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Mineralogical characterization and comparative study of two processing methods of iron ore from the Anini deposit (NE Algeria)

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Abstract. The objective of this article is to study the possibilities of enrichment of the iron ore from Jebel Anini and to develop these mineral resources in order to use them in the metallurgical complex of Annaba. Representative samples were taken from Anini iron mine located in the northwest of the Wilaya of Setif. After sampling, mineralogical, chemical and size particles' characterization was carried out. However, the analyzes

performed by (XRD, SEM and FX) show that the ore is iron type hematite clay and siliceous gangue. The average contents of Fe₂O₃, SiO₂ and Al₂O₃ are respectively 55%, 26.20% and 12%. The data collected after several preliminary tests of enrichment by washing (wet sieving) of the ore reveal significant results in iron content is 62% Fe₂O₃, 2 to 3% of quartz and 2 to 3% of clay. The tests conducted by wet magnetic separation show, on the one hand, remarkable results in iron content of 65.11% against 2.46% SiO₂ and 1.73% Al₂O₃ and, on the other hand, that the enriched product meets the standards required by metallurgy, releases from processes can be used as an addition in the preparation of cement.

Keywords: Algeria, Anini, iron ore, characterization, particle size, enrichment, steel, cement.

Мінералогічна характеристика та порівняльне дослідження двох методів обробки залізної руди родовища Аніні (північно-східний Алжир)

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Анотация. Метою статті є вивчення можливості збагачення залізної руди родовища Джебель-Аніні та можливості використання цих мінеральних ресурсів за допомогою використання металургічного комплексу Аннаба. Репрезентативні зразки були відібрані у межах залізрудного родовища Аніні, розташованого на північний захід від Вілайи Сетіфа. Після відбору зразків, визначалися розмір частинок мінералів, встановлювалися їх хімічна та мінеральна характеристики. Втім аналіз, проведений (XRD, SEM і FX), показує, що руда являє собою гематитову глину залізного типу і кременисту породу. Середній вміст Fe₂O₃, SiO₂ і Al₂O₃ становить відповідно 55%, 26,20% і 12%. Дані, зібрані після кількох попередніх випробувань зі збагачення шляхом промивання (мокрого просіювання) руди, показують важливість отриманих результатів щодо вмісту заліза 62% Fe₂O₃, 2-3% кварцу і 2-3% глини. Випробування, проведені методом мокрої магнітної сепарації, показують, з одного боку, чудові результати в вмісті заліза 65,11% проти 2,46% SiO₂ і 1,73% Al₂O₃, а з іншого боку збагачений продукт відповідає стандартам, необхідним для металургії, а відходи процесу збагачення можуть бути використані як додаток в приготуванні цементу.

Ключові слова: Алжир, Аніна, залізна руда, характеристика, розмір частинок, збагачення, сталь, цемент.

Introduction. Iron oxide is the most sought-after ore in the world due to its utilitarian properties, such as hardness, strength and durability; it is used mainly for

the production of various types of steel, which makes it essential for all industries. In its native state, iron is a generally dark metal, constituting about 5% of the

earth's crust. It is a very reactive element and oxidizes very easily. In nature, it occurs in the form of mineral rocks, whose metallic iron can be economically extracted. The ores are usually rich in iron oxides and the color varies from dark gray and bright yellow to dark purple. The iron itself is usually in the form of magnetite (Fe_3O_4), hematite (Fe_2O_3), goethite, limonite or siderite (Minerals Information Institute).

Hematite is also known as "natural ore", and that is the form of the most common rock on the surface of the earth which is most often used in industry.

As the use of steel is multiple and demand for it has increased considerably in recent years due to the growing consumption of large emerging countries, especially China, the price of iron ore, has risen sharply which has diverted a relatively quiet market away from other commodities (Olivier., 2012).

The subsidiary SOMIFER-spa, of the group Ferphos operates the mines of Khanguet (Tebessa), Sidi Maarouf (Jijel) and Djebel Anini (Setif). The latter contains geological reserves of 35.75 million tons with 55% Fe_2O_3 .

The deposit of Jebel Anini is exploited by small mines, it is encased in karst cavities carved in limestone of Cenomanian-Turonian age; it consists of a ferriferous compound comprising a rocky group of hematite made of hematite debris loose clay (Chaabia et al., 2015).

Thus, several hematitic veins have been identified with a minimum width of 5 m and a maximum length of 500 m (Chaabia et al., 2015).

The iron ore of the Jebel Anini deposit is not intended for the steel industry even though its iron content is important because the amount of silica is very high. Besides, by performing chemical analysis of crushed samples of different size fractions, it was found that the iron content changes when the rate of quartz decreases.

For this purpose it would be advisable to conduct research to study the possibilities of recovery of the iron mass with a maximum reduction of silica (quartz) so that it can be acceptable for steel consumers.

Over the past five decades, financial markets have seen the emergence of a new raw material; iron ore, which was at the beginning of the century marketed exclusively on the basis of long-term contracts concluded directly between the large mining companies and the client industries, mainly steel producers (about 98% of its world production is destined for the steel industry). Indeed, iron ore is an essential raw material for the development of modern economies (Olivier, 2012).

It represents nearly 95% of all metals used in modern industrial societies (Yellishetty et al, 2010; Casali, 2013).

Mineral processing is defined as the process whereby a crude mined ore is separated to remove undesirable minerals whose value is negligible. These are commonly referred to as "gangue". The separation in question may be carried out by gravity concentration equipment, flotation, magnetic separation and electrostatic separation (Sanjay Kumar et al, 2014).

Iron ore beneficiation encompasses all methods used to improve chemical, physical or metallurgical characteristics and to ensure that iron ore meets the technical requirements for the manufacture of steel. These techniques include crushing, screening homogenization, concentration and agglomeration. When the use of iron ore is not possible because of its low metal content, iron ores are mainly processed by crushing, grinding, screening, classification, gravity separation, magnetic separation and flotation technologies (Outotec, 2012). Magnetic separation is most commonly used to separate natural magnetic iron ore (magnetite) from a variety of less magnetic and non-magnetic materials. Today, magnetic separation techniques are used to benefit more than 90% of all iron ore. This method is used for separating weakly magnetic iron minerals such as hematite, gangue.

Materials and Methods. *Sample collection in the field.* Samples were collected in Zone I, Zone II, Zone III, the central area, and the storage area, which covered the entire mine and avoided segregation errors to ensure better representation of samples. As a result, these coordinates were converted into the UTM system, to be exploited in the national coordinate system (UTM Nord Sahara 1959, zone 31). The iron ore sampling points taken from the study area are presented in a map using ArcGis 10.2.21 software (Figure 1).

Multiple comparison test of the distribution of elements (Fe_2O_3 , SiO_2 , Al_2O_3 , CaO , MgO) in the different sampled zones:

To detect possible heterogeneities in the distribution of the different elements between the different sampled areas, the results of preliminary analysis by X fluorescence were submitted to an estimation by analysis of the variance (ANOVA) whose probability was assigned to the interval confidence of 95.00%, followed by the Tukey test to measure the differences in oxide contents between the different sampling zones.

According to the ANOVA test results; there is no significant variation in the average contents of the sampled elements (Fe_2O_3 , SiO_2 , Al_2O_3 , CaO , MgO) between the different sampling zones, these results testify to the representativity of the samples taken.

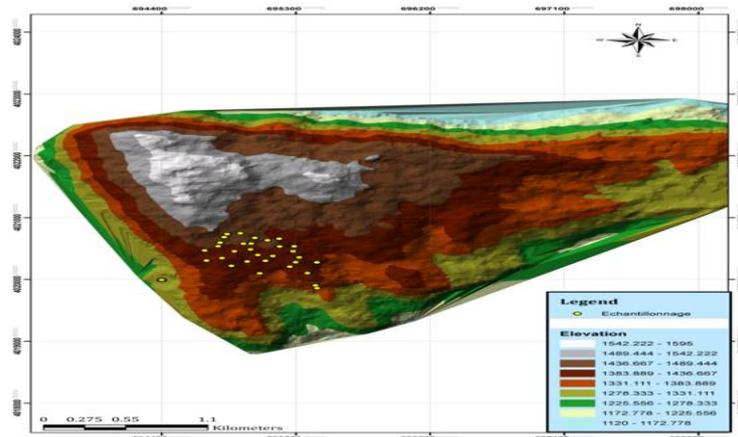


Fig. 1. Districts sampled in Jebel Anini

Preliminary analysis results. A total of 35 samples were taken (7 samples in each zone) and prepared in the Mineral Laboratory of the Mining Department at Annaba University. Subsequently,

from each sample, a quantity of 10 grams was sent to the laboratory of the "Hadjar-soud" cement company of Skikda for chemical analysis. The analysis results are shown in the table below.

Table 1. X-ray Fluorescence Preliminary Analysis Results of Iron Ore from Anini

| Content (%) N° of Sample | Zones | Fe ₂ O ₃ | SiO ₂ | Al ₂ O ₃ | CaO | MgO |
|-----------------------------|--------------|--------------------------------|------------------|--------------------------------|-------------|-------------|
| 01 | Zone I | 44.86 | 18.48 | 9.44 | 1.76 | 0.62 |
| 02 | Zone I | 51.08 | 20.52 | 6.75 | 1.05 | 0.49 |
| 03 | Zone I | 50.18 | 24.07 | 12.64 | 1.34 | 0.74 |
| 04 | Zone I | 48.45 | 16.19 | 10.57 | 1.20 | 0.69 |
| 05 | Zone I | 49.57 | 20.65 | 8.33 | 1.07 | 1.10 |
| 06 | Zone I | 45.63 | 17.41 | 7.89 | 0.82 | 0.83 |
| 07 | Zone I | 47.57 | 18.22 | 7.53 | 1.82 | 1.10 |
| 08 | Zone II | 50.94 | 28.78 | 11.34 | 0.93 | 0.85 |
| 09 | Zone II | 50.86 | 24.19 | 9.86 | 0.44 | 0.82 |
| 10 | Zone II | 52.27 | 18.80 | 6.88 | 1.55 | 0.62 |
| 11 | Zone II | 50.18 | 27.10 | 8.07 | 1.05 | 1.01 |
| 12 | Zone II | 51.08 | 25.75 | 10.01 | 0.30 | 0.69 |
| 13 | Zone II | 54.91 | 16.52 | 7.66 | 1.18 | 0.88 |
| 14 | Zone II | 48.38 | 27.83 | 10.11 | 1.06 | 0.55 |
| 15 | Zone III | 53.48 | 25.87 | 9.63 | 1.06 | 0.98 |
| 16 | Zone III | 52.66 | 22.37 | 7.62 | 1.25 | 1.01 |
| 17 | Zone III | 50.54 | 19.66 | 9.18 | 0.89 | 0.64 |
| 18 | Zone III | 48.73 | 21.71 | 6.81 | 0.78 | 0.70 |
| 19 | Zone III | 51.08 | 26.64 | 9.29 | 0.65 | 0.77 |
| 20 | Zone III | 45.88 | 20.62 | 7.34 | 0.90 | 0.90 |
| 21 | Zone III | 51.56 | 26.47 | 12.06 | 0.82 | 1.11 |
| 22 | Central zone | 48.86 | 27.79 | 13.23 | 1.95 | 0.52 |
| 23 | Central zone | 52.06 | 20.98 | 13.89 | 1.64 | 0.63 |
| 24 | Central zone | 51.10 | 25.47 | 12.63 | 0.72 | 0.88 |
| 25 | Central zone | 54.13 | 22.54 | 12.71 | 1.38 | 0.67 |
| 26 | Central zone | 54.09 | 28.25 | 11.71 | 0.71 | 0.89 |
| 27 | Central zone | 53.38 | 12.64 | 6.34 | 1.03 | 0.71 |
| 28 | Central zone | 55.78 | 16.96 | 12.68 | 0.54 | 0.83 |
| 29 | Storage zone | 53.11 | 23.24 | 10.51 | 1.60 | 0.59 |
| 30 | Storage zone | 52.37 | 25.44 | 7.18 | 0.74 | 0.81 |
| 31 | Storage zone | 51.31 | 24.05 | 11.03 | 0.80 | 1.06 |
| 32 | Storage zone | 48.65 | 21.53 | 11.27 | 0.58 | 0.98 |
| 33 | Storage zone | 49.21 | 19.98 | 21.53 | 0.51 | 0.97 |
| 34 | Storage zone | 50.73 | 14.39 | 10.46 | 1 | 0.73 |
| 35 | Storage zone | 54.85 | 18.81 | 12.41 | 0.92 | 0.91 |
| Average | | 50.84 | 21.99 | 10.18 | 1.02 | 0.80 |

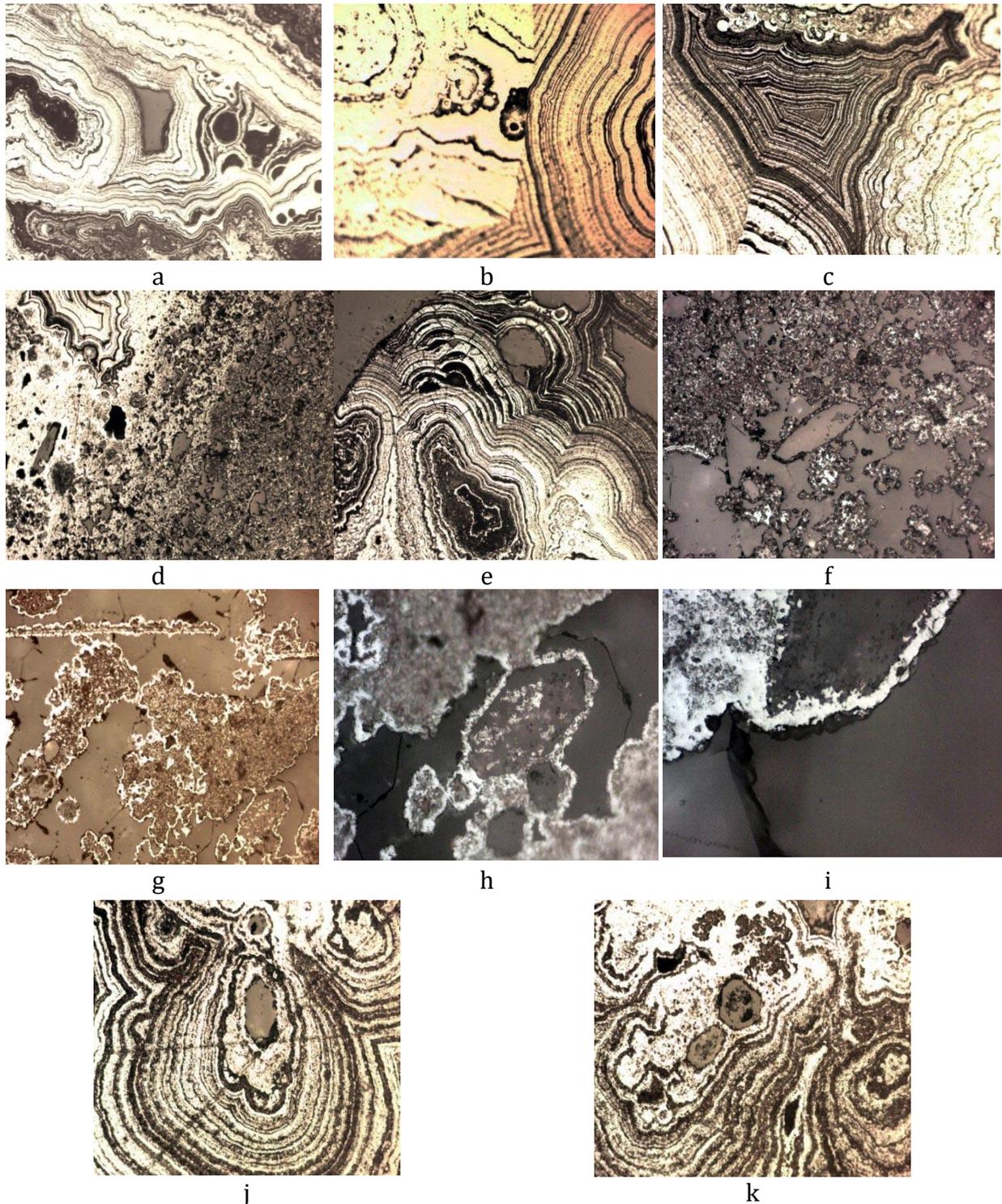


Fig. 2. Mineralogical composition of the studied ore

Chemical characterization of Anini mineral oxides. *Mineralogical characterization of the ore.* Ore samples subjected to optical microscopic observations with reflected light showed the presence of the following main minerals:

Reflected light microscopy. A / Predominant compound of metallic minerals:

Hematite ; most of the sample consists of colloform (type of sedimentary texture) hematite which previously fills Opel-spares. Sometimes this

porosity is not completely filled with hematite and open spaces are common (Image a- 5X). (Open space in the center of the image 440 μm in diameter).

Hematite layers are thick (20-40 μm) and parallel (Image b-10X). Sometimes, while filling open spaces, there are rhythmic sequences of the Senate and layers of a dark, mineral color, as shown in Image c-10x). SEM studies will help us identify this mineral. Iron oxide precipitation sometimes

shows a multistep process with various superimposed episodes with different directions (Image d - 5X).

This sample includes two different types of mineralization:

A / Massive hematite (described below), very rich in iron (60-70% of ferrum)

B / iron oxide disseminated in a gangue, two types are shown in the image e-5X).

Type B – Mineralization

The hematite is quite resistant , of rounded shape, plus or minus and up to 150 µm. It (hematite) presents a stage of later formation, in comparison with the rock (Image f- 20X).

Occasionally, iron oxide particles are composed of 2 (or more) different minerals. In this case, the hematite is distributed along the grain boundaries, the core being other iron oxide (Image g-20X).

Frequently, hematite clearly replaces quartz (Image h- 50X)

Even frequent, in the mineralization of type B, sometimes oolitic textures have been seen: from a quartz core (not roundel, well-defined), successive layers of hematite are deposited in a conchoidal-shape. (Image i and j-k-20X).

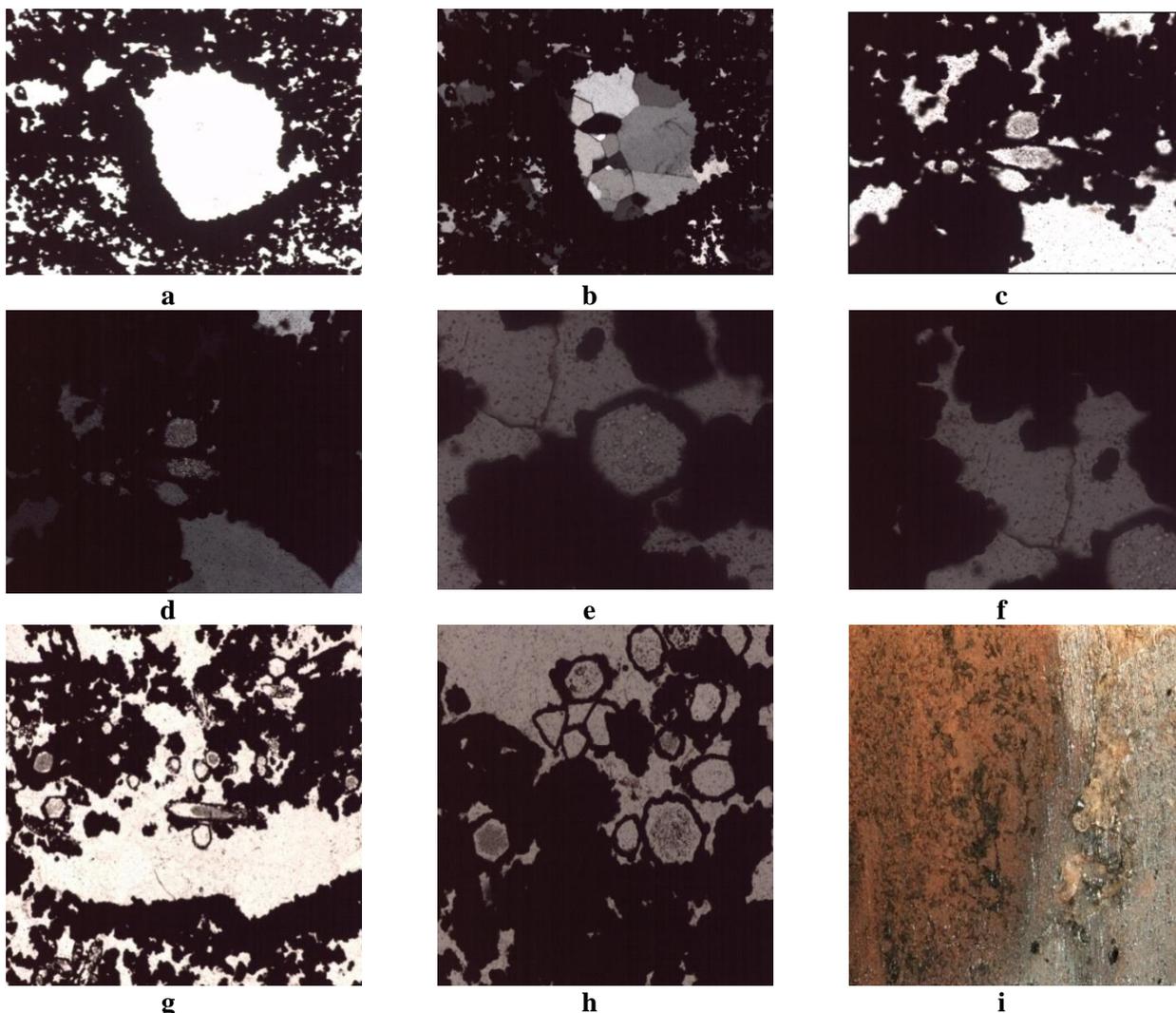


Fig. 3. Mineralogical composition of the studied ore

Transmitted optical microscopy. The gangue consists mainly of crystalline quartz up to 960 µm (~1mm) in diameter (Fig. A and b). Parallel polar, and numbers a- (5X), and cross-polarized numbers b- (5X). It is frequently (at least, larger crystals) polycrystalline quartz. This quartz seems to be previously formed, compared to hematite and there is presence of many fluid inclusions and mineral

(submicron) on its surface. Although not very common, there is another type of quartz: small idiomorphic crystals characterized by a partial replacement by microcrystals of calcite (micrite). This fact is illustrated in image c, e-50X, =, and d-f-50X, Vertical.

This idiomorphic quartz appears to be of hydrothermal origin and of small size (not more

than 60 μm). Microcrystalline calcite found on the surface of hydrothermal quartz is only 4 μm in diameter (Image g-50X, Horizontal). There are some apatite crystals (elongated digits) included in the first type of quartz (the largest) Image h-50X, Horizontal. Mineral inclusions (below 2 μm in

diameter) in quartz are sometimes transparent compounds with Fe in their composition either ankerite or siderite. Image i is representative of the texture of mineralized rock. It is common that hydrothermal quartz also covered by hematite is two types of quartz previous to hematite in time.

X-Ray Diffraction Analysis (XRD).



Iron ore sample > 125 μm



Iron ore sample < 125 μm

The mineralogical analysis carried out by XRD confirmed the mineralogical composition of this mineral identified by optical microscope. According to the spectrum illustrated in the figures

below (Figure 4-5), it is noted that the predominantly observed mineral phase is represented by hematite-quartz.

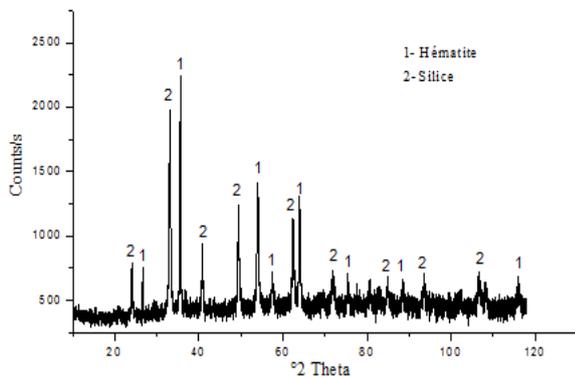


Fig. 4. Spectrum of a sample of Anini iron ore (Setif) obtained by X-ray diffractometer (sample No. 1)

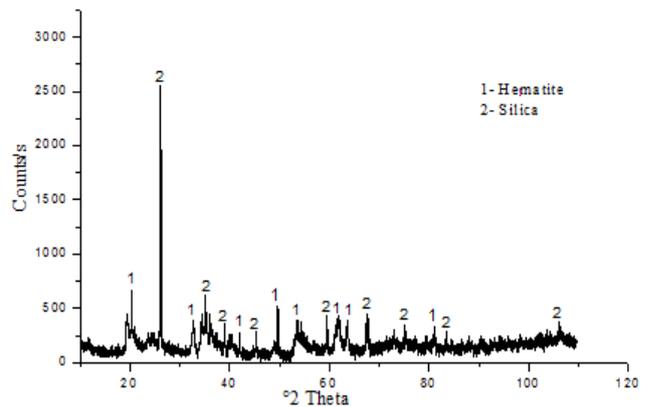


Fig. 5. Spectrum of a sample of Anini iron ore (Setif) obtained by X-ray diffractometer (sample No. 2)

Analysis by Scanning Electron Microscopy (SEM) and EDX.

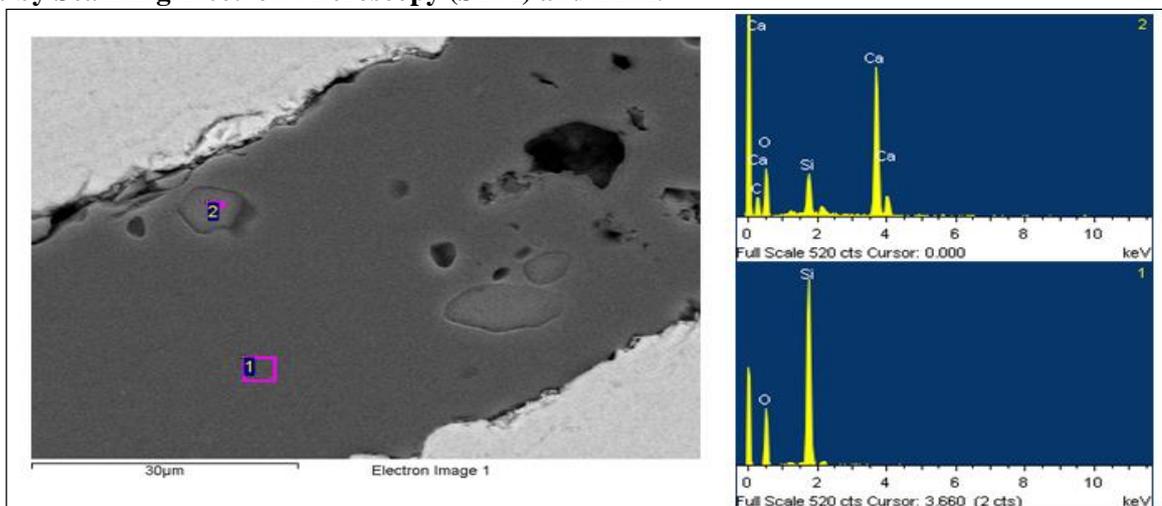


Fig. 6. Observation by Scanning Electron Microscopy (SEM) and EDX (sample No. 1)

Table 2. Processing option: all elements analysed (sample No. 1)

| Spectrum | In stats | C | O | Si | Ca | Total |
|------------|----------|-------|-------|-------|-------|--------|
| 1 | Yes | | 61.41 | 38.59 | | 100.00 |
| 2 | Yes | 19.06 | 52.73 | 3.85 | 24.36 | 100.00 |
| Max | | 19.06 | 61.41 | 38.59 | 24.36 | |
| Min | | 19.06 | 52.73 | 3.85 | 24.36 | |

All results in weight %

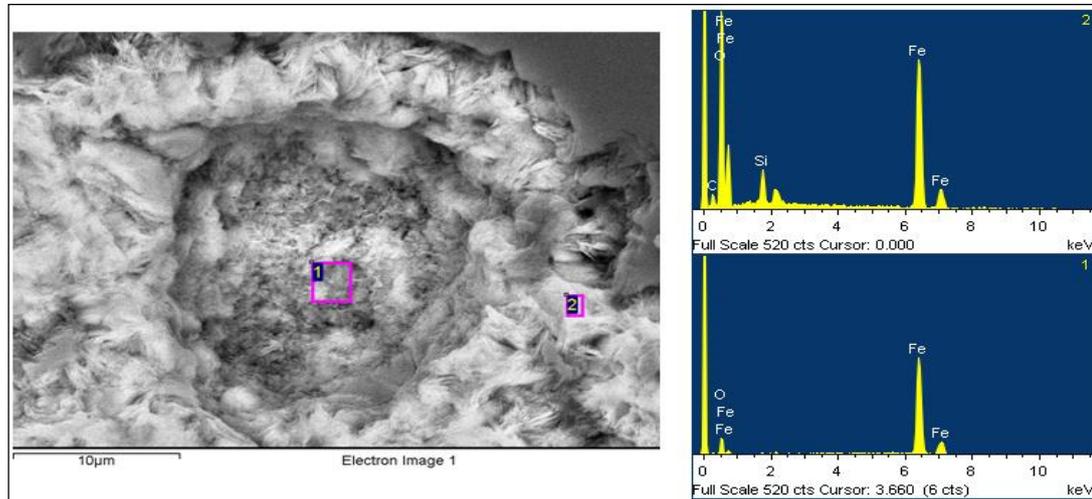


Fig. 7. Observation by Scanning Electron Microscopy (SEM) and EDX (sample No.2)

Table 3. Processing option: all elements analysed (sample No. 2)

| Spectrum | In stats | C | O | Si | Fe | Total |
|------------|----------|------|-------|------|-------|--------|
| 1 | Yes | | 13.19 | | 86.81 | 100.00 |
| 2 | Yes | 9.16 | 50.40 | 2.23 | 38.20 | 100.00 |
| Max | | 9.16 | 50.40 | 2.23 | 86.81 | |
| Min | | 9.16 | 13.19 | 2.23 | 38.20 | |

All results in weight %

Preliminary enrichment study of Anini iron ore: washing (settling). According to the results from the chemical analysis (after the wet sieving process) of the different particle size classes of the Anini iron deposit, carried out by atomic adsorption spectrometry, there is a significant decrease in percentages after washing, it is also noted that the iron content is 61.57% as against 55.98%, in the unwashed crude ore. Similarly, the silica content decreases from 26.20% to 2.30% in the washed ore, the same for the Al_2O_3 content which goes from 12% to 3%, which confirms the remarkable results obtained by the washing process (wet sieving). A comparison of the results of the chemical analyses obtained after the application of this method is decisive (Chaabia et al., 2015).

- in the refuse of the washing operation (wet sieving), we observe a change in iron contents up to 61.98% against a significant decrease in silica content of the order of 2.36% and alumina of 3.33%. The analysis of the results shows the high percentage of silica and alumina (37.37% and 10.69%) recovered in the sieve pass (Chaabia et al, 2015).

- the results of X-ray analysis of concentrated samples of the washing operation (wet sieving) of the four classes show that the mineralogical phase observed consists mainly of hematite (Fe_2O_3), however some traces of quartz and calcite are observed (Chaabia et al., 2015).

Enrichment tests of Anini iron ores by wet magnetic separation. From the obtained results, the high intensity magnetic separation (HIMS) obtained, gave a significant increase in iron content, and a remarkable decrease in the combined fraction of clay and alumina. The Fe_2O_3 content is 65.11%, with an increase of 28.87% compared to starting content (Fe_2O_3 content in crude ore is 50.52%).

In addition, the silica and alumina contents decreased from 24.06% and 7.80% to 2.46% and 1.73% respectively. The importance of the results of this study resides in the efficiency of the "HIMS" process in terms of ore beneficiation to make it usable in the iron and steel industry (Chaabia et al., 2015).

The processing of Anini iron ore by the (HIMS) high-intensity wet magnetic separation process reveals significant results as a result of the

increase in iron content and the remarkable decrease in clay impurities and quartz (Chaabia et al., 2015).

The iron content is 65.11% against a feed content of 55.98%. Furthermore, the silica and alumina contents have significantly decreased by 2.46% and 1.73% respectively; these levels largely meet the standards of the metallurgical industry. Given the release characteristics obtained by this method (12.16 Fe₂O₃, 24.55 SiO₂ and 7.02 Al₂O₃), the latter is used for the manufacture of building materials (Portland cement) (Chaabia et al., 2015).

Conclusions. The research carried out on this deposit, as part of this study, allowed us to draw the following conclusions:

- The economic success of any mining sector requires a physico-chemical characterization of the ore envisaged. In the case study conducted on the enrichment of Anini iron ore carried out in the laboratory of Mining Resources Valorization and Environment of the University of Annaba, the studied ore was found to be very complex and, consequently to exhibit a diversity of ferriferous minerals and gangue minerals. Two methods are used for the enrichment of iron ore of Anini, whose yield is acceptable for the metallurgical industry with some advantages in favor of the magnetic separation; among these advantages we can mention:

- Rejection ores for this method obey the requirements of the cement plant including Portland cement.

- The iron content in the concentrate recovered by this method is significantly higher than that obtained by washing.

- The range of particle size classes used in the magnetic separation method is much larger than those used in washing. This allows us to use almost all of the prepared ore.

- Magnetic separation is a modern method compared to washing, which is a very old method.

- The expansion of the Algerian iron and steel industry is largely based on the use of all iron ore resources.

The Anini deposit represents one of the main sources in the field of iron ore supplies for the domestic steel industry. Considering these remarkable advantages in favor of the high intensity wet magnetic separation "HIMS", this method is strongly recommended for the preparation and enrichment of Anini iron ore, and as prospects can be cited; the rejection of the magnetic separation

which contains 16% of iron can be treated by other more efficient techniques which allows us to recover the rest of the iron from this rejection.

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