HEMATITE & GOETHITE INCLUSIONS IN DOLOMITE FROM LOW-GRADE BANDED IRON FORMATIONS: *PHYSICAL PARAMETER EVALUATION TO OPTIMIZE ORE BENEFICIATION*

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Introduction

Challenges for Geometallurgy (Low-Grade) Iron ore

Prediction of ore behavior

Downstreaming Ore Processing

Crucial to:
- Resource evaluation
- Development
- Decision making

!

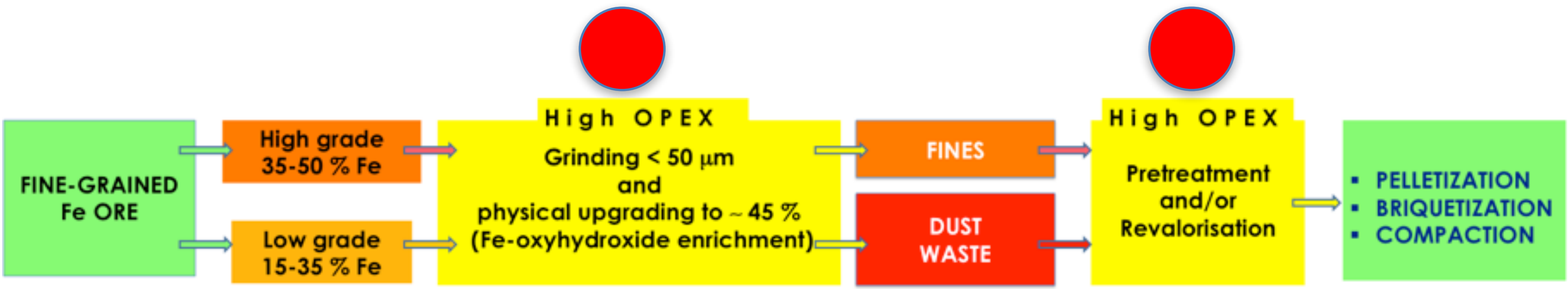
Early determination of ore's properties & ore processing potential

= > cost reduction & productivity benefits

Definition of geometallurgical key parameters

prior to quantification & 3D modelling
(« systematic geometallurgy »)

What needs to be quantified ?



= > Reduction of OPEX

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Introduction

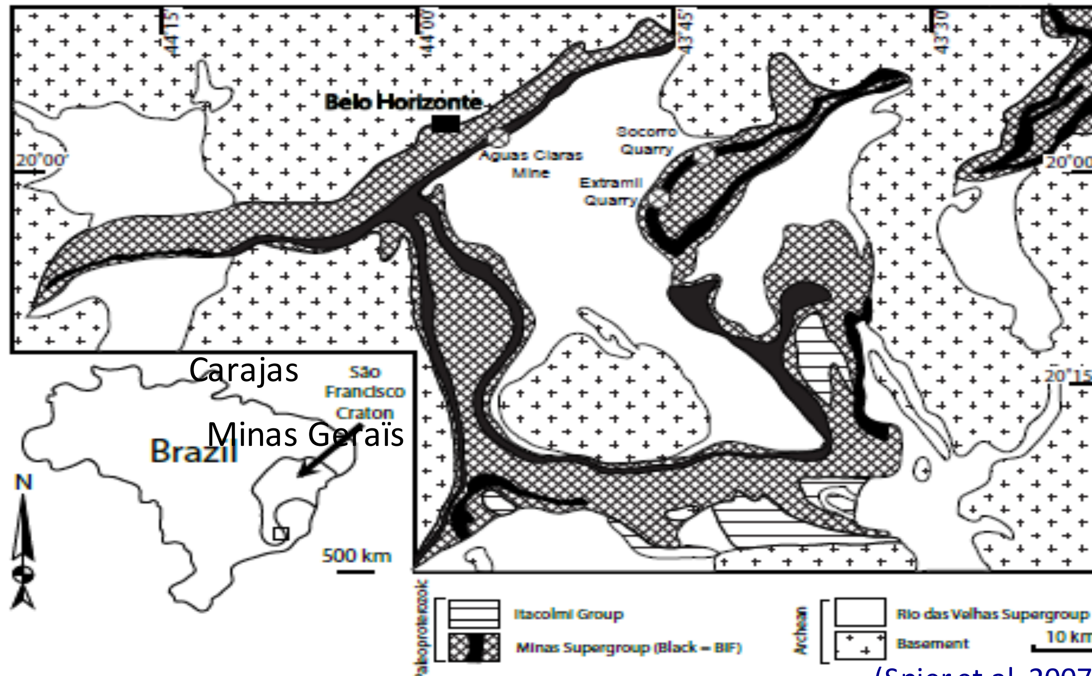
Iron Quadrangle, Minas Gerais

2nd largest iron ore producer outside China

<u>*Largest deposits:*</u>

Carajas region (Amazon basin, Para)

Iron Quadrangle (Minas Gerais).



(Spier et al, 2007)

381 Mt total iron ore production (part from carbonate iron ore)

61 Mt produced from fines (16 %) *(Vale, Samarco (stopped since 2015's dam burst)*

= > Increasing pelletisation since 2012 (Lu et al. 2015).

Challenges carbonate bearing iron ore Pelletisation-briquetisation-compaction

EFFECT OF MINERALOGY & MINERAL CHEMISTRY

1. Changes in **Carbonate mineralogy** (dolomite, kutnahorite..):

   Ca : Mg ratios are specified by steel producing customers (Johnson et al. 2012).
   = > Carbonates complicate pellet making with required Ca : Mg ratios

2. Carbonate reduction reduces pellet strength

   (endothermic calcination of carbonate minerals removes heat from induration process = > if not compensated= reduce pellet quality)

EFFECT OF MINERALOGY & MINERAL CHEMISTRY

Changes in **Iron mineralogy** (hematite-goethite ratio):

Goethite presence

1. Increases impurities, such as Al (may be also due to kaolinite): impact sintering behavior

= > decrease of heat available during melting

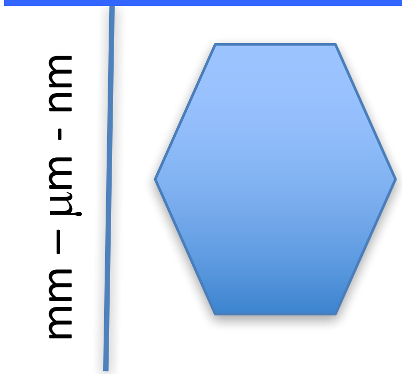
= > formation of higher viscous melts
=> addition of more coke
= > increasing coke-consumption.

2. Deteriorates the granulation efficiency (goethite rich ore is more porous)

Introduction

EFFECT OF ORE TEXTURE
on ore pellitisation efficiency, reactivity in sintering and melting reactions

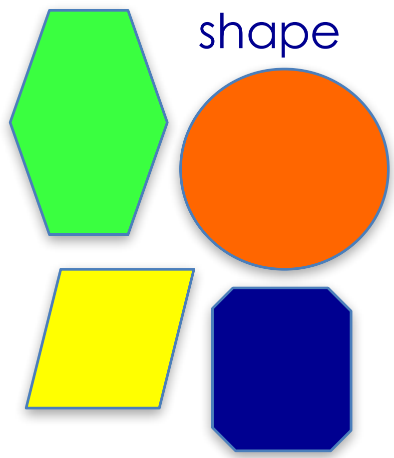
Crystal size



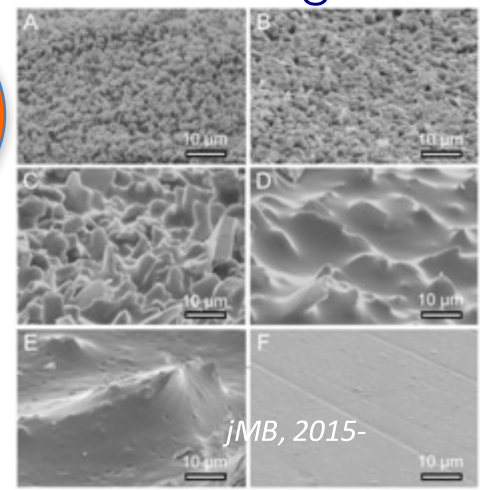
Higher efficiency
&
reactivity at low crystal sizes

Crystal morphology

shape



Surface roughness



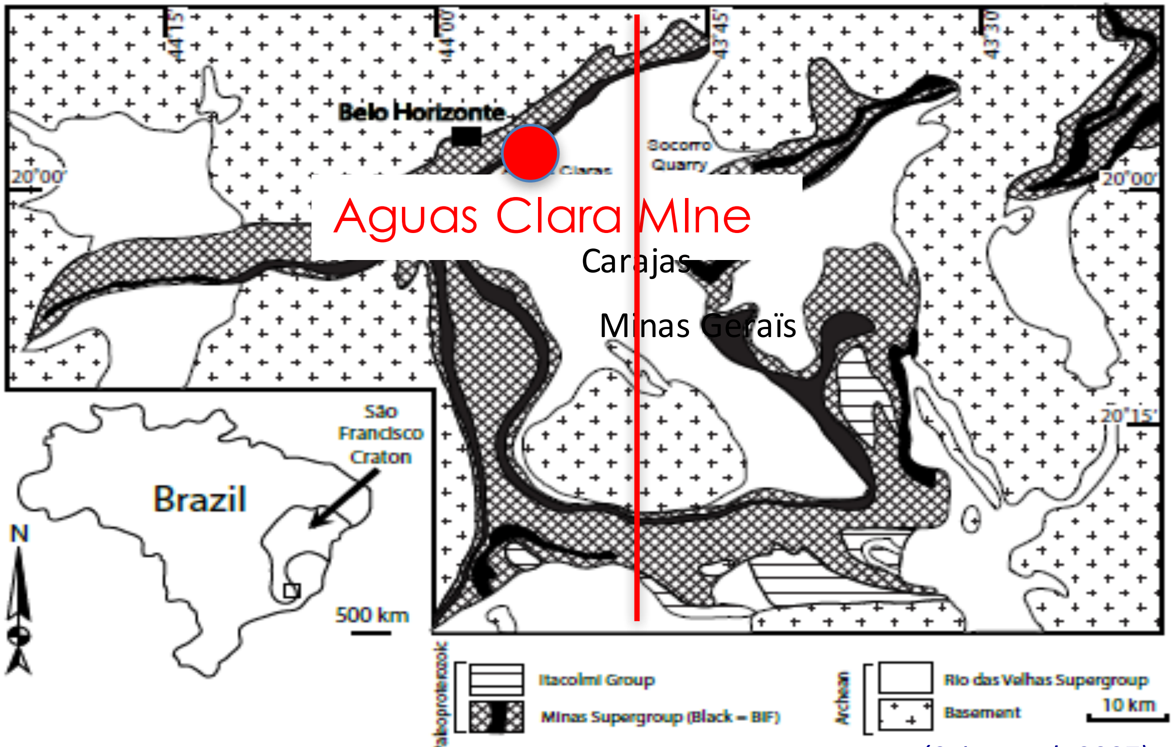
Porosities

Low ore porosity & presence of liberated fine quartz/carbonate particles
⇒ beneficial for sintering

Iron ores of fine crystal size coupled with low degree of hydration favor high productivity & low coke rates during sintering

Iron Quadrangle, Minas Gerais

Low degree of deformation, Low T°C mineral transformation; < 400°T	High degree of deformation, high T°C mineral transformation; > 400°T



(Spier et al, 2007)

Iron Quadrangle, Minas Gerais, Brazil

High grade iron ores (35-50 % Fe)
fine grained (< 50 μm)
⇒ requiring fine grinding to liberate the iron oxides
⇒ the sintering step is the major dust source
⇒ the produced fines are pelletized & commercialized

Low-grade BIFs (15 - 35 % Fe),
contain micro- and nano- metric iron-bearing inclusions within quartz and/or carbonates, mainly dolomite (~ 20 - 50 μm).

⇒ **often stocked as tailings, not valorised**

How to unlock these resources ?

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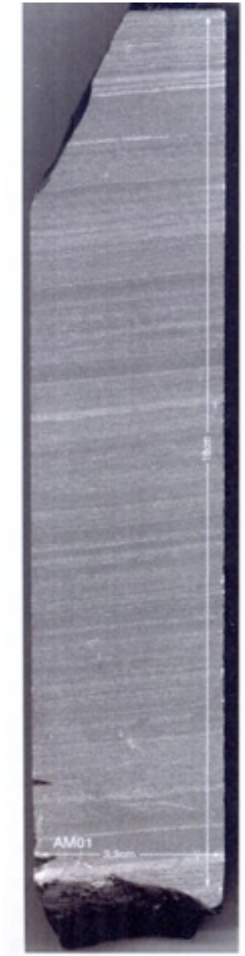
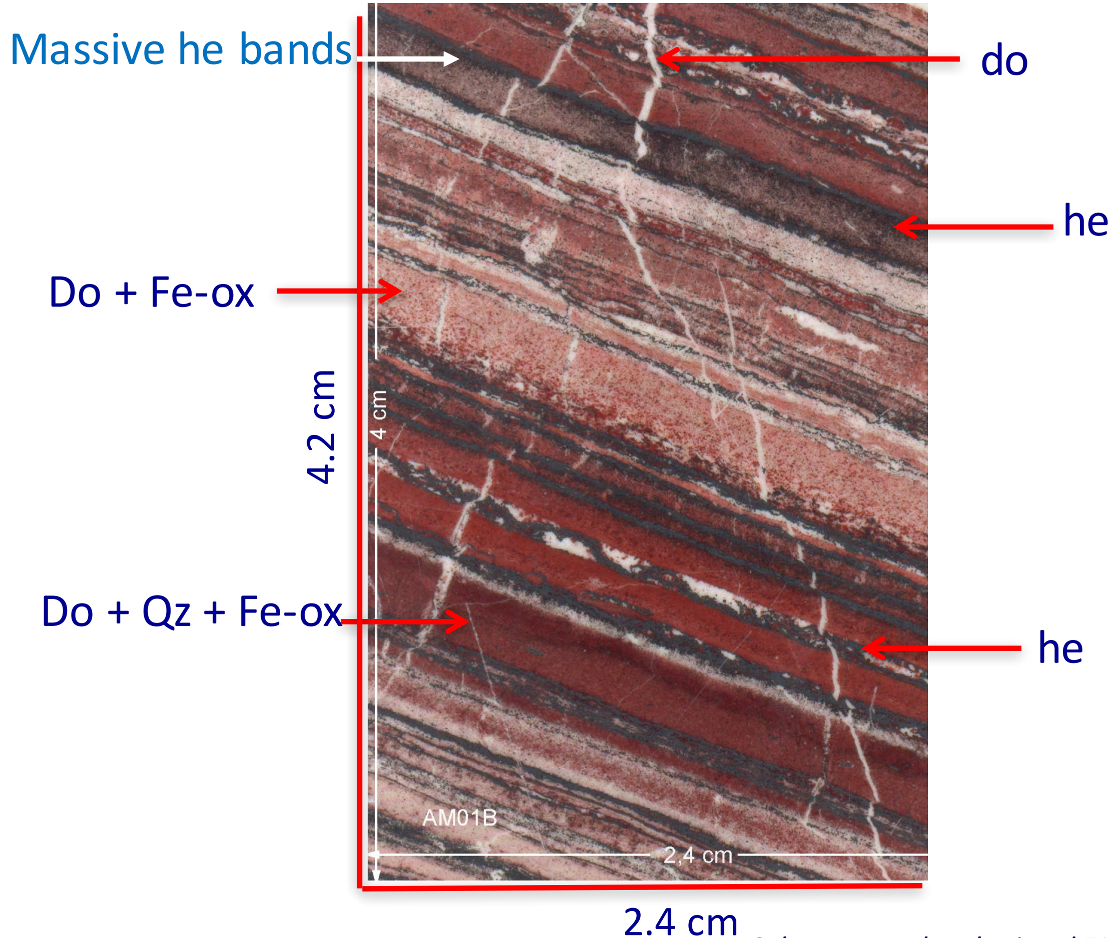
ORE CHARACTERISTICS

Aguas Clara
drill-core
200 m

Low grade ore





Orberger et al. submitted EJM

ORE CHARACTERISTICS

Low grade laminated BIF, Àguas Claras Mine

Chemical composition (wt.%)

$FeO + Fe_2O_3$	26.7
SiO_2	0.2
MnO	0.3
MgO	15.5
CaO	22.3
P_2O_5	0.1
Al_2O_3	<0.05
H_2O	0.2
CO_2	34.1

Hazardous elements (ppm)

As	< 20
Cd	< 1
Cr	< 50
Pb	< 60
U	< 1

Electron microprobe analyses
(point analyses)

dolomite crystals = homogeneous

29 wt. % CaO
21 wt. % MgO
0.4 wt.% MnO

Highly variable FeO up to 7 wt. %

= f(iron oxy hydroxide inclusions dolomite crystals (Morgan et al. 2013).

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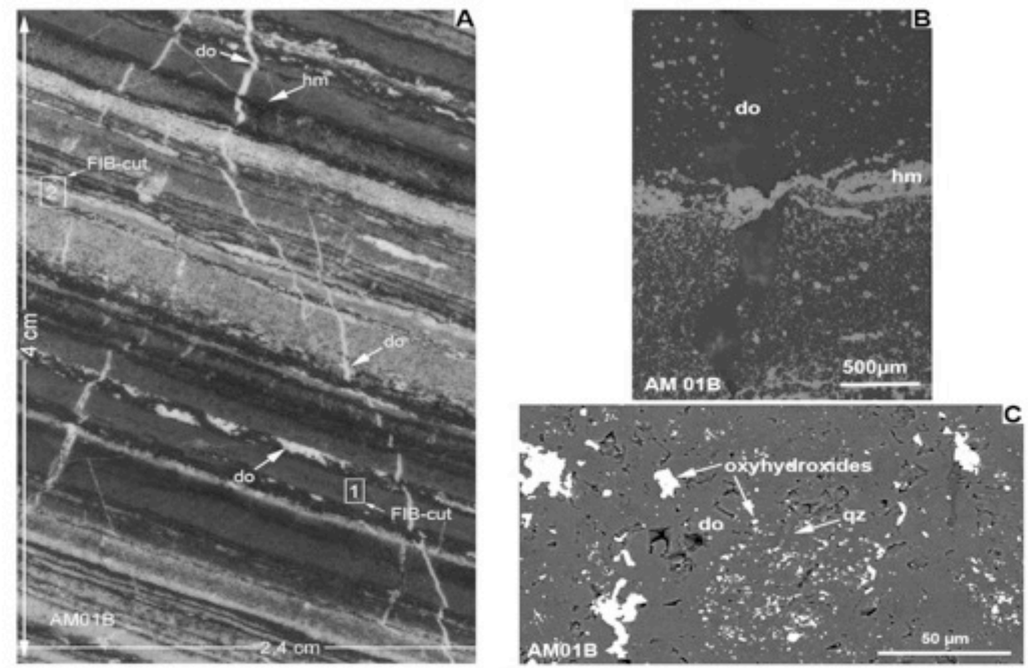
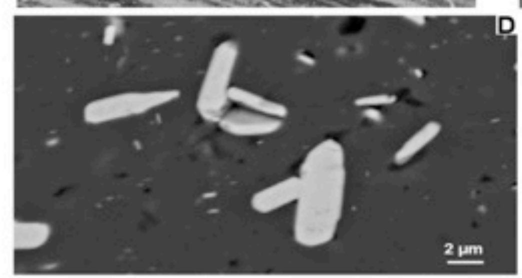
ORE CHARACTERISTICS

Iron oxides 3 Types:
(Optical Microscopy, SEM, Raman spectroscopy):

- Massive layers lenses: fine grained, specularite (needles, subhedral)
- Agglomerated, subhedral interstitial to dolomite and quartz
- Euhedral inclusions (platy) in dolomite and quartz





Dolomite:
- Porous (in matrix)
- Recrystallised as lenses

ORE CHARACTERISTICS

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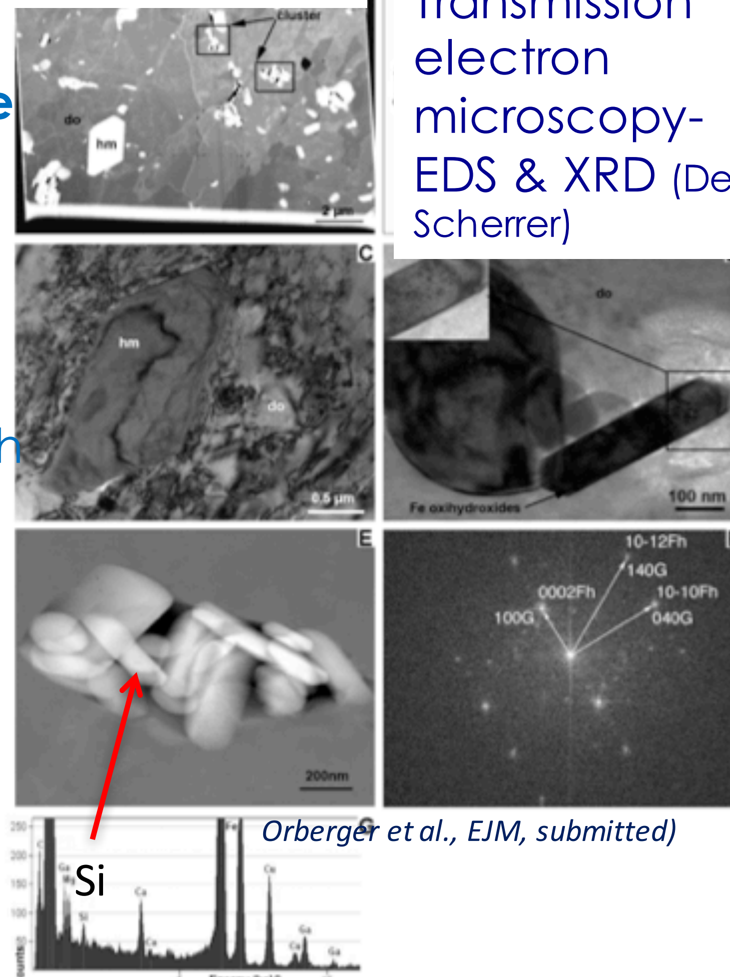
Recrystallized Dolomite

- Triple junctions: Grain boundaries: euhedral hematite
- Distorted due to high dislocation intensity

Porous Dolomite

- Closed porosities
- Filled by clusters of Hematite/goethite

FIB-foil overview



Transmission electron microscopy-EDS & XRD (Debeye Scherrer)

Orberger et al., EJM, submitted)

Discovery (first time):

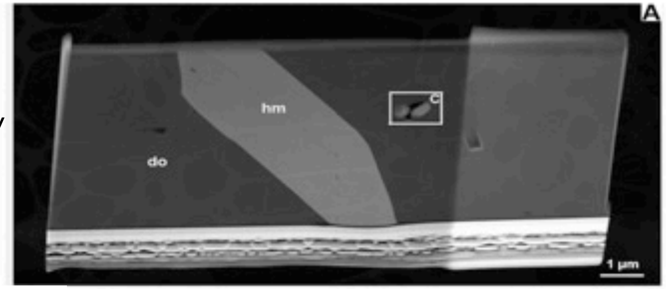
Iron HYDROXIDES inclusions

- Goethite/Ferrihydrite
- Traces of Si
  => *increase stability*
- Platy and lath-shaped forming clusters
- In pores (former fluid inclusions)

ORE CHARACTERISTICS

FIB-TEM

FIB-Foil Overview

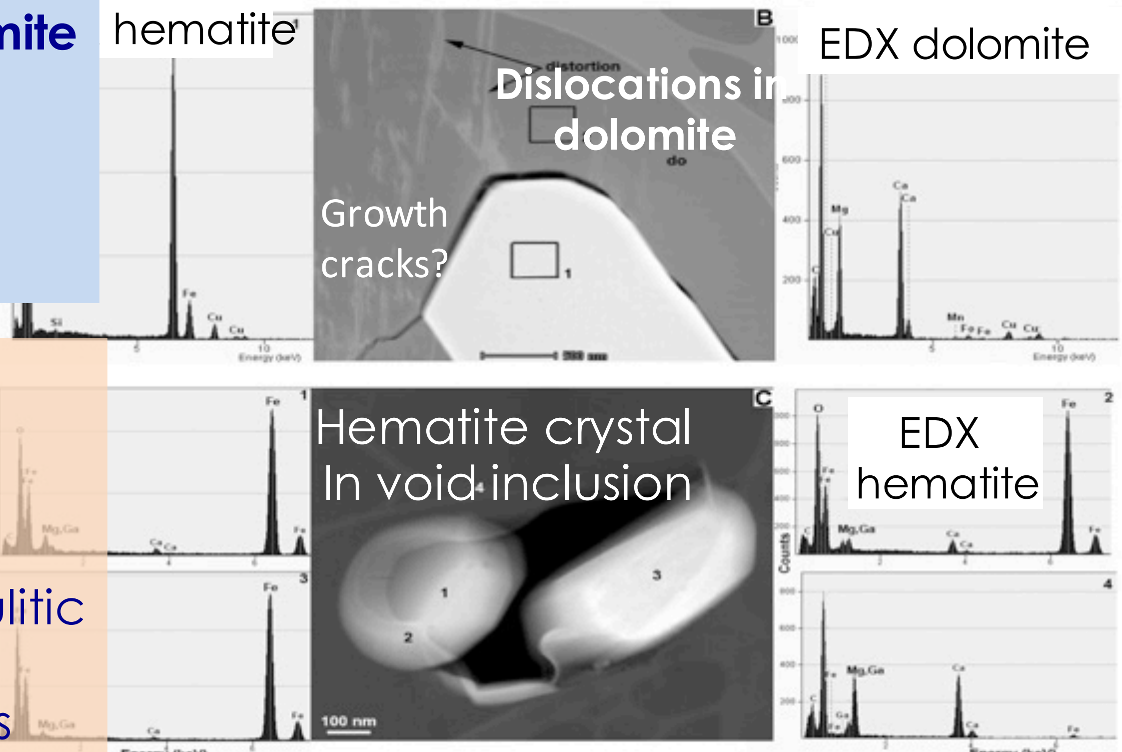


Recrystallized Dolomite

- Dislocations
- Pores
- Cracks

Hematite

- Euhedral
- Lath shaped
- Subhedral/spherulitic
- Oignon structure
- Clustered in pores



CURIE BALANCE ANALYSES ORE CHARACTERISTICS

New magnetic mineral
Cooling < 350° C

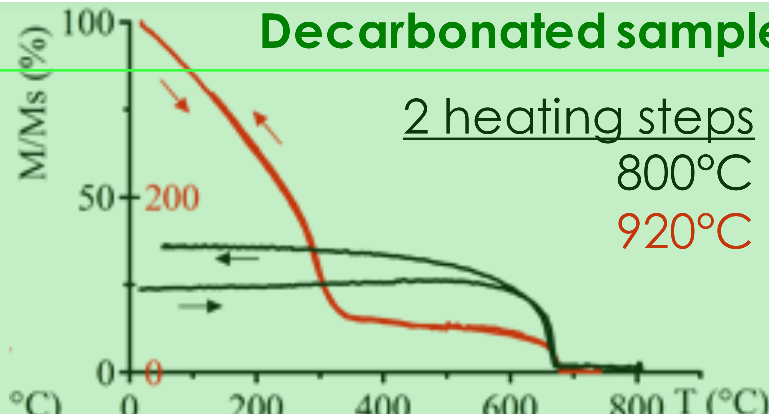
A new magnetic phase
Increase with T increment

680°C

30 min before cooling

Determination of the T-interval for the formation of new magnetic mineral

Decarbonated sample + standard pure dolomite



2 heating steps
800°C
920°C

Heated until 920 °C
= > increase in magnetization is observed during cooling below 350 °C.

Conditions:normal air atmosphere, 0.375 T, linear temperature increase of 10˚C min^{-1};

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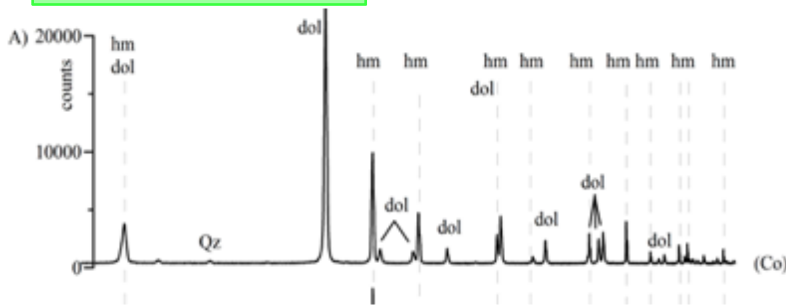
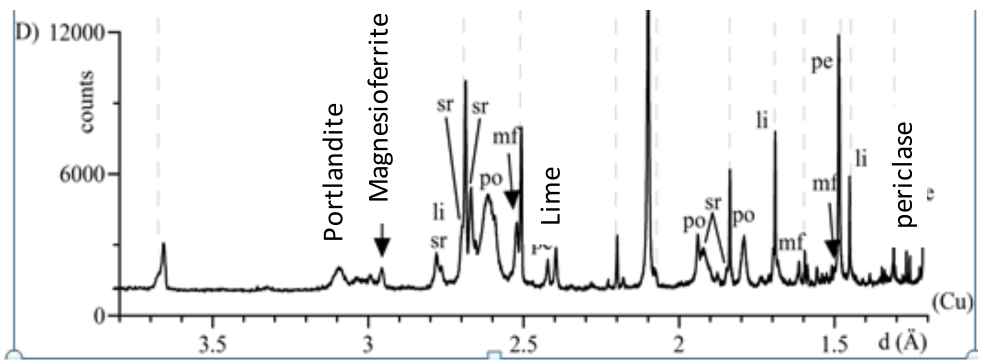
ORE CHARACTERISTICS

XRD

Whole rock



Residue from Curie Balance



Residue from Curie balance:

- Magnesioferrite $Mg,(Fe^{3+})_2O_4$ (cubic)
- Lime CaO
- Portlandite $Ca(OH)_2$ (trigonal)
- Srebrodoskite $Ca_2(FeAl)O_5$ (orthorhombic)

appear upon cooling < 350 °C

The formation of the new magnetic mineral results from two processes at:

1- T° > 680 °C and < 900 °C
Only possible if Goethite is present
2- T° > 900 °C *(without goethite)*

CONCLUSIONS

High resolution cross-method approach
=> unambiguous results

Key-parameter definition

- Grain size < 50 µm

Do: homogeneous composition

1. porous poorly crystalline + (Fe-Ox-Hydrox inclusions)

=>**porosity estimation**

2. *massive (Fe-ox inclusions)*

He: trace element-free

- veins
- platy, laths (nm),
- individual (µm),
- agglomerated (mm)
- inclusions or clusters in do-pores (nm)

Goe: (app. < 1 wt.%)
included in closed porosities platy as clusters
(Al-free, Si-bearing *(increase stability),*

can occur interstitial « crusts » (Spier et al. 2007)

Density adjustment (do: 2.84; he: 5.3)
The two dolomite population behave differently

What to quantify?

downscaling: drill core –polished thin sections
RGB camera -> MLA, QEMSCAN….

Porous dolomite
+
Fe-inclusions
Rose colour

Massive dolomite+ qz
+
Fe-inclusions
Dark red

Massive dolomite
Veins

white

Hematite agglomerates

QEMSCAN

Massive Hematite veins and lenses

Parameter determination for beneficiation design

CONCLUSIONS

Decision making

Formation of density contrasting – magnetic minerals sintering = energy consumption

use for parameter definition: **gravity & magnetic separation**

Mineral	D
Magnesioferrite $Mg,(Fe^{3+})_2O_4$ (cubic)	4.65
Srebrodoskite $Ca_2(FeAl)O_5$ (orthorhombic)	3.76
Lime CaO (cubic)	3.35
Portlandite $Ca(OH)_2$ (trigonal)	2.23

appear upon cooling < 350 °C

Ongoing:
Grinding parameter determination

Studies on CB residue

- Grain size increase?
- Phase chemistry,
- morphologies, surfaces
- Inclusions

Thanks

Vale

CAPES- COFECUB (French-Brazilian Project)

CNRS