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Geochemical analysis of the Maastrichtian phosphate stratum “Couche 3” and its exploitability in the Sidi Daoui mine (Ouled Abdoun, Morocco)

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Original Research

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Abstract:

The Couche 3 (C3) of Sidi Daoui has long been considered an unexploitable low-grade phosphate stratum and was left behind. Nowadays, with the exhaustion of high-grade phosphate resources, the l’Office Chérifien des Phosphates (OCP) Group plans to launch the exploitation of C3 by private mining companies. This study was undertaken under the authority of Sidi Daoui’s exploitation service, IDK/CP-467 to investigate the feasibility of launching the exploitation of C3 in Sidi Daoui. Phosphate samples were taken from the stockpiles and analyzed for BPL (Bone Phosphate of Lime) and impurities. The analysis shows that the C3 of Sidi Daoui belongs to the category of low-grade phosphates, with a vertical gradient decreasing from the top (upper C3) with 61.42% BPL to the bottom (lower C3) with 58.59% BPL. Through these results, it is concluded that the upper C3 can achieve a relatively medium grade product, by using a selective exploitation method accompanied by a relevant and suitable mining processing approach, or by mixing its phosphate with that of high-grade strata coming from other mines such as Sidi Chennane, MEA Lahrech, or El Hlassa.

Keywords: Sidi Daoui; OCP group; Couche 3; Phosphate mine; BPL

1. Introduction

Phosphates are phosphorous complexes with the chemical formula PO43-, which were formed from organic matter accumulated in sea depths (Filippelli, 2011; Gross, 2017). Phosphorus is a non-replaceable essential nutrient to feed the world, with limited global reserves. Although toxic in its pure form (Takagi et al., 2020), phosphorus is a vital element for life and growth, with over 90% used in agriculture as one of the most nutrients for soil fertilizers (Bindraban et al., 2020; Dehghan and Yazdi, 2023). Phosphate can also be processed to produce phosphoric acid, which is utilized in a variety of applications ranging from food and animal feed to cosmetics and electronics, etc. (Long and Bunka, 2011; Cordell et al., 2009). Moreover, the ever-increasing global demand for phosphate has a direct impact on its production, which is expected to reach its highest level between 2028 and 2084, with 50% of reserves depleted (Cooper et al., 2011).

Phosphate is mined as marine sedimentary strata in North Africa (e. g. Morocco), China, the Middle East, and North America (Cooper et al., 2011). Based on estimates conducted by the United States Geological Survey (USGS), Morocco holds approximately 50 billion metric tons of phosphate, which represents about three-quarters (3/4) of the world’s phosphate reserves that might last for 300-400 years (Dabiri et al., 2017; Ayad, 2022; Saadat et al., 2023). These appreciable reserves known since 1908 allow Morocco to become the first world exporter of phosphates and the second world producer after China, with mining capacities exceeding 40 million tons per year (Edixhoven et al., 2013). The phosphate deposits in Morocco occur in four (4) main basins (Fig. 1-a), from northeast to southwest: Oulad Abdoun, Gantour, Meskala, and Boukraa (Buccione et al., 2021). Phosphate mining is done in the open pit through a production cycle consisting of drilling, blasting, ripping and dozing, loading, and hauling, producing large quantities

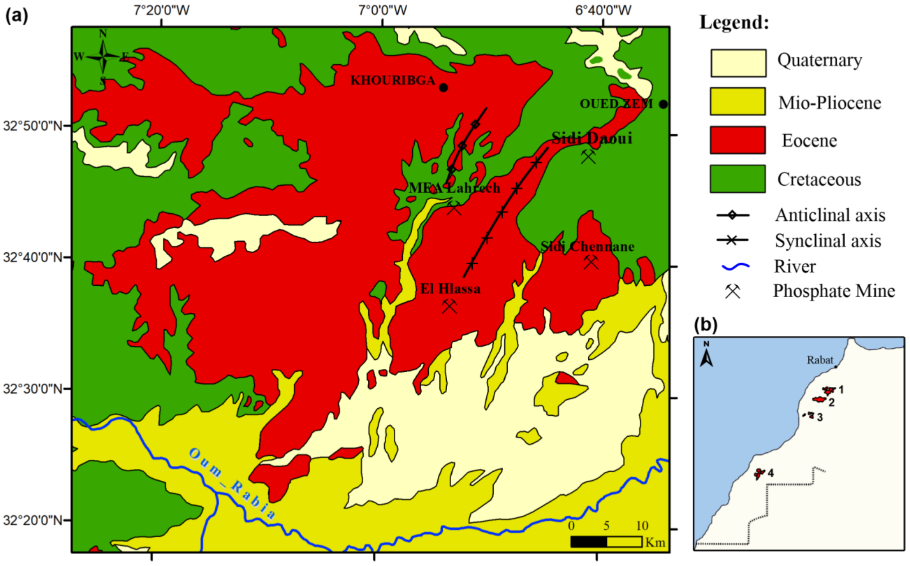

Figure 1. (a) Location of the Sidi Daoui phosphate deposit within the Ouled Abdoun basin (modified after (Ayad and Bakkali, 2017); (b) the main Moroccan phosphate basin: 1) Oulad Abdoun, 2) Gantour, 3) Meskala, and 4) Boukraa.

of rocks excavated without sorting and stored in stockpiles (Ayad, 2022).

The main phosphate mines exist in the Ouled Abdoun Basin located near the Khouribga city, about 160 km southeast of the capital Rabat. It comprises at least 26.8 billion tons of Morocco's phosphate reserves (53.6%). In this basin, the phosphate is extracted in four (4) open-pit mines: MEA Lahrech, El Hlassa, Sidi Chennane, and Sidi Daoui (Lawson, 1931) (Fig. 1-b). In this study, we focused on the Sidi Daoui mine which is one of the oldest phosphate deposits in Ouled Abdoun, located near the city of Oued Zem. This mine was initially discovered in 1919, with significant phosphate reserves deposited as a sequence of several phosphate-rich strata, named 'Couche' such as Couche 3 (C3), C2, C1, etc., inter bedded by marls and limestone levels (Lucas et al., 1979; Pufahl and Groat, 2017). These reserves are exploited by the Moroccan agency OCP.

The exploitation of phosphate at the Sidi Daoui mine was marked by some notable dates. From a chronological point of view, Couche 1 has been mined since 1952 due of its thickness and phosphate quality. The exploitation of Couche 2 began in 1978. Sillon A and B were also added to the exploitation circuit in 1979. However, Couche 3 was considered an unexploitable low-grade phosphate stratum and it was left behind.

In Sidi Daoui (Fig. 1), phosphate is often mined up to some required capacity according to the client's grade demands. The continued and growing demand for phosphate has increased the extraction of high-grade strata. Almost all high-grade phosphate strata are exhausted and only C3 phosphate stratum remains in place. This stratum has long been considered a low-grade phosphate stratum and it has been either left uncovered or under spoiled material. However, with the exhaustion of high-grade phosphate resources, the exploitation of low-grade phosphate strata has become a necessity, encouraged by the increasing development of new mining processing technologies capable of improving the quality of phosphate to a commercial level. Nowadays, the OCP Group plans to launch the exploitation of the C3 by leasing the task to private mining companies.

Given that there are no publications on the exploitability of the C3 phosphate stratum in the Sidi Daoui mine, our research is undertaken to study the feasibility of launching the exploitation of this stratum. The aim of this paper is to investigate the phosphate grade (BPL) of the different phosphate levels of the C3 and estimate its potential reserves as crucial parameters for decision-making.

2. The Sidi Daoui phosphate deposit

The Sidi Daoui deposit is part of the Ouled Abdoun phosphate basin located south of the Moroccan Central Massif in the Western Meseta (Ayad, 2023) (Fig. 1). In this area, the phosphates are part of the South Tethyan phosphogenic province, which extends from North Africa to the Middle East over some 5,500 km and accounts for over 85% of the world's known phosphate reserves (Jasinski, 2020).

The phosphate of Sidi Daoui presents a facies of particular features. It is red colored, clayey, and rich, which have formed on the western and northern very slight tilted slopes. In this facies, the apatite is less rich in fluorine, less carbonated and less rich in CaO. The calcite is not as well crystallized; the dolomite presents a tendency to dedolomitization; the clays show characteristic weathering features (Lucas et al., 1979).

From a lithostratigraphic point of view, the phosphate series in this area is characterized by a tabular morphology deposited as a succession of phosphate strata intercalated with Maastrichtian-Lutetian marl-limestones levels. It is capped by a thin Quaternary cover and lies on the Paleozoic basement composed of schists, granite, and quartzites, metamorphosed and folded during the Hercynian period (Yans et al., 2013). Phosphate-rich strata have been given informal names, all of which have the term 'Couche'(= stratum) with Arabic numerals (C3, C2, C1, C0, C0', SA, SB), based on their stratigraphic positions (Kocsis et al., 2014). This phosphate series is found 25 meters below the

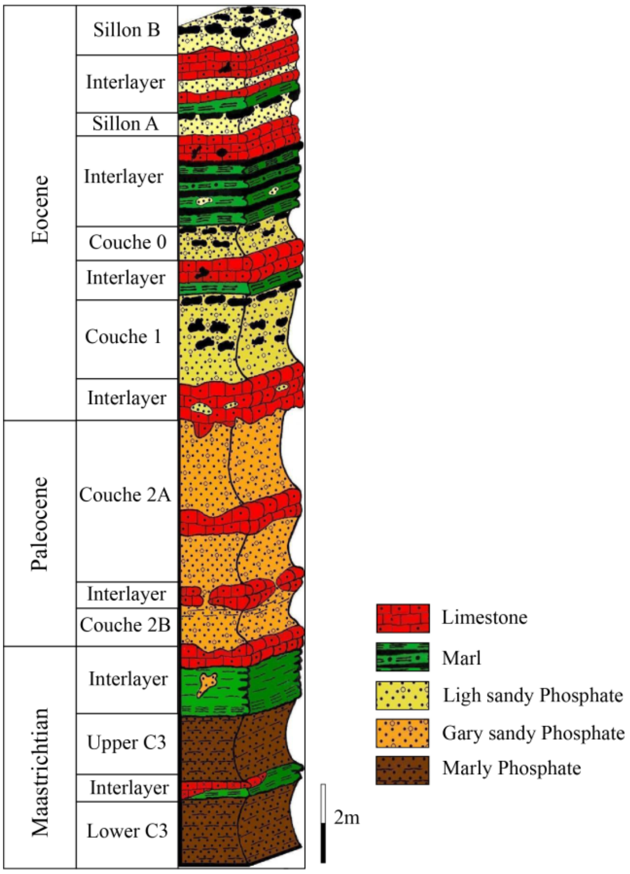

Figure 2. Lithostratigraphic column of the Sidi Daoui Phosphates Series. Stratigraphy and mining terminology of the phosphate strata are adopted after the geological department of Sidi Daoui. C3, C2, C1, C0, C0', SA, SB: exploited phosphatic strata.

surface and is overlain by a fossiliferous marly limestone known as 'Thersitae slab' (Fig. 2).

From a structural point of view, the tabular structure of the Sidi Daoui phosphate series as well as other phosphate deposits of the Ouled Abdoun Basin suffer from the inclusion of many sterile bodies composed of phosphate limestone and marl blocks considered as waste rocky material. These bodies of diameter ranging from 10 m to more than 150 m are the result of a natural collapse caused by the dissolution of Senonian gypsum strata located at the base of the phosphate sequence (Ayad and Bakkali, 2022).

2.1 The "Couche 3" of Sidi Daoui

The "Couche 3" of Sidi Daoui is Maastrichtian in age (Upper Cretaceous), according to their selachian fauna. This stratum holds more than 34% of Ouled Abdoun's phosphate reserves. It is formed of compact to friable yellow marly phosphate and bounded at the base by yellow Senonian marls and at the top by bioturated marls (Fig. 2). This stratum is known for its abundance of vertebrate remains, particularly the presence of fish bones and marine animals such as mosasaurid specimens (Leblanc et al., 2012).

The lithological section shows that C3 is divided into a highly fossiliferous upper yellow phosphatic stratum (Upper C3 = UC3) with an average thickness of 2.31 m, and a basal bonebed, lower grey phosphatic stratum (Lower C3 =LC3) with an average thickness of 1.69 m. Each stratum is divided into two phosphate levels separated by an interlayer of soft marls and bone-bed limestone (Fig. 3).

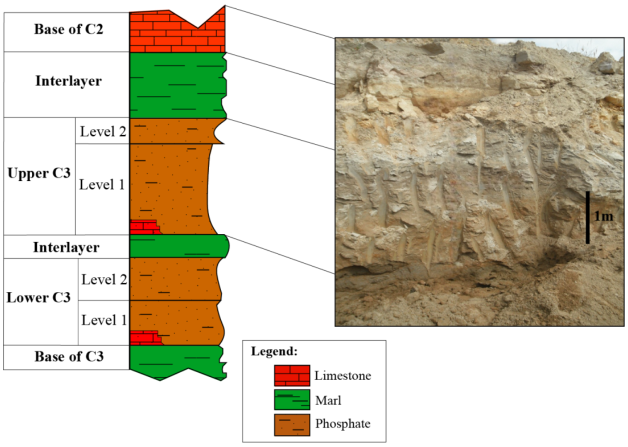

Figure 3. Lithology and divisions of the C3. The photograph was taken from the Sidi Daoui's quarry.

In Sidi Daoui, C3 phosphate reserves are defined in four categories according to their situations: C3 uncovered, C3 under C2, C3 under spoil materials, and C3 under spoil tip. To better show the distribution of the different categories of reserves in the study area, we performed a spatial mapping of these reserves according to the data provided by the geometers of Sidi Daoui's exploitation service, IDK/CP-467 (Fig. 4).

Table 1 shows that the C3 reserves buried under spoil tips are the most abundant at Sidi Daoui deposit. These reserves exceed 60,000,000 m^3 in volume and 12,000,000 m^2 in surface area. The C3 uncovered reserves come second with

Table 1. The volume corresponds to each category of C3 phosphate reserves in Sidi Daoui.

Couche 3 reserves	Volume (m^3)
C3 uncovered	6 328 050
C3 under C2	3 287 280
C3 under spoil materials	6 258 960
C3 under spoil tip	60 403 110

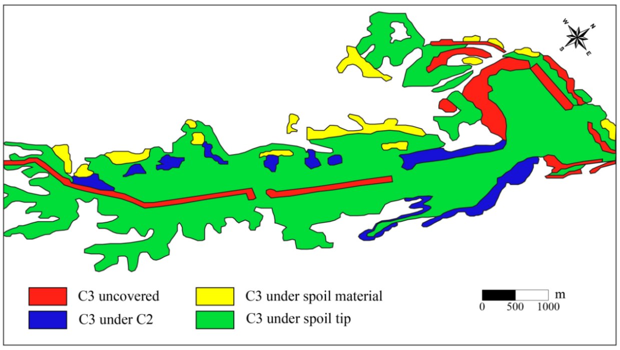

Figure 4. Evidence maps of the spatial distribution of the different categories of C3 phosphate reserves across Sidi Daoui. Refer to Table 1 for the volume of each category.

a volume of 6,328,050 m^3 and a surface area of 1,280,981 m^2.

3. Materials and methods

This work was carried out in collaboration with the authority of Sidi Daoui's exploitation service, IDK/CP-467. The analytical methodology for this study is the geochemical analysis of the C3 phosphate stratum. The samples were taken from the excavated phosphate come from different locations and stockpiled around the mine. The sampling work necessitates a hand spade for sampling and polythene bags for conserved samples. First, the samples are crushed in a mortar until obtain fine-grained size, and then powdered. The product is then conserved into polythene numbered bags and transferred for geochemical analysis for a particular assay and analyzed in the laboratory for BPL and impurities (e. g. SiO_2 and CO_2) (Fig. 5). The laboratory tests were carried out in by the Sidi Daoui's treatment service (Point B).

The chemical analysis is carried out following the standard analytical methods used for phosphates. For the impurities, the CO_2 is determined through a hydrochloric attack which allows to carbon dioxide appear as an important factor in the reactivity, while SiO_2 is determined by the gravimetric method.

This geochemical analysis is used to classify C3 phosphate reserves as high, medium, or low grade, by comparing the results with the known phosphate cut-off grades shown in Table 2. These grades are determined in BPL (Bone Phosphate of Lime): Tricalcium phosphate of lime (P_2O_5, 3CaO) BPL: % $Ca_3(PO_4)_2$ (Shariati et al., 2015). BPL can be calculated by the equation: BPL = $2.185 \times \%P_2O_5$. The grade of phosphate depends thus on the content of phosphor, as well as the amount and type of impurities.

Table 2. The principal phosphate cut-off grades used by the OCP group a function of % BPL.

% BPL	**Phosphate grade**
SHT > 75 %	SHT: Super high grade
73% ≤ THT < 75%	THT: Very high grade
71.5% ≤ HTN < 73%	HTN : High normal grade
69.5% ≤ HTM <71.5%	HTM : High medium grade
68% ≤ MT <69,5%	MT : Medium grade
61% ≤ BT <68%	BT : Low grade
56% ≤ TBT < 61%	TBT: Very low grade

Figure 5. a) Collection of samples from a phosphate stockpile using a hand spade. b) Some of the collected phosphate samples.

Table 3. Averages %BPL of C3 obtained before and after phosphate washing.

	Upper C3	Lower C3
% BPL before washing	50.70	50.79
% BPL after washing	61.42	58.59

Phosphate of cut-off grades: SHT, THT, HTN, HTM, and MT is economically exploitable material, which can be sold as is, while phosphate of cut-off grades BT and TBT does not meet market requirements due to its high content of impurities (CO_2 and SiO_2), and must therefore be effectively enriched by mineral processing to meet market requirements (Ryszko et al., 2023).

4. Results and discussion

The results of BPL analysis are shown in Table 3. From this Table, C3 can be categorized as very low-grade phosphates (TBT). The upper C3 has an average of 50.70% BPL before washing and 61.42% BPL after washing, while the lower C3 has an average of 50.79% BPL before washing and 58.59% BPL after washing. It can be observed that there is a vertical gradient of phosphate grade, which decreases from the top (upper C3) to the bottom (lower C3). According to these results, no level of C3 exceeds 64% BPL, which is the last phosphate cut-off grade that meets market requirements.

Moreover, the impurities content is not negligible. For example, a change of 1% or 2% in the impurities of a phosphate deposit, essentially the principal oxides SiO_2, and CO_2, could have a significant impact not only on the production of the phosphate but also on the profitability of the entire mining project (Alouani, 2016). In our case, the low-grade phosphate of C3 is certainly impacted by the high quantity of impurities which reaches 16.81% on average for upper C3 and 31.31% for lower C3 (Fig. 6), certainly has a significant impact on BPL.

With its very low-grade, C3 can be mined profitably only by the exploitation of a high quantity of phosphate supported by an appropriate selective exploitation method. Hence, it may be necessary to compute the volume and tonnage of both the upper C3 and the lower C3 to get a clear overall view. Since the grade establishes the difference between phosphate deposits which may and may not be classified as exploitable, tonnage cannot be estimated without considering the question of grade. Thus, the volume of phosphate is calculated for the cut-off grades BT, TBT, and < TBT

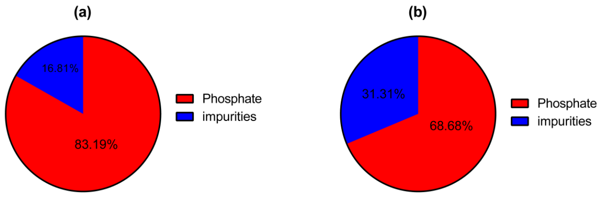

Figure 6. Phosphate and impurities within (a) upper C3 and (b) lower C3.

Table 4. Volume of phosphate of upper and lower C3 (in m^3).

	BT	**TBT**	**< TBT**	**Total**
Upper C3	1 017 032	11 187 352	38 647 216	50 851 600
Lower C3	889 903	1 420 793	3 936 400	18 154 588
Total	1 906 935	15 255 480	59 114 985	76 277 400

(Table 4), using the following equation:

$$\text{Volume} = \text{Average thickness} \times \text{Surface area} \times \text{Recovery rate } (0.9)$$

Table 4 shows that the volume of phosphate decreases from the top (Upper C3) to the bottom (Lower C3) of the C3 for the three studied phosphate grades BT, TBT, and $<$ TBT. The percent of phosphate volume according to the different grades for both Upper and Lower C3 is shown in figure 7. Figure 7 shows that the phosphate grade $<$ TBT is the most dominant category, with approximately 76% for upper C3 and 80.5% for lower C3, followed by the grade TBT of about 22% for upper C3 and 16% for lower C3, while the BT grade represents the lower part with only 2% for upper C3 and 3.5% for lower C3.

For the tonnage, it depends on the cut-off grades; each has a specific coefficient that converts volume into tonnage. The conversion coefficients are previously defined by the mining engineers of the OCP Group as 0.891 for BT, 0.540 for TBT, and 0.495 for $<$ TBT. The results of the conversion are shown in Table 5.

With the values in Table 5, we can distinguish the tonnage for the three major cut-off grades: BT, TBT, and $<$ TBT, for both upper C3 and lower C3. It can be observed that the tonnage of upper C3 surpasses that of lower C3 for the three major cut-off grades. In addition to the disparity in the mean phosphate grade, it is shown that the upper and lower C3 also have a disparity in tonnage.

At the end of this study, we recommend three perspectives for launching the exploitation of C3 in Sidi Daoui:

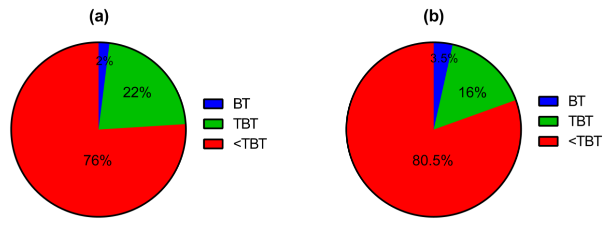

Figure 7. Pie charts showing the proportion of volume of each phosphate cut-off grades for (a) upper C3 and (b) lower C3.

1. *Exploitation of the upper C3:* the choice to select upper C3 is encouraged by its large tonnage which exceed 26 million ton, regardless of its low grade of 61.42% BPL which does not meet market requirement. Therefore, the OCP's mine operators can exploit large scale to offset low grades. However, the low tonnage of the lower C3 does not favor its exploitation with an average low grade of 58.59%BPL.
2. *Using a selective exploitation approach:* In the case of the C3, it seems that a separate and selective exploitation method can be more profitable to achieve a relatively high-grade product, by taking the upper C3 of relatively high-grade and high tonnage without being salted by the inter blended strata of marl and limestone to protect the quality of the phosphate, and leaving the lower C3 in place, which allows to increase BPL to approximately 4.5%. Using this method, the drilling and blasting stage concerns only the interblended strata, this makes it possible to preserve the contents of the rich phosphate strata. However, this method increases the cost of phosphate mining essentially for the loading, and hauling stages, hence, an additional cost of about 0.2 $\$/m^3$ will be generated by this operation since each level or stratum (phosphate of gangues) necessitates an independent mining operation.
3. *Enrichment of phosphate:* the excavated material can be used to produce a high-grade product by using low-grade phosphate of the upper C3 through enrichment via effective mineral processing methods such as physical separation, flotation, calcination, and leaching with organic acids. Otherwise, the beneficiation of phosphate can be done by mixing the phosphate of the upper C3 of Sidi Daoui with that of high-grade phosphate strata from Sidi Chennane, MEA-Lahrech, or El-Hlassa since the high-grade phosphate resources are exhausted at Sidi Daoui.

5. Conclusion

In practice, OCP Group mining engineers and geologists usually estimate the grade and tonnage of phosphate reserves before starting the exploitation stages of any mining project. In this study, the Couche 3 (C3) phosphate stratum, which has long been considered an unexploitable stratum due to its low grade, is investigated for possible exploitability. To conduct this study and provide an explicit

Table 5. Tonnage of phosphate of upper and lower C3 (in ton).

	BT	**TBT**	**< TBT**	**Total**
Upper C3	906 175	6 041 171	19 130 372	26 077 718
Lower C3	792 903	2 196 790	10 131 545	13 121 238
Total	1 699 078	8 237 961	29 261 917	39 198 956

analysis, this work carried out a geochemical analysis of BPL and impurities for the upper and lower C3 levels. According to these geochemical analyses, no level of C3 exceeds 64% BPL, which is the last phosphate cut-off grade that meets market requirements. However, it can be noted that this stratum shows a vertical gradient of phosphate grade that decreases from the top (upper C3) of 61.42% BPL to the bottom (lower C3) of 58.59% BPL. Moreover, the large volume and tonnage of the upper C3 can encourage the exploitation of this stratum using a selective exploitation method by taking the upper C3 and leaving the lower C3. Also, it is recommended to mix the phosphate of C3 with that of high-grade strata (from other deposits) in order to increase the global BPL and thus the desired volume of phosphate.

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Authors contributions

Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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