 | 0.75 | 3.96 | 0.00 | 13.30 |
| Magnetite (Mg) | 4.05 | 0.10 | 1.03 | 0.00 | 5.37 |
| Goethite (Go) | 26.60 | 21.28 | 16.13 | 7.89 | 3.07 |
| Quartz (Qz) | 2.22 | 0.889 | 5.19 | 0.85 | 0.69 |
| Pore (Pr) | 25.72 | 22.26 | 22.61 | 17.58 | 27.22 |

In figures 2A to 2F the results of chemical analyses in terms of $Fe_{(T)}$, $SiO_2$, P, FeO, $Al_2O_3$ and LOI (loss on ignition), respectively, are shown.

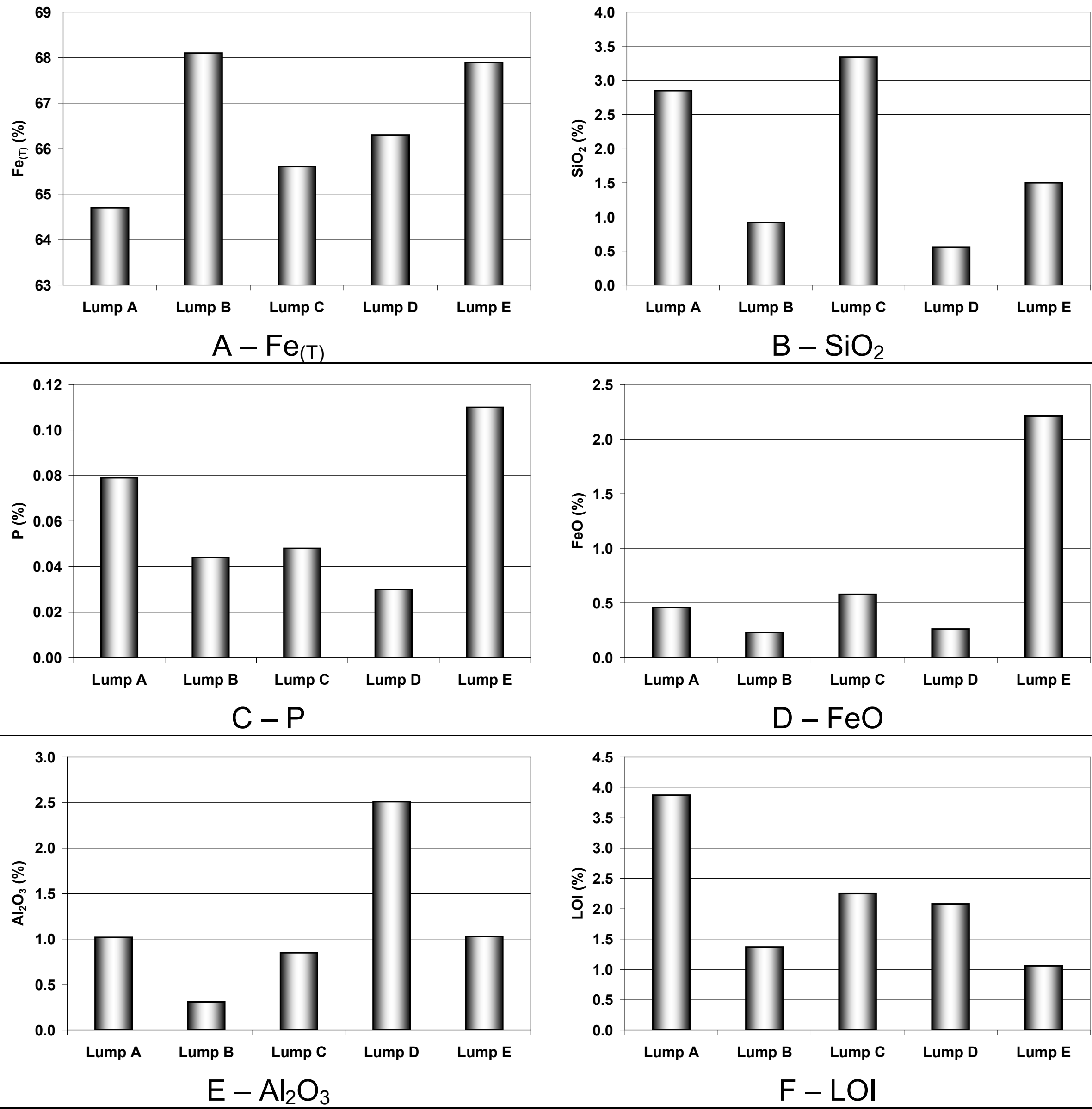
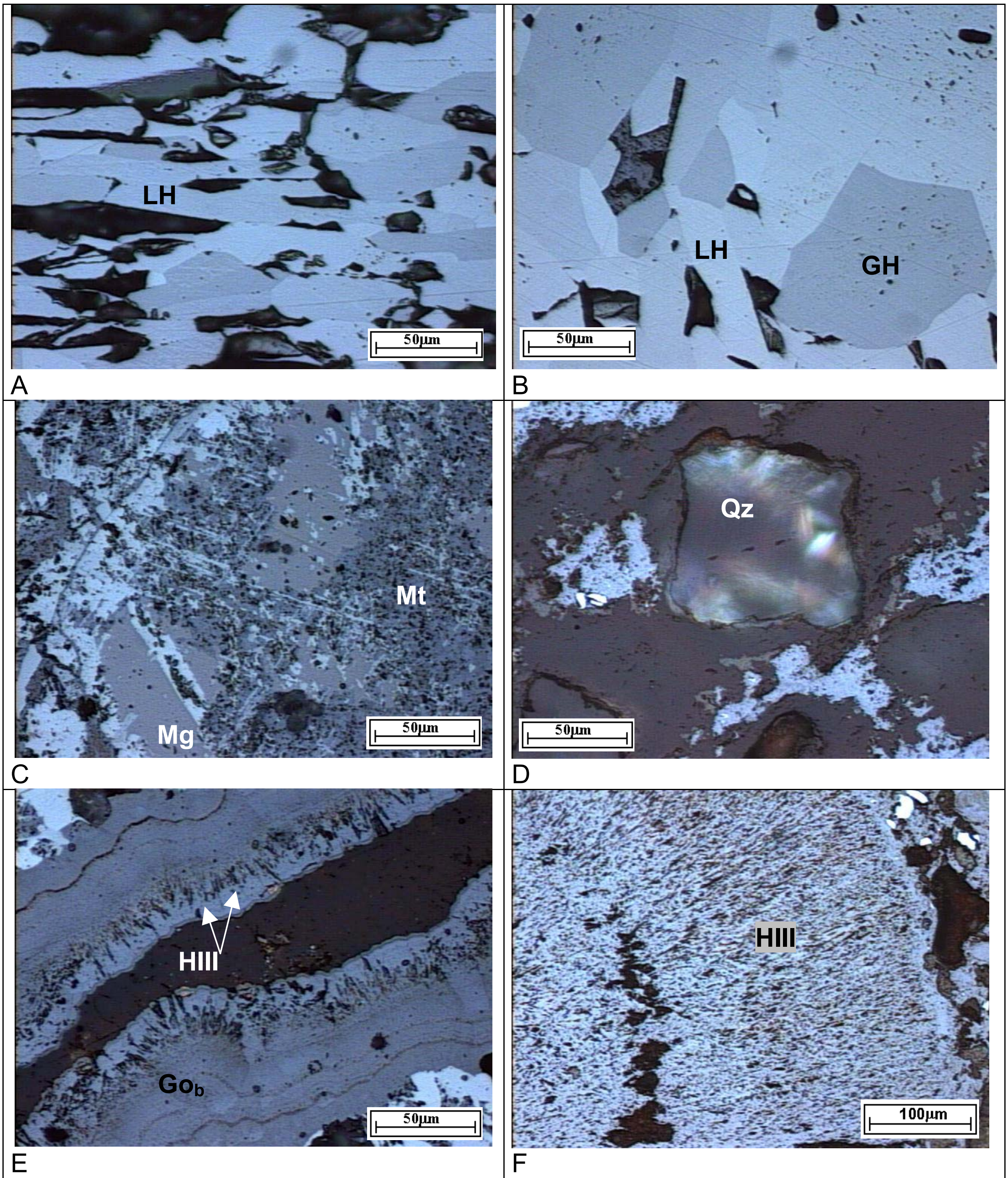



**Figure 2**. Results of chemical analysis of lump ores used in Usiminas.

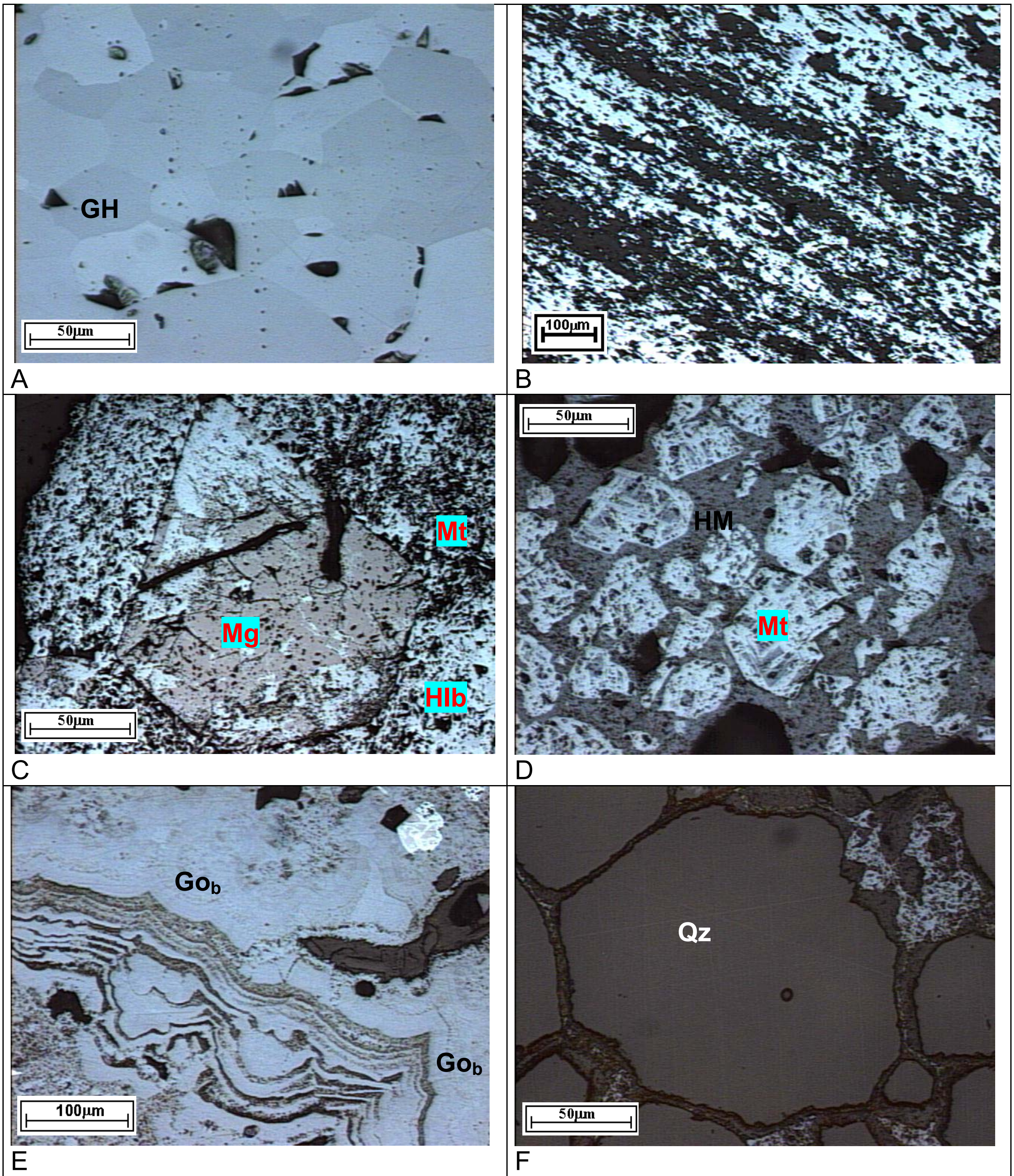
Table 4 shows the mineralogical and microstructural characteristics of the five lumps analysed.

Figures 3 to 7 show the microstructure of Lumps A to E, sequentially.



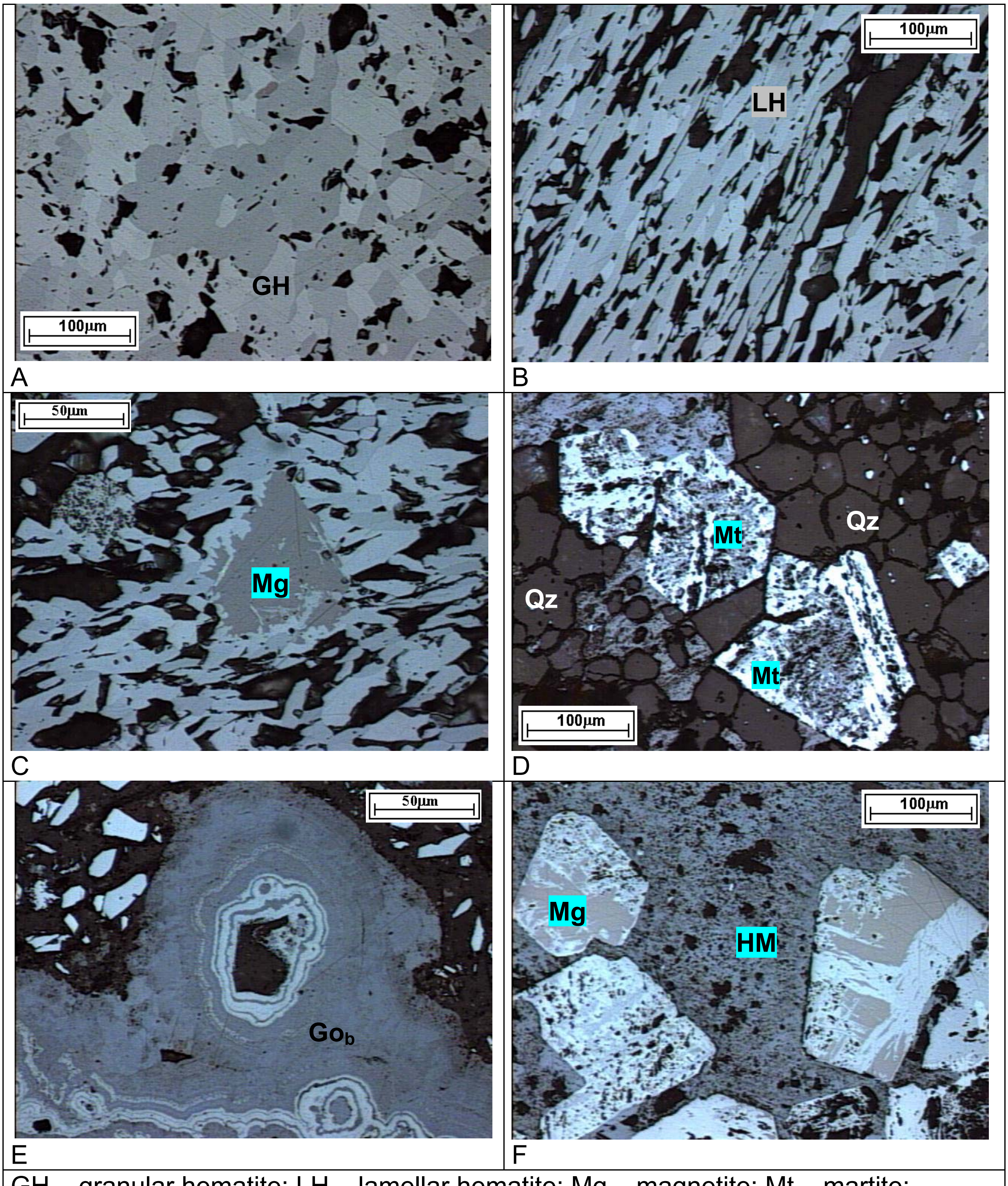

GH – granular hematite; LH – lamellar hematite; Mg – magnetite; Mt – martite; Go$_b$ – botryoidal goethite; Qz – quartz; HIII – hematite type III comes from dehydratation of botryoidal goethite.

**Figure 3**. Micrographics of Lump A.



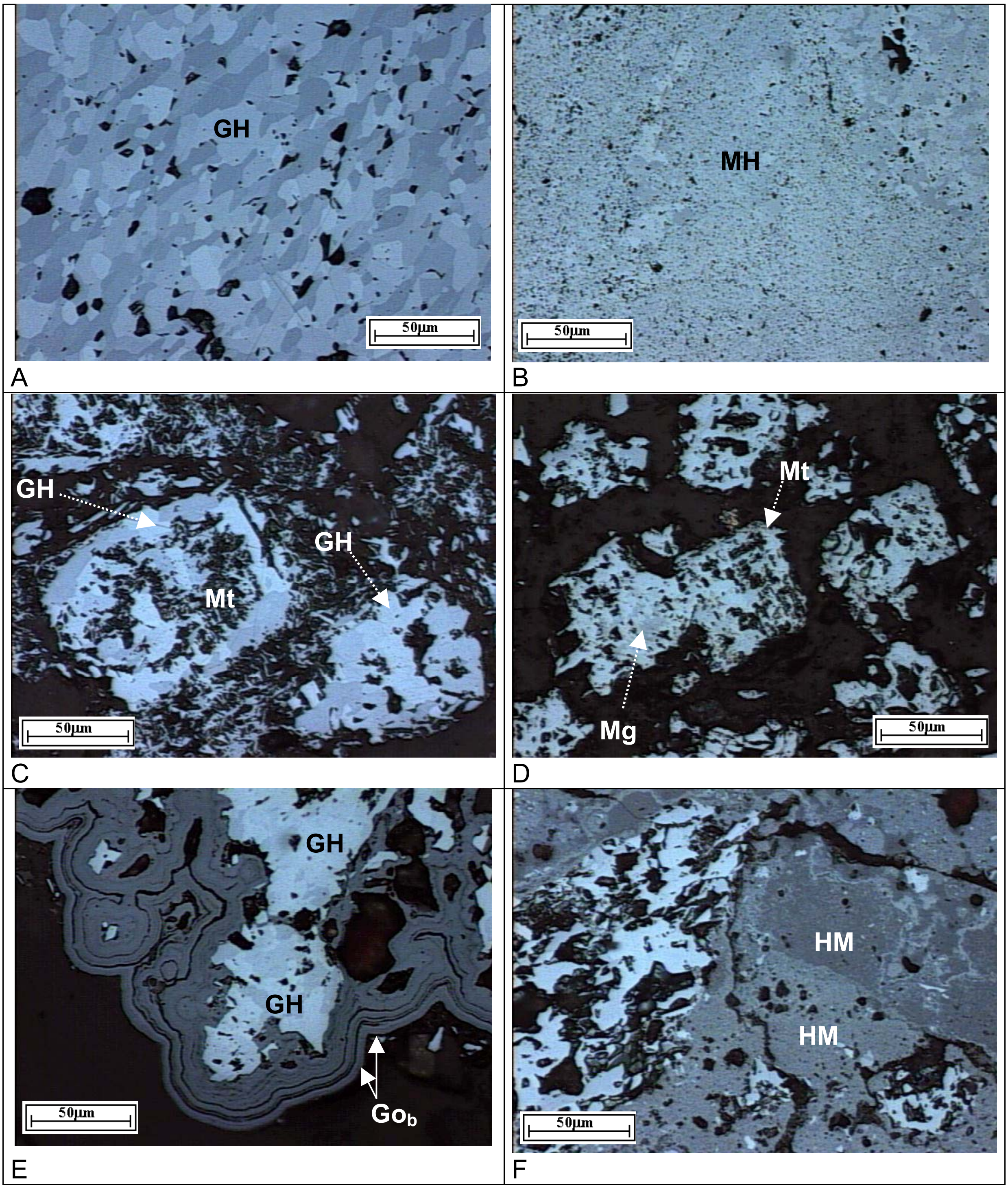

GH – granular hematite; LH – lamellar hematite; Mg – magnetite; Mt – martite; $Go_b$ – botryoidal goethite; Qz – quartz; HIb – hematite type Ib comes from Mt evolution; HM – hydrated mineral (massive goethite and/ or limonite).

**Figure 4**. Micrographics of Lump B.



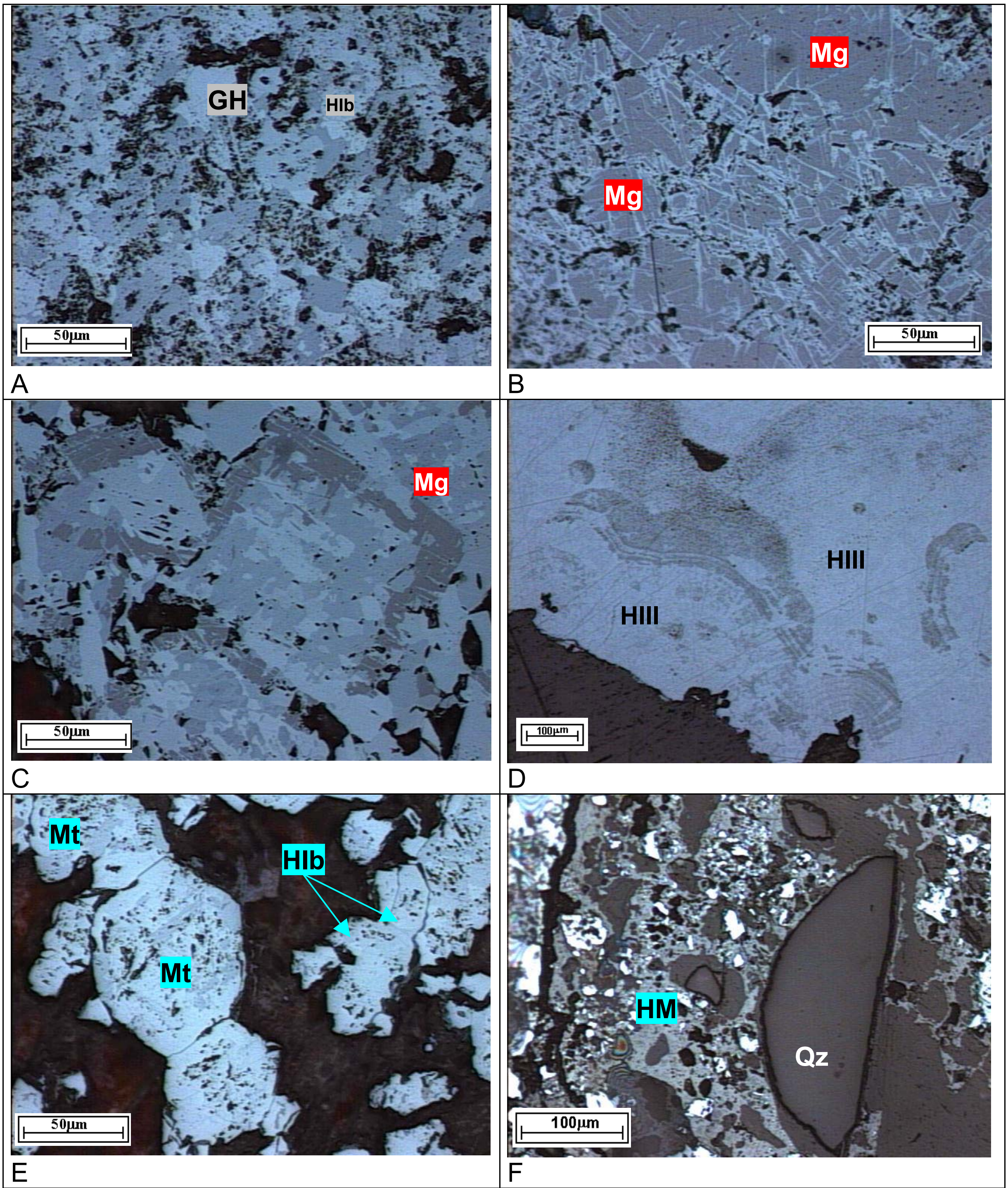

GH – granular hematite; LH – lamellar hematite; Mg – magnetite; Mt – martite; Go$_b$ – botryoidal goethite; Qz – quartz; HIb – hematite type Ib comes from Mt evolution; HM – hydrated mineral (massive goethite and/or limonite).

**Figure 5**. Micrographics of Lump C.




GH – granular hematite; MH – microcrystalline hematite; Mg – magnetite;
Mt – martite; $Go_b$ – botryoidal goethite; HM – hydrated mineral.

**Figure 6**. Micrographics of Lump D.




GH – Granular Hematite; Mg – magnetite; Mt – martite; HM – hydrated mineral (goethite and/or limonite); Qz – quartz; HIb – hematite type Ib comes from the Mt evolution; HIII – hematite type III comes from dehydratation of $Go_b$.

**Figure 7**. Micrographics of Lump E.

## 4 DISCUSSION

Similar trends can be observed in the analyses of minerals by both optical microscopy and X-ray diffraction, as shown in tables 2 and 3. There is also a proportion of the chemical composition to the contained minerals in the ores.

All lump ores have more than 64% iron content, which is a characteristic of high grade hematites from the Quadrilátero Ferrífero. The less amount of $Fe_{(T)}$ in Lump A and Lump C is a consequence of their higher $SiO_2$ content.

Lumps B and D are better than Lumps A and E for using in the blast furnace, once phosphorous content in iron ores shall be the least possible.

High FeO content indicates that the transformation of magnetite to martite, and subsequently to hematite, does not go into completion in Lump E, resulting in this case a great amount of residual magnetite, as can be seen in tables 2 and 3.

In the blast furnace, the oxide $Al_2O_3$ causes increase in the volume of slag making it thereby more viscous, so that addition of MgO is needed to ensure the slag flow to the outside of the furnace hearth. In this context Lump D has the highest $Al_2O_3$ content, as indicated in table 2, as it comes from the gibbsite.

The main mineralogical characteristics of the five anayzed lumps, table 3, agree with the compositions reported by Rosière et alii[4] in table 1.

Lump A has hematites (granular and lamellar), goethite and martite as main minerals, and magnetite and quartz as secondary minerals. Its fabric is granoblastic to lepidoblastic. Additional features are porosity between 20% and 35%, particles classified as sub-round to sub-angular, and crystals contact surface classified as irregular to straight.

Lump B has hematites (granular and lamellar) and goethite as main minerals, and hematite type Ib (coming from martite evolution) and quartz as secondary minerals. Its fabric is granoblastic to lepidoblastic. Its porosity lies between 15% and 30%, and the additional particle characteristics are the same of Lump A.

Lump C has granular hematite and goethite as main minerals, and lamellar hematite, quartz, martite, hematite type Ib, and magnetite as secondary minerals. Its fabric is mainly granolblastic. Lump porosity and particle characteristics are the same of Lump B.

Lump D has granular and microcrystaline hematites as main minerals, and goethite as secondary mineral. Its fabric is granoblastic to microgranular. Its porosity lies between 13% and 30%, the particles are sub-angular to sub-round and crystals contact surface is classified as irregular to lightly straight.

Lump E has granular and microcrystaline hematites and martite as main minerals, and hematite type Ib, magnetite, goethite and quartz as secondary minerals. Its fabric is granoblastic to lepidoblastic. Lump porosity lies between 20% and 30%, its particles are classified as angular to round, and crystals contact surface is irregular to slightly straight.

It can be seen that all investigated iron ores have hematite as main mineral. In addition goethite in Lump A, and martite in Lump E are also main minerals. Lumps B and C are semi-hydrated. As secondary minerals, quartz is always present except in Lump D.

Based on Vieira[5] conclusions and according to the results shown in table 3, the five investigated lump ores can be classified as presented in table 5 that shows the chemical characteristics ($Fe_{(T)}$ and $SiO_2$) and the geometallurgical properties. For the latter, a correlation was established between the fabric and the following parameters: crepitation, RI, RDI, $T_S$ and $\Delta T_{SM}$.

**Table 4** – Mineralogical and microstructural characteristics of the five iron ores used in Usiminas

| Lump Ore | Classification | Mineralogy | | Fabric | Porosity (V/V%) | Roundness | Contact surface |
|---|---|---|---|---|---|---|---|
| | | Main | Secondary | | | | |
| A | Hematitic/ Hydrated/Martitic | LH, GH, Go, Mt | Mg, Qz | Granoblastic to lepidoblastic | 20 to 35 | Sr to Sa | Irregular to straight |
| B | Hematitic/ Semi-hydrated | GH, LH, Go | HIb, Qz | Granoblastic to lepidoblastic | 15 to 30 | Sa to Sr | Irregular to straight |
| C | Hematitic/ Semi-hydrated | LH, Go | GH, Qz, Mt, HIb, Mg | Mainly granoblastic | 15 to 30 | Sa to Sr | Irregular to straight |
| D | Hematitic | LH, MH, GH, | Go | Granoblastic to microgranular | 13 to 30 | Sa to Sr | Irregular to slightly straight |
| E | Hematitic/ Martitic | LH, Mt, MH, GH | HIb, Mg, Go, Qz | Granoblastic to microgranular | 20 to 30 | Ag to Ro | Irregular to slightly straight |

Classification: GH – Granular Hematite; LH – Lamellar Hematite; MH – Microcrystalline Hematite; HIb – Hematite type Ib; Go – goethite; Mt – Martite; Mg – Magnetite; Qz – Quartz.
Mineralogy: main > 10 %; secondary > 1 % (see table 3). Roundness: Ag – Angular; Ro – round; Sa – Sub-angular; Sr – Sub-round.
Roundness refers to the particles and contact surface refers to the crystals.

**Table 5** – Predicted classification of the studied lump ores according to Vieira conclusions[5].

| Classification | Geometalurgical Properties | Chemical Characteristics | |
|---|---|---|---|
| | Crepitation, RI, RDI, $T_S$, $\Delta T_{SM}$ | $Fe_{(T)}$ | $SiO_2$ |
| Best | Lump C | Lump B | Lump D |
| | Lump D | Lump E | Lump B |
| | Lump E | Lump D | Lump E |
| Worse | Lump B | Lump C | Lump A |
| Worse | Lump A | Lump A | Lump C |

## 5 CONCLUSIONS

The five lump ores studied have high iron content, which is a main characteristic of iron ores from the Quadrilátero Ferrífero in Minas Gerais state. As a consequence they have low gangue, basically composed by quartz.

The analyzed iron ores are compact with porosity lying between 15% and 30%, and having hematite as the main mineral. Martite and goethite are also occasionally present as main mineral. Magnetite, quartz and goethite are the usual secondary minerals. Two lumps have microcrystalline hematite.

Better metallurgical characteristics (crepitation, RI, RDI, $T_S$ **and** $\Delta T_{SM}$) are expected with granoblastic fabric contained iron ores instead of lepidoblastic ores. In the present study the five lump ores presented different amounts of each of these fabrics. Based on the fabrics, the expected classification of metallurgical characteristics of the lumps ranking from best to worse is as following: Lump C, Lump D, Lump E, Lump B and Lump A.

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