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Sedimentary Aspects, Composition And Environmental Issues Related To The Beneficiation of Low Grade Sandy Phosphorites From Sehib Mining District, Gafsa, Southern Tunisia

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الجوانب الرسوبية والتكوين والقضايا البيئية المتعلقة بتخصيب الفوسفوريت الرملي منخفض الجودة من منطقة سهيب، قفصة، جنوب تونس

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Abstract:
Sedimentary, mineralogical and geochemical study is carried out to assess the impact of the change of the depositional environment induced by a major detrital discharge on Lower Eocene phosphorite composition. The detrital discharge is driven by a forced regression during Upper Ypresian. The consequences of such a situation are summarized in major shift in the redox conditions of the depositional environment resulting in a major drop of Cd content in the sandy phosphorites (Cd content drops from 90µg g-1 in the commercial phosphorites to 8µg g-1 in the sandy phosphorites) and interpreted as strong indicator of deposit environment oxic alteration, leading to the termination of the phosphate formation. Disruption of sediment structure producer of carbonate-fluoapatite, which previously furnished with pore water chemical conditions (pH, alkalinity) and constituents such as Ca2+ Mg2+ F-, and dissolved organic molecules have a key role in regulatiing carbonate fluorapatite formation. The interpretation of some inter-element relationships confirms such points of view. Phosphate-silica separation by flotation, using a phosphate-enriched fraction with a particle size suitable for flotation, is carried out in conventional cells combining three steps (1) anionic flotation of phosphate yields a concentrate. Removal of the anionic collector and oil coating from the surface of the particles present in the pre-concentrate by sulfuric attrition in a thick pulp (60 to 75% solids) with a pH of approximately 4. Cationic flotation of the residual silica from the pre-concentrate with a collector based on amine or amine salts combined with DO. This double flotation process is generally very selective. From feed containing 15 to 65% TCP (Tri-calcium phosphate), the concentrates contain 70 to 80% TCP for phosphate recovery of 75 to 90%.

Keywords: Phosphorites, Beneficiation, Compositional trends, mineralogy, geochemistry, Sehib, Tunisia

الملخص
أُجريت دراسة رسوبية ومعدنية وجيوكيميائية لتقييم تأثير تغير بيئة الترسيب الناجم عن تدفق رسوبي كبير على تركيب الفوسفوريت في العصر الإيوسيني السفلي. وقد نتج هذا التدفق الرسوبي عن انحسار قسري خلال العصر الإيبريسي العلوي. وتتلخص نتائج هذه الحالة في تحول كبير في ظروف الأكسدة والاختزال لبيئة الترسيب، مما أدى إلى انخفاض حاد في

محتوى الكادميوم في الفوسفوريت الرملي (انخفض محتوى الكادميوم من 90 ميكروغرام/غرام في الفوسفوريت التجاري إلى 8 ميكروغرام/غرام في الفوسفوريت الرملي)، ويُفسر هذا الانخفاض كمؤشر قوي على تغير بيئة الترسيب نحو الأكسدة، مما أدى إلى توقف تكوين الفوسفات. يؤدي اضطراب بنية الرواسب، التي تُنتج كربونات فلوراباتيت، والتي كانت مُجهزة مسبقًا بظروف كيميائية مناسبة (الأس الهيدروجيني، القلوية) ومكونات مثل أيونات الكالسيوم والمغنيسيوم والفلوريد، بالإضافة إلى الجزيئات العضوية الذائبة، إلى دور محوري في تنظيم تكوين كربونات فلوراباتيت. ويؤكد تفسير بعض العلاقات بين العناصر هذه الآراء. يتم فصل الفوسفات عن السيليكا بالتعويم، باستخدام جزء غني بالفوسفات ذي حجم جسيمات مناسب للتعويم، في خلايا تقليدية تجمع بين ثلاث خطوات: (1) التعويم الأنيوني للفوسفات ينتج عنه مُركّز. إزالة المُجمِّع الأنيوني والطبقة الزيتية من سطح الجزيئات الموجودة في المُركَّز الأولي عن طريق الاحتكاك بحمض الكبريتيك في لُبٍّ كثيف (60 إلى 75% مواد صلبة) عند درجة حموضة تقارب 4. ثمّ التعويم الكاتيوني للسيليكا المتبقية من المُركَّز الأولي باستخدام مُجمِّع قائم على الأمين أو أملاح الأمين مع الأكسجين المذاب. تتميز عملية التعويم المزدوجة هذه بانتقائية عالية عمومًا. فمن مُغذِّيات تحتوي على 15 إلى 65% من فوسفات ثلاثي الكالسيوم، تحتوي المُركَّزات على 70 إلى 80% من فوسفات ثلاثي الكالسيوم، ما يُؤدي إلى استخلاص الفوسفات بنسبة 75 إلى 90%.

الكلمات المفتاحية: الفوسفوريت، المعالجة، الاتجاهات التركيبية، علم المعادن، الجيوكيمياء، سهيب، تونس

Introduction

Upgrading the P2O5 concentration in low-grade sandy phosphorites from levels usually below 15-20% to about 28-30% for commercial usage is the main goal of beneficiation. These ores frequently have high siliceous (quartz) or carbonaceous (calcite, dolomite) gangue, necessitating the use of both physical and physico-chemical methods. The progressive depletion of reserves of rich or easily enriched phosphates in Tunisia is leading to an interest in minerals with low P2O5 content, among which are the siliceous phosphate deposits in the vicinity of Sehib (Mzinda, Jellabia and Oued Elkhasfa) (Fig. 1) These deposits, very important in terms of reserves, cannot be processed by simple washing techniques; they require other, more or less complicated enrichment techniques such as flotation. The objective of this work is to study the petrographic, mineralogical, and granulochemical characteristics, and to assess the P2O5 content, of sediments collected from the different layers of the sandy phosphate of Mzinda, Jellabia, and Oued Elkhasfa. This study aims to identify the mineral phases that affect the quality of the low grade ore and to estimate its relative importance in order to select the appropriate method for its removal (Htiwech and Ennafati, 1981; Henchiri, 1981; Yakdhane and Naffat, 1981; Yakdane and Henchiri, 1994; Henchiri, 2002). The identification of the mineralogical composition especially that of these mineral phases and their locations (as accompanying minerals or as inclusions), will serve as a guide for determining the most suited techniques that can be adopted for the processing of the sandy phosphate (Zafar et al, 1996). This study offers a method for the beneficiation of phosphate ores that have a silica-containing gangue and a carbonate-containing gangue. The method entails subjecting the phosphate ore particles to controlled attrition to remove at least some of the silica-containing gangue and the remaining magnesia-rich carbonate-containing gangue, as well as recovering a concentrated phosphate product. The flotations include a carbonate flotation, a silica flotation, and a phosphate flotation. As an alternative, the controlled attrition can be used before the carbonate flotation and after the silica flotation.

Concentration methods, generally known as flotation (Herman, 1980, Abuzeid, 2008), can be divided into two categories: physical methods, which rely on gravity and are used only for coal, and physicochemical methods, which are infinitely more flexible and have much more varied applications. They are essentially based on the property of solids to be wetted unevenly by water according to their chemical composition. Thus, if natural sphalerite or galena is finely pulverized, the sulfides will float on the surface of the water, while the gangue will sink to the bottom of the container. To enhance this property and minimize the size of the processing equipment, the following are added to the water (Sis and Chander, 2003):

- Foaming agents (frothers), which promote the production of air bubbles in the liquid and, consequently, the formation of abundant foam that will retain one of the constituents of the powdered ore (Yu et al, 2024);
- Collecting reagents, which stabilize the foam and increase the buoyancy of the particles. There are two types of collectors: (1) anionic collectors: these act through negative ions to create a hydrophobic coating on basic minerals. They leave acidic minerals unaffected; (2) cationic collectors: these have a hydrophobic positive ion. They act on acidic minerals (quartz, feldspar, mica, clay minerals) while leaving basic (metallic) minerals unaffected. (Herman, 1980; Budemberg et al. 2025).
- Depressing reagents, which, by modifying the buoyancy of certain components, aid in their separation and enable differential flotation, in which several minerals (generally sulfides) are separated from each other and from their gangue. These are generally highly polar substances (electrolytes).

The flotation of phosphate ores is the most important application, practiced mainly in America, in Florida, where the processing capacity of the plants exceeds 10,000 tons per day. It appears that Russian apatite and phosphorite, whose main deposits are located in the Hibinogorsk district, near the Arctic Circle (Golovanov and Levski, 1968), are also partially flotated. In most of the processes used, it is the phosphate that is carried along in the scum, the collecting agents being oleic acid, sodium oleate or similar oils, saponified or not, sometimes naphthenic acids from petroleum or even a resinous oleate or soap whose base is tetramethylammonium hydroxide (Liu et al. 2018; Elgillani and Abuzeid, 1993).

The gradual depletion of rich or easily enriched phosphate reserves in Tunisia has led to an interest in low-P_2O_5 ores, among which are the phosphate deposits of Sehib (southern basin) and Sra Ouertane (northern basin). These deposits, which are very significant in terms of reserves (111 million tons at Jellabia (MKI, 1982), cannot be processed using simple washing techniques; they require other enrichment methods such as flotation (Yakdhane and Naffeti, 1981; Yakdhane and Henchiri, 1990; El-Shall et al, 2004; Amirech et al. 2018; Derrardjia et al. 2024).

Exploration history overview in the Sehib region

Several works have been undertaken in the Sehib region and its surroundings (East sector of Gafsa basin) (Fig. 1) for the recognition of the sandy phosphate, indeed, during the 1970s, the geological works undertaken by the Belgian company COMTAIN S.A, focused on the execution of 7 trenches and 5 downholes at the outcrops and 19 boreholes with 800m mesh downstream. The reconnaissance work by boreholes downstream of Jellabia undertaken since the 1980s by the company BULGARGEOMINE and by the Phosphate Company of Gafsa CPG, served to reduce the grid spacing from 800m to 400m by the execution of 52 boreholes and 2 wells. During the 1970s, geological work undertaken by the Belgian company COMETAIN S.A. at Mzinda involved the excavation of 12 trenches at outcrops and 3 boreholes downstream. During the 1980s, geological work undertaken by CPG on the deposit resulted in the drilling of 9 wells, 3 access shafts, and 15 boreholes, subcontracted to BULGARGEOMINE. In 1993, the CPG resumed geological exploration of the Mzinda deposit. In this context, 61 works (trenches, boreholes, and crosscuts) were carried out, up to the maximum ratio of 10. The additional geological exploration work deemed necessary for the evaluation and characterization of reserves down to the hydrostatic level of the two deposits is as follows:

Jellabia: 11 boreholes (average depth 150 m).

Mzinda: 19 boreholes (average depth 150 m).

The sandy phosphate reserves were estimated at 111 million tonnes in a feasibility study for mining in the region (MKI, 1982).

Geological setting and phosphate lithologies

The Sehib phosphate deposit lies along the southeastern part of Gafsa basin in southern Tunisia (Fig.1). The phosphate occurs in Ypresien age sediments (Early Eocene) of the Metlaoui formation (Burollet, 1956; Larnaud, 1963). The sedimentary rocks of the Sehib (Fig. 2) area range in age from Upper Cretaceous) to Quaternary. The thick transgressive limestone of the Abiod formation, represents the Campanian age. This unit crops out in the core of the anticline to the south of Sehib. This unit is overlain by a thick sequence of marls of Danian to Montian age (Early to middle Paleocene) called Haria Formation. The base of Eocene (Ypresien age) is represented by thick chalky limestone overlain by a unit of coquina and bioclastic material called Thelja Member. The principal phosphate series (Chouabine Member) is overlain by the Kef Edour Member limestone beds (Fig. 3). All the three members have been assigned to the Metlaoui formation, Burollet (1956; Larnaud, 1963). The principal phosphate series is an average of 14.3 meters thick. It is composed of alternating phosphate and marl with a detrital discharge demarcating its top (Ben Amor, 1985; Henchiri, 2002).

The sandy phosphate facies is made up of three distinct beds (Fig. 2). The C0 bed presenting over the entire site averages approximately 4.0 meters in thickness. It's the uppermost phosphate bed of the series. C0 bed has grey green to yellow colour. Its facies is sandy or marly with occasional fossils (phosphatized fish bones and teeth..) and gravels. The next lower bed (C0I bed) is separated from the C0 bed by an average of 0.2 meters of marl. The marl is greenish-grey to black, occasionally fossiliferous and phosphatic with calcite concretions. The C0I bed is not present over all part of the property. Bed C0I averages approximately 2.3 meters in thickness but it can reach an extreme thickness of 7.3 meters. The CI Sup. bed underlies C0I bed. An interbed of marl, fossiliferous sands, and calcite concretions separates these two beds. The CI Sup. bed is present over most of the Sehib area. The phosphate bed is beige, to black in colour, sandy, soft and marly. It averages approximately 3.3 meters in thickness, but reaches extremes of over 7 meters.

Material and methods

Sampling

Many samples were selected from various phosphate deposits (Fig.1) from Mzinda (western Sehib), Djellabia (central Sehib) and Oued El Khasfa (east southern Sehib). Mzinda and Oued El-Khasfa samples were from open trenches. The samples of Djellabia were from pits and open trenches.

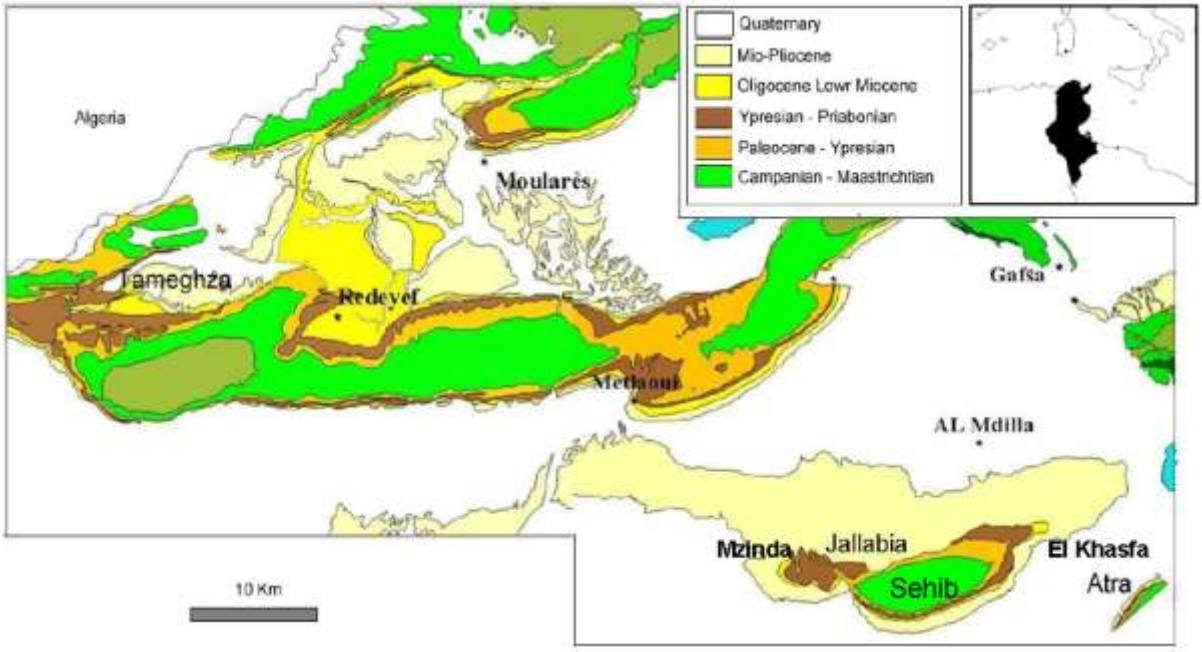

Figure 1 Location and geological map of Gafsa basin showing the Sehib and its surroundings phosphate fields (after Zargouni et al., 1995).

Grain size analysis

In the laboratory, each sample is dried in an oven at 70°C for 24 hours. During drying, the sediment mass is stirred three or four times, gently but thoroughly, to prevent clumping, which can occur due to the cementation of fine particles. After removal from the oven, the sample is homogenized by manual stirring, and 500 g are isolated for analysis. Sieving is performed dry, using a set of 11 AFNOR sieves: (0.071 – 0.1 – 0.125 – 0.16 – 0.2 – 0.315 – 0.5 – 0.63 – 0.8 – 1 and 2 mm) arranged in two columns on a vibrating table. The six coarsest sieves (mesh size from 2 to 0.315 mm) undergo 30 minutes of vibration, while the five finest sieves (mesh size from 0.2 to 0.071 mm) undergo one hour of processing. The residue collected on each sieve is weighed on a balance with a precision of 1 mg.

Mineralogy

Mineralogical identification is carried out by measuring the diffraction of electromagnetic X-ray radiation, whose wavelengths, ranging from 0.01 to 10 nm, are on the order of the distances separating the atomic planes of the crystal lattices. X-ray diffraction analysis is performed using Philips PW 3710 equipment (Cu Kα radiation), located at the research center in Metlaoui.

Chemical analyses

Atomic absorption spectroscopy allows for the detection and quantification of the maximum number of chemical elements in a sample. It involves stirring a two-gram sample under boiling and reflux in 100 ml of hydrochloric acid of known concentration for various time intervals (15 min, 30 min, 1 hr, 1.5 hrs, 2 hrs, 4 hrs). The liquid phase is separated from the solid phase by centrifugation. In the liquid phase, elements such as F_2O_3 and CaO are determined by complexometry, while potassium and sodium are determined by flame spectrometry, and P_2O_5 by UV-visible spectroscopy. Silica is determined gravimetrically after digestion with three acids (HCl, H_2SO_4, HNO_4). Atomic absorption spectroscopy is widely used for the qualitative and quantitative analysis of trace elements.

Flotation experiments

Mechanical preparation necessary for the flotation experiments is carried out in two desliming stages: primary and secondary. A desliming operation is performed on the crushed all-in aggregate to approximately 12.5 mm. Primary desliming to 32 µm consists in asorting using hydrocyclones to a particle size of 160 µm. Regrinding in

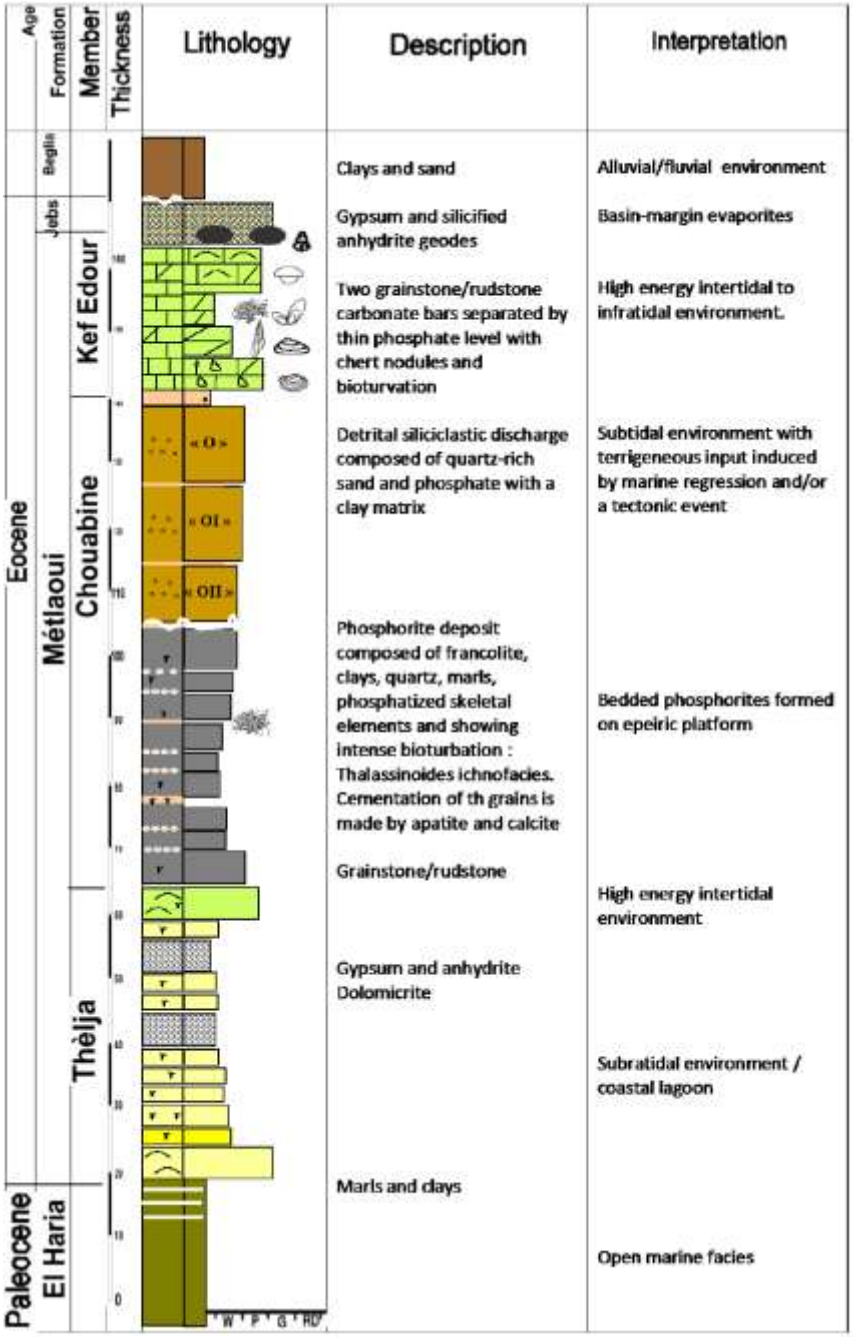

Figure 2 Schematic lithostratigraphic section of Metlaoui Formation and distribution of the various phosphate lithologies. In Melaoui Formation the gray color intensity of phosphatic strips is fonction of their phosphate enrichment.

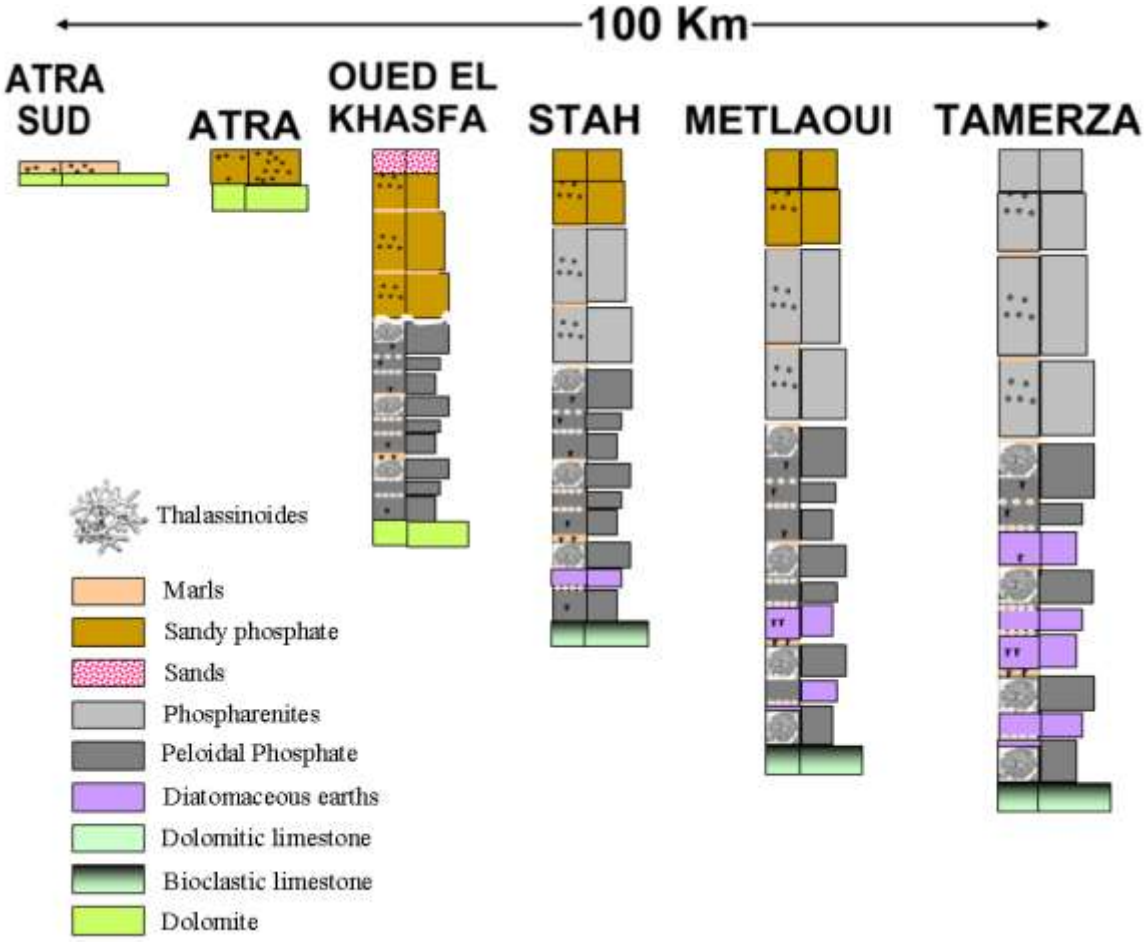

Figure 3 Correlation of the Chouabine Member in the Gafsa Basin showing the predominance of the detrital discharge in eastern part of the basin

a ball mill of the fraction larger than 160 µm. Secondary desliming where the resulting product then undergoes a flotation stage. Reagents used are fatty acids and amines all combined with diesel oil. The equipment used is located in the centre des recherché de Metlaoui.

A standard machine (237 FL-A) with a 0.25-liter cell that rotated at 1800 rpm was used for the flotation testing. Before any reagents were added, a 50 g ore sample was treated with 180 mL of tap water in the flotation cell and stirred for two minutes. The pulp's pH was then brought down to a slightly acidic 6. After that, chemical agents were applied to the pulp for two minutes for the depressant and three minutes for the collector. For a total of three minutes, the pulp was aerated and the froth product was collected. Both floated and non-floated items underwent filtering, water washing, drying, weighing, and chemical analysis. For a total of three minutes, the pulp was aerated and the froth product was collected. Both floated and non-floated items underwent filtering, water washing, drying, weighing, and chemical analysis.

Results and interpretations

Sedimentary aspects

The field work was carried out in the four localities of the Sehib area (Oued El Khasfa, Jellabia and Mzinda). The best exposure profiles are in Oued El Khasfa (Fig. 4a and b). The average thickness of Oued El Khasfa's commercial phosphate series underlying the sandy phosphate, is 14.3 meters (Fig. 4b, b). It is made up of clay, marl, and phosphate in succession. Tightly packed, well-sorted rocks comprised of phosphate peloids, coprolites, and bone fragments make up the phosphate-rich beds. They make up the majority of the commercial phosphate deposits and are found in the Lower Ypresian series.



Figure 4 Field views of the sandy phosphate quarry in Sehib region.

The profile exposure linked to intercalated lenticular bodies of calciclastic deposits surrounded by the commercial phosphate from the bottom and by the sandy phosphate from the top exhibits a striking erosion truncation (Fig. 4c) that can be differentiated from the overlying limestone beds of Kef Edour Member (Fig. 4d). These ubiquitous bodies range in size from 1 to 3 meters in height and 9 to 12 meters in width, having a concave up cross-section. Skeletal-rich (Ostrea, bivalve shells, e.g., pecten) and coarse-grained sediments with a low proportion of mud (calcirudite) make up the majority of their petrographic composition.

The mining operations to extract the commercial phosphate start by the removal of the Kef Edour dolomitic limestone beds (Fig. 4e) and then proceed to remove the sandy phosphorite beds (Fig. 4f) which are piled in a separate place since they are deemed to be valuable and prone to treatment and concentration.

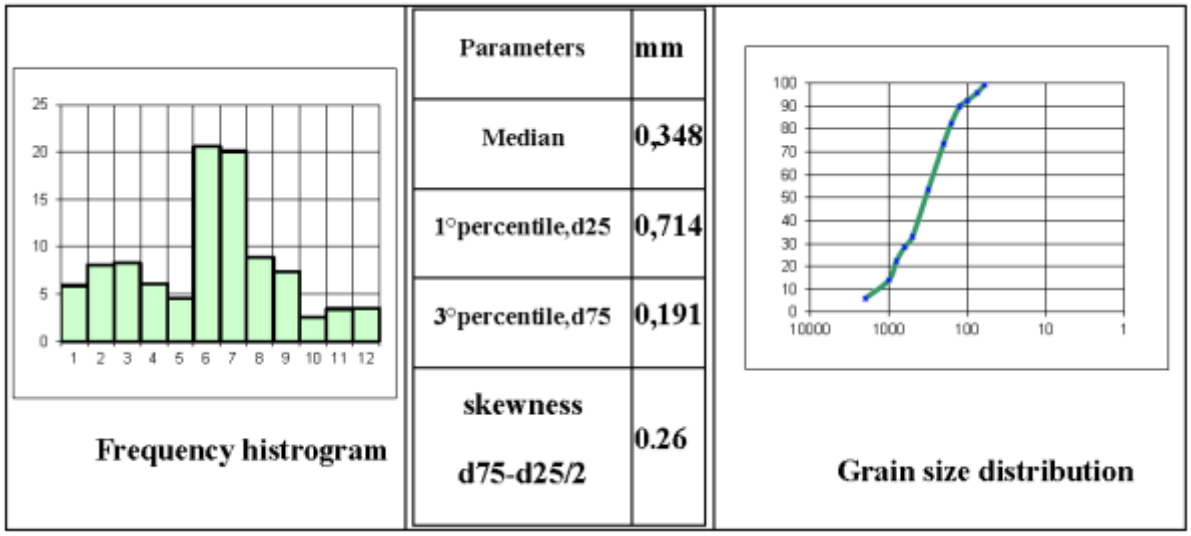

Figure 5 Grain size distribution of the sandy phosphorite

Grain size distribution

The semi-logarithmic grain size distribution curves of the cumulative retained material from the sandy phosphate samples taken at Mzinda (Fig. 5) show that the sediments have a more or less homogeneous grain size distribution. These curves are S-shaped and therefore have only one inflection point. They are symmetrical, with the middle portion being the best sorted. The fine and coarse fractions are less abundant and more poorly sorted. The inflexion occurs around 400 µm. The coarse fraction is small but larger than the fine fraction and increases in importance from layer C0 to layer CI Sup. The frequency histograms show almost a single cluster corresponding to the middle fraction.

In general, the sand-rich phosphate at Mzinda is well sorted, as a population of grains (related to the duration of transport which induces increasing sorting of the particles). The size of these grains is average, and the grain sorting is positive since there is an increase in the coarse fraction going from CO to CI Sup. (related to the decrease in energy of the hydraulic environment).

Mineralogical composition

The XRD analyses of selected sand-rich phosphorites give the following mineralogical composition (Fig. 6): CFA (> 50 %), calcium and magnesium carbonate (10 %), quartz (15 %), clay minerals (7 %), feldspar (5 %) and low quantities of limonite detrital clay minerals (especially smectites). The main phosphatic mineral is francolite making up a content of P_2O_5 ranging from 17-22 % within the deposit; therefore the prospects for an economic exploitation were sufficient but should be supplemented by an eventual flotation processing. The sand-rich phosphorites are composed of phosphatic grains, non-phosphatic grains, cements, and pores. Phosphatic grains are composed of bioclasts, structureless grains, and lithoclasts.

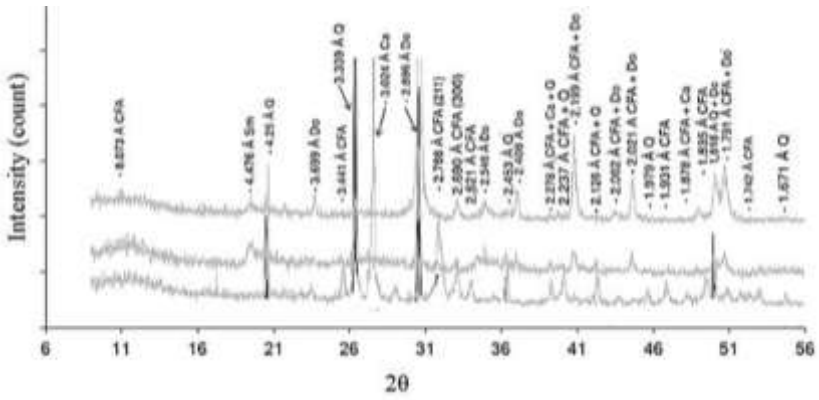

Figure 6 Representative X-ray diffraction spectra of sand-rich phosphorite samples composed of: Q= quartz, CFA = francolite, C = calcite, D = dolomite.

Chemical composition

Compared chemical composition of selected apatite grains from the pristine and the reworked facies is shown in Table 1. The transition from the pristine facies to the reworked facies is associated with a noticeable decrease in Cd, F, Na_2O, SO_3 contents. These elements are presumed to be linked to the apatite phase (including organic matter) and interpreted to be the most leacheable elements in apatite lattice. It is worth noting the slight increase in P_2O_5 content in the reworked apatite grains.

Table1 Compared chemical composition of apatite grains from Sehib phosphate series.

Phosphorite facies	P_2O_5 %	CaO %	F %	Na_2O %	SO_3 %	SiO_2 %	Cd (ppm)
Commercial phosphate	34,62	54,07	1,96	0,55	2,22	0.86	90
Sandy phosphate	35,80	55,23	1,55	0,14	1,14	1.4	8

Grain size-specific chemical analyses were carried out also on some sieve-sorted samples of sand-rich phosphorites to assess SiO_2 and P_2O_5 contents co-variations along the 12 grain size fractions. Table 2 shows the results of granulo-chemistry (fractionation) of the selected sample.

Table 2 Grain-size-specific chemical analyses of sand-rich phosphorite sample.

Mesh (mm)	Cumulative	%	%P_2O_5	%SiO_2	%CaO	%MgO	%Fe_2O_3	%Al_2O_3	Cd (ppm)
2000	23.368	23.368	12,25	19,79	32,08	6,14	0,98	2,03	6
1000	40.148	16.78	14,34	20,86	32,3	5,05	1,09	2,46	6
800	49.946	9.828	15,24	20,48	30,44	17,38	0,95	2,2	7
630	54.65	4.674	11,67	39,57	24,77	1,02	0,6	1,03	5
500	57.28	2.63	11,64	19,73	22,84	2,8	0,8	1,77	5
315	63.144	5.864	10,42	49,2	20,84	1,64	0,65	1,03	5
200	66.897	3.654	12,7	42,78	22,63	1,68	0,8	1,6	5
160	68.24	1.442	16,97	14,06	31	1,96	0,74	1,66	6
125	70.364	2.124	18,69	19,25	36,5	3,41	0,7	1,88	5
100	83.054	12.69	8,33	15,4	30,66	8,55	1,05	2,93	5
> 71	94.912	11.858	4,43	17,01	26,4	8,29	0,98	3,5	7
< 71	98.398	3.486	4,43	21,6	22,11	9,11	1,8	4,44	6

P_2O_5

The total P_2O_5 contents of the sand-rich phosphorites (Fig. 7a) vary between 17 wt. % and 23 wt. %. The high value of 16.89 in the fraction of 2 mm is ascribed to coprolitique grains. The most richest fractions are those comprised between 0,6 and 0,2 mm and 0.1 and 0.06 mm. This is explained by the peloidal texture of the phosphorites of Sehib.

Cd/P2O5

Cd/P_2O_5 ratios, between (2000-160 µm) fractions, show constant variations (Fig. 7a). The highest averages are occurred in the fine grain fractions (clayey fractions); decrease of P_2O_5 but persistence of Cd. Note that Cd, in this case, seems to have completely independent variation from the P_2O_5 contents. However, the clay fractions do not really show a clear tendency for Cd enrichment compared with coarse grain size. Cd seems to be scattered throughout the grain fractions especially the coarser fractions. Practically, Cd is higher in coarser grains, in fact, quartz grains present many previous weathering traces and dissolution features (etch pits and dissolution cupules) in which Cd found a preferential site of fixation when detrital discharge and reworking of sediment take place.

Higher Cd concentrations in the in situ series have been originated from reducing conditions, which cause the precipitation of Cd-rich sphalerites. Reworking of phosphate sediment on oxic sea bottoms, results in organic matter (primary source of the large amounts of P required to form accumulating CFA deposits) decay, sulphide oxidation and partial removal of Cd from the sediment. It may also explain Cd-low concentrations in this sequence.

SiO_2/P_2O_5

Figure 7b and 4d indicate that the SiO_2 content seems to have an opposite variation with that of the P_2O_5 through the various grain size fractions. Fractions with higher P_2O_5 content have the lower SiO2 and vice versa. This is explained by the factor of spatial competition and mixing between quartz and apatite grains. The SiO_2/P_2O_5 ratios (Fig. 7d) are much more higher in the coarser grain size (between 0,8-0,071 mm fractions) in which the SiO_2/P_2O_5, gets near (1.5). The lowest averages SiO_2/P_2O_5 ratios (0.3) occur between (2-0,8 mm) fractions. The highest averages of SiO_2/P_2O_5 ratios are practically attributed to the abundance of quarts sand-sized grains. The fractions between (160-75 µm) have a moderated SiO_2/P_2O_5 ratios averages (0.6) in which there is an obvious contribution of siliceous clasts.

Fe-Al

Fe/P2O5 and Al/P2O5 ratios (Fig. 7e-f) apparently have similar variations throughout the various grain size fractions. The highest averages are attributed to the clayey fractions. Fe rates are mostly ascribed to the Fe-rich smectites as they were trapped in an anoxic zone; others probably of diagenetic origins are common such as pyrite, goethite, and glauconites (suboxic to oxic zone)

Benificiation using flotation technique

Phosphate-silica separation by flotation, using a phosphate-enriched fraction with a particle size suitable for flotation, is carried out in conventional cells according to two basic schemes (Fig. 8):

- Anionic flotation of phosphate with fatty acids combined with diesel oil (DO) from a single particle size fraction or from two particle size fractions conditioned and floated separately.

- Double flotation combining three steps:

Anionic flotation of phosphate yields a concentrate. Removal of the anionic collector and oil coating from the surface of the particles present in the pre-concentrate by sulfuric attrition in a thick pulp (60 to 75% solids) with a pH of approximately 4. Cationic flotation of the residual silica from the pre-concentrate with a collector based on amine or amine salts combined with DO.

This double flotation process is generally very selective. From feed containing 15 to 65% TCP (Tri-calcium phosphate), the concentrates contain 70 to 80% TCP for phosphate recovery of 75 to 90% (Baudet et al., 1986). If we take the example of the sandy phosphate from Oued Elkhasfa, the granulochemical study shows that the fraction must be taken, for the C01 layer (Fig. 7b), in the dimension range between 500 and 1000µm.

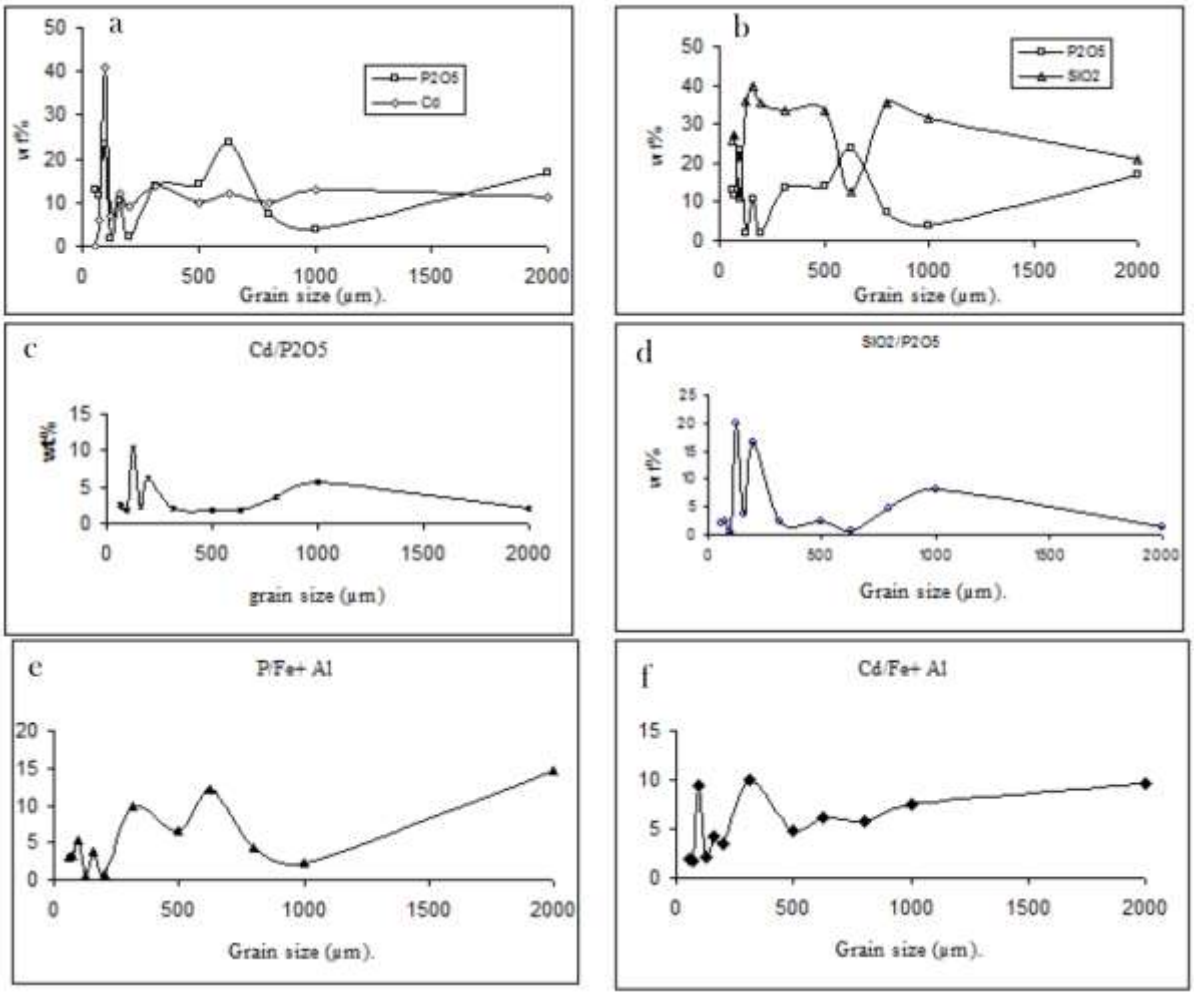

Figure 7 (a) Variation of Cd and P_2O_2 contents in the grain size fractions of a sand-rich phosphorite sample. (b) Variation of SiO_2 and P_2O_5 contents in the grain size fractions. (c) Variation of Cd and P_2O_5 ration along the grain size fractions. (d) Variation of SiO_2/P_2O_5 ration in grain size fractions. (e) Variation of the ration P/Fe+Al in grain size fraction. (f) Variation of the ration Cd/Fe+al along the grain size fraction.

Discussion and summary

The collected data provide insights on the impact of the quartz-rich detrital discharge on the lower Eocene phosphatogenic environment and the phosphorite composition. Phosphate grain formation in aqueous environment is completely related to the physico-chemical and biological conditions of the depositional environment. The impact of the detrital discharge on the depositional environment of phosphorites is a major shift from anoxic to suboxic chemical conditions of the phosphogenic depositional environment resulting in phosphate-depleted pore water leading to low quality francolites (Pufahl and Groat, 2016). P_2O_5 and SiO_2 contents vary in contradictory trends (inverse relationship) throughout the grain size fractions. The highest SiO_2 rates are correlated with the decrease of P_2O_5 rates. This might be explained by the introduction of spatial competition factor interpreted as a source of degradation of phosphorite quality.

The benificiation of the sandy phosphates of Sehib using flotation can face several constraints, both technical and regional. Indeed, the persistence in the conditioned fractions of quartz grains coated with thin layers of phosphate, which can go unnoticed even after grinding, can lead to problems in the final P_2O_5 recovery,

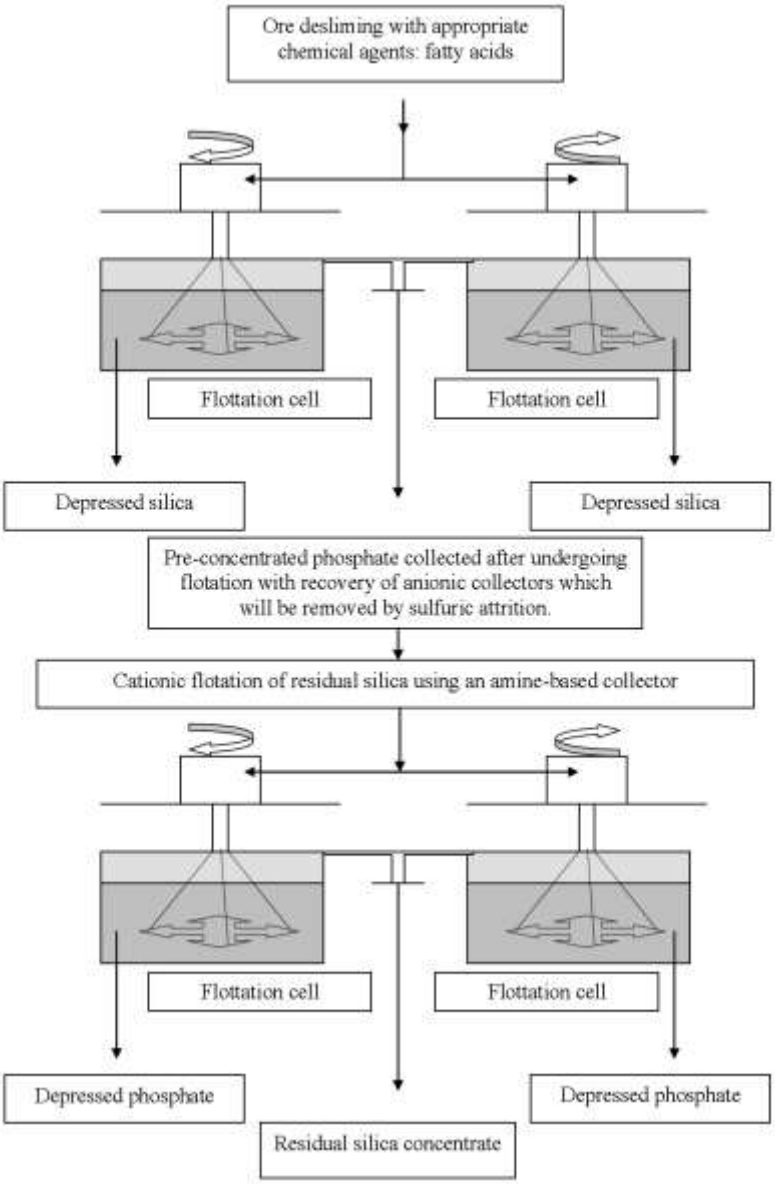

Figure 8 Two-stage flotation process for separating quartz (silica) from phosphate.

namely: relatively low P_2O_5 content and reduced yield. It should be noted that successive grindings of the sandy ore can, over time, cause wear on the grinding equipment, given the varying hardness of the quartz grains (Amirech et al, 2018). Flotation can be very sensitive in terms of the specific consumption of chemical products and reagents, since any overuse or poor choice of fraction sizes can directly impact production costs (Zhang et al, 1997).

At the regional level, the silica phosphate flotation project, which has not yet been launched, appears to depend on several factors, such as, (1) Selectivity of the operation. This factor is very important; indeed, the operation must focus solely on the siliceous layer. Any contamination, especially from the overburden marls, can exacerbate the already low P_2O_5 content and yield. Therefore, special precautions must be taken to eliminate any foreign material that could reduce quality. (2) Ratios (ratio between waste rock tonnage and ore) clearly impact extraction costs. The relationship between the two will be linear for low ratios and exponential for high ratios. (3) Brittle tectonics of the region can create risks regarding slope stability, transport, and the organization of the mine profiles, access roads, and spoil heaps. (4) Extent of the deposits, since the sandy phosphate is a characteristic of Sehib and its surrounding areas (Mzinda, Jellabia, southern Sehib, Oued Elkhasfa, M'dhilla). (5) Available reserves were estimated at 111 million tons in a technical feasibility study of mining in the region conducted by MKI in 1982. (6) Availability and consumption of water needed to meet the project's requirements (Table 3). Phosphate flotation is entirely dependent on the presence and availability of water, which is a primary necessity.

Table 3 Water needs of the Gafsa Phosphate Company and the potential exploitation regions.

Water needs of the Gafsa Phosphate Company	650L/sec	
Exploitation regions		
Elgouifla	Elbarka	Moulares
260L/sec to supply the laundries of Mdhilla and Metlaoui	260L/sec to supply the Kef Edour laundries	65L/sec to supply the Redeyef laundries
The future needs of the Gafsa Phosphate Company: 350L/sec, distributed as follows:		
50L/sec : Generalization of fines recovery in all laundries. 150L/sec : Sandy phosphate flotation project. 150L/sec : Tozeur-Nefta Phosphate Project .		

In the Gafsa region, water is not an obstacle to launch the sandy phosphate flotation project. The Gafsa Phosphate Company has invested in the search for new water reserves in the regions, both for its own needs (flotation project) and to contribute to the development of the region and especially the mining centers. During the past few years, and due to surging demand, particularly for phosphate fertilizers, Chinese state-owned enterprises showed more interest in investing in beneficiation technologies (flotation, calcination) to process of the unexploited reserves of low grade phosphate rocks of Sehib into higher-value products.

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