Journal of Geoscience and Environment Protection, 2018, 6, 193-209
http://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Petrography and Mineralogy of the Eocene Phosphate Deposit of Tobène (Taïba, Senegal)

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How to cite this paper: Dione, N.P., Diagne, M., Diouf, M.B., Fall, M. and Giresse, P. (2018) Petrography and Mineralogy of the Eocene Phosphate Deposit of Tobène (Taïba, Senegal). *Journal of Geoscience and Environment Protection*, **6**, 193-209.
https://doi.org/10.4236/gep.2018.65016

Received: March 15, 2018
Accepted: May 22, 2018
Published: May 25, 2018

Abstract

The Tobène deposit forms, with those of NdomorDiop and KeurMor Fall, the large phosphate deposit of Taïba. The Tobène site has been the subject of lithostratigraphic, biostratigraphic, mineralogical, petrographic and geochemical studies. The lithostratigraphic and biostratigraphic studies dated the series from Lutetian to Bartonian composed of five lithological units, which are assembled by [1] in three formations. The mineralogical study shows three groups of minerals associated with the different phosphatic facies identified in the various sectors of Tobène: 1) characteristic minerals of sedimentological conditions; 2) minerals of diagenetic origin; 3) minerals of alteration. The petrographic study allowed an inventory of the constituting visible grains of the microfacies as well as the different phases of diagenetic and post-diagenetic transformations that may have affected them. It thus appears that the phosphatic ore of Tobène has undergone an extensive diagenesis (compaction, dissolution-recrystallization, epigenesis) to which a relatively intense ferruginization has been added.

Keywords

Tobène, Phosphate, Petrography, Mineralogy, Alteration

1. Introduction

The phosphatic mineralization in Senegal has been the subject of numerous stratigraphic and paleontological studies [2]-[10] showing a variation of the characters according to the structuring and compartmentalization of the deposits.

The phosphates of Taïba are with those of Matam, located in the North of Senegal, the most important phosphate deposits pointed out and exploited in Senegal [1]. The Taïba series, formed around a NE-SW synclinal ridge, in a very calm tectonic basin, contains phosphatic calcic and alumino-calcic phosphatic units. It is exploited in three deposits: NdomorDiop, KeurMor Fall and Tobène (**Figure 1**).

The Tobène panel, the last to be exploited, is located to the southeast of those of NdomorDiop and KeurMor Fall and the preliminary studies on there are relatively brief.

The aim of this paper is to characterize the phosphatic ore of Tobène, from a lithostratigraphic, petrographic and mineralogical point of view, compared to the other panels.

2. Geographical and Geological Context

The phosphate deposit of Taïba is located approximately 80 km in the northeast of Dakar, in an important dune relief site extending over 25 km long and 10 km wide.

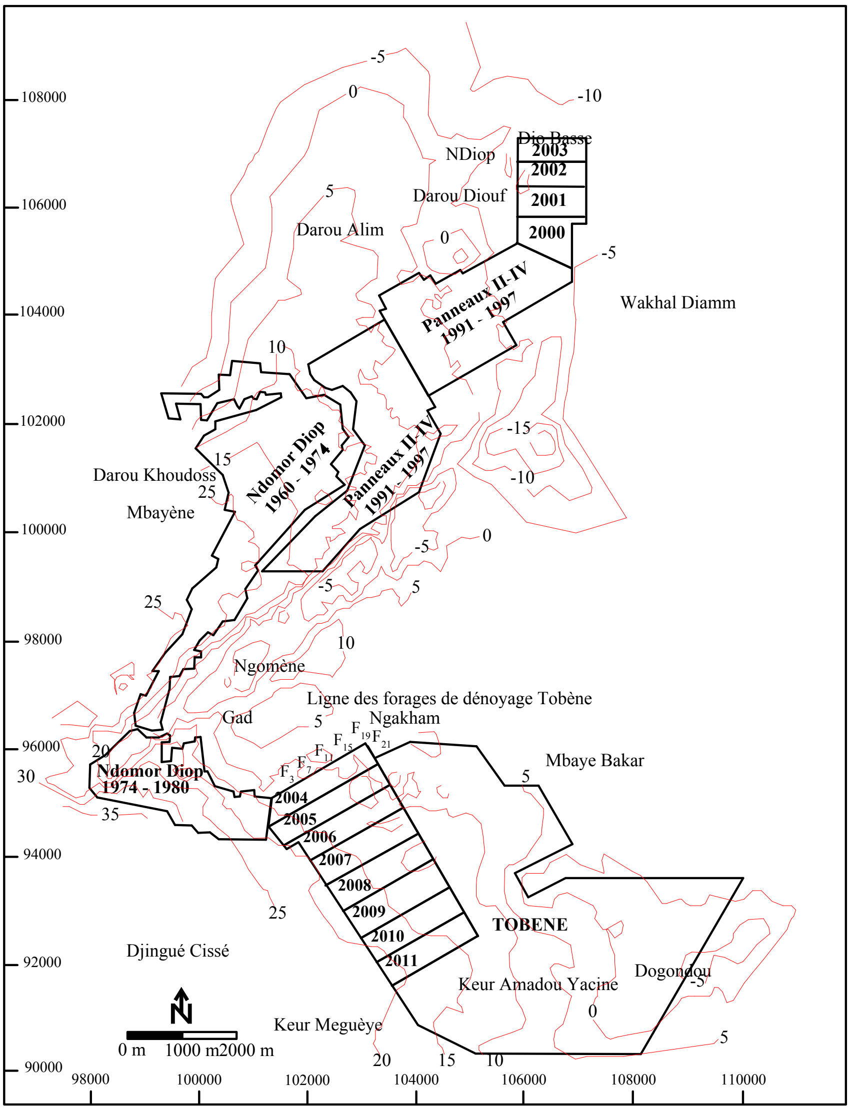

Figure 1. The main panels and isobath map of the wall of the Taïba deposit.

The structural environment of formation of the deposit corresponds to that of an asymmetric syncline with NE-SW axis (**Figure 1**). The fault trough of the synclinal ridge functioned as a structural trap favourable to the phosphatic sedimentation (Slansky *in* [5] [11]). This rather particular environment seems to be on the basis of the configuration of the deposit in three panels [12] corresponding to the three panels of Taïba.

Moreover, this phosphate series of Taïba belongs to the Senegalese sedimentary basin which is a part of the senegalo-mauritanian-guinean basin. This basin, the largest of the West African passive margin with approximately 340,000 km^2, extends over 1400 km between Cap Blanc in Mauritania and Cape Roxo in Southeast of Guinea Bissau (**Figure 2**), through Senegal and Gambia [13].

Relied on the West African craton, this coastal basin is limited in the North by the Reguibat ridge, in the East and Southeast by the Mauritanides chain, and on the South by the Bové basin. In the West, it opens largely on the Atlantic Ocean, allowing the deposit of a mainly marine origin series, which begins at the Trias-Lias and ends at the Miocene.

The microfauna present particularly in the calcium phosphates of Tobène characterizes a depositional environment oscillating between a littoral platform, where the detrital supply come from, and an intermediate to external platform favourable to the deposit of the calcium phosphate. The foraminifera, in particular, allowed giving to this series a middle Lutetian to Bartonian age [14].

3. Material and Methods

This study was carried out on boreholes cores of the Tobène deposit. The sampling interested 42 boreholes distributed in the western, central and eastern sections of the panel (**Figure 3**). It was carried out according to various oriented transects, so as to highlight the meaning of any possible correlation of the characters noted.

The petrographic study using a polarizing microscope concerned essentially the samples of phosphatic facies, with the purpose of a microstructural characterization of these facies. In the same context, other facies associated with the phosphate, particularly some calcareous or clayey phosphates, have also been described microscopically. The various thin sections concerning these facies were made in France, at the University of Dijon and that of Perpignan.

The mineral plan is reconstituted with the help of diffractograms carried out in the laboratory of the "Centre de Formation et de Recherche sur les Environnements Méditerranéens del'Université de Perpignan (CEFREM)", with a diffractometer with anticathode of cobalt.

4. Results

4.1. Lithostratigraphy

The lithological studies carried out of the whole of Tobène panel highlight a series composed of five lithological units.

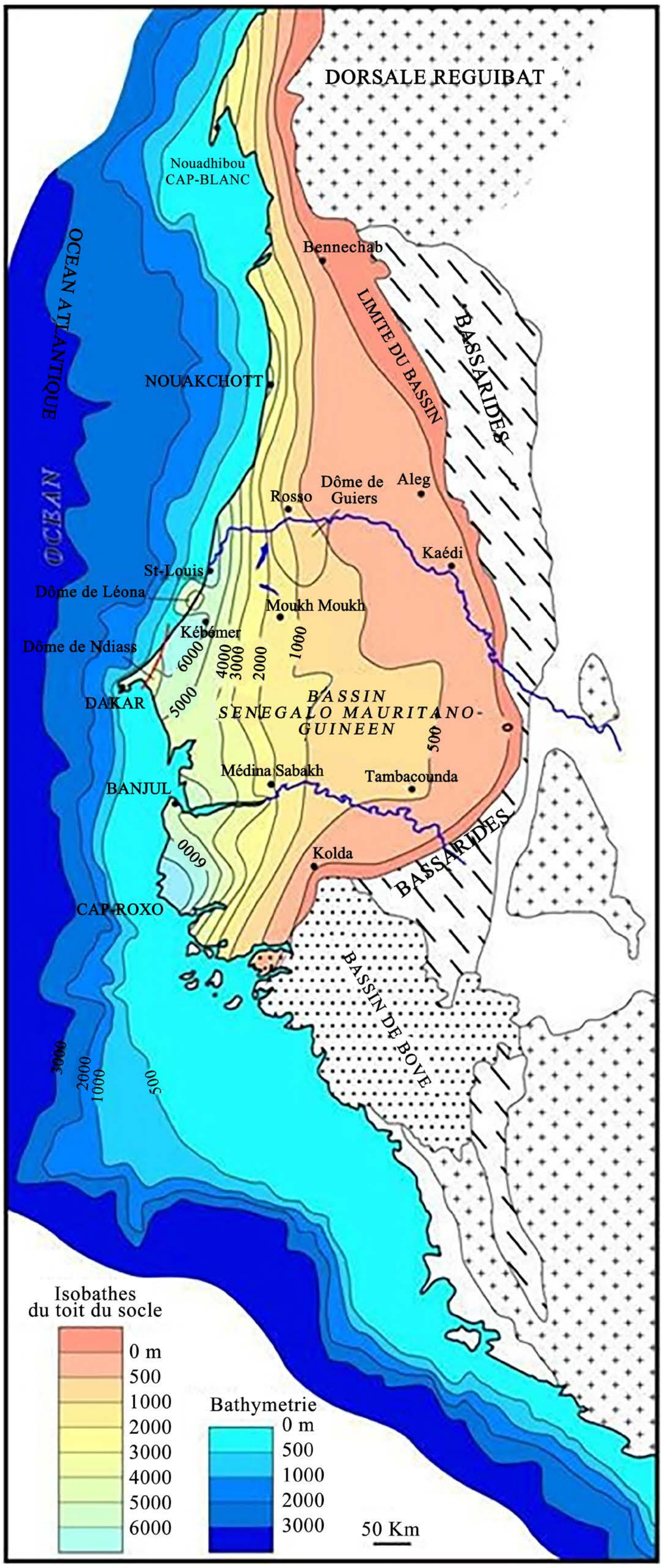

Figure 2. Regional context of the Senegal-Mauritania-Guinea sedimentary basin [1].

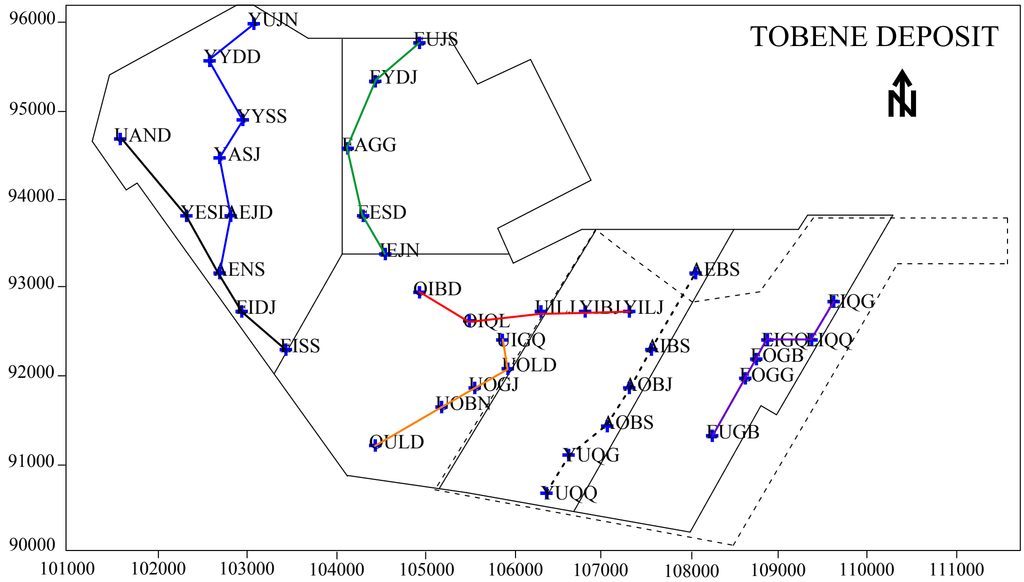

Figure 3. Location map of the boreholes of study.

- At the base, attapulgites sometimes associated with clayey limestones constitute the wall of the phosphate layer. More to the West, this wall evolves towards a phosphatic limestone. Its height deepens gradually towards the east of the panel (Figure 4).
- Above attapulgites rest on gray-to-beige heterogeneous phosphates, more or less consolidated and containing numerous inclusions of various kinds, notably flint benches. In the west of the panel, they show a lateral variation of facies with a passage to phosphatic or clayey limestone alternating with calcareous phosphate. In the central sector, they thicken towards the South-South-East where they can form the main part of the phosphate layer. They disappear laterally towards the northeast of the western sector, towards the northeast and east of the central sector.
- Then, homogeneous phosphates, of variable color, often soft even pulverulent. Silicified by places, they present clayey or clayey phosphatic intercalations. In the eastern sector of the deposit, this level can be sandy (EOGG, EOGB, EIGQ surveys). The homogeneous phosphates have thicknesses ranging from 3 and 8 m. The highest thicknesses are noted in the boreholes where the limestone levels abound.
- Green to brown more or less variegated clays, varying in thickness (0.6 m on average, until more than 3 m in YYDD borehole). They can pass laterally to phosphatic clays. As for the previous facies, the height deepens in the eastern sector. The facies is often affected by silicification but is rarely ferruginized. This unit is absent in some boreholes in the eastern sector (e.g. EUGB borehole: Figure 5).
- A silico-ferralitic unit, usually silicified and ferruginized, consisted from the bottom up of phosphate, called "off-layer" by the miners of Taïba, and a

sandy phosphatic part. In the eastern sector of the panel, it serves as roof to the homogeneous phosphate when the roof clays are absent.

4.2. Petrography

As in other phosphate deposits, the constituent elements of the Tobène phosphates are divided into biogenic and lithogenic particles.

4.2.1. The Biogenic Particles

They mainly comprise foraminifera, but also gastropods, echinoderms, cirripedia (barnacles), calcareous seaweeds and bones of fishes, characterizing a shallow littoral environment.

The foraminifera are more diversified in the western and central sectors, where we observed daucina, globigerine, textular, uvigerine, nummulite, bolivinitidae, alveoline, orbitolinespecies. So, the abundance and diversification of these organisms decrease from bottom to top of the boreholes and therefore of the phosphate series. In general, the frequency of other bioclasts (microgasteropods, debris of echinoderms, barnacles or calcareous seaweeds) evolves similarly.

The bioclasts have not always retained their structure or their initial mineralogy. Many tissues are micritized, unstructured. The phosphate epigenesis is frequent, particularly in the walls of foraminiferal tests (**Figure 6**).

The recrystallization affects many mollusca debris, especially the microgasteropods. The primary porosity of foraminifera, barnacles and microgasteropods is variously obturated by oxidized phosphate, micritic calcite that sometimes recrystallized by dissolution-recrystallization, as suggested by the intercrystalline voids observed in the sparite and the micritic ranges still remaining within macrocrystalline calcite. In the western sector, some chambers of foraminifera are

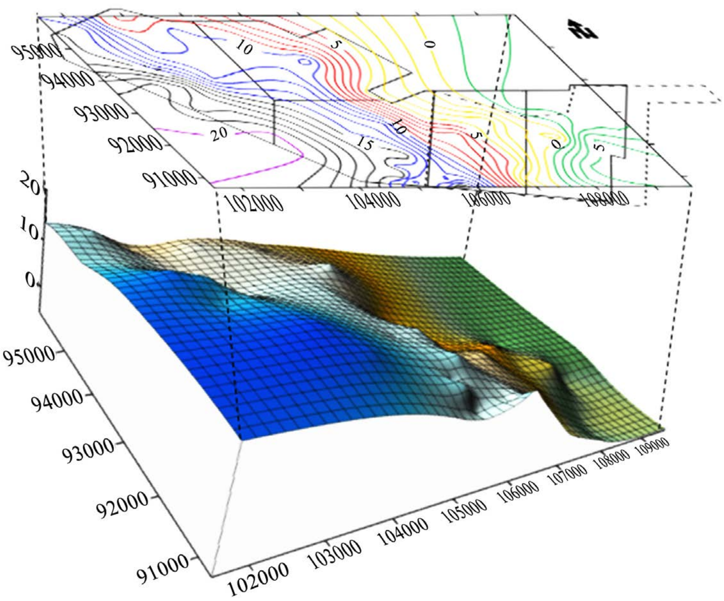

Figure 4. Three-dimensional view of the wall structure of Tobène.

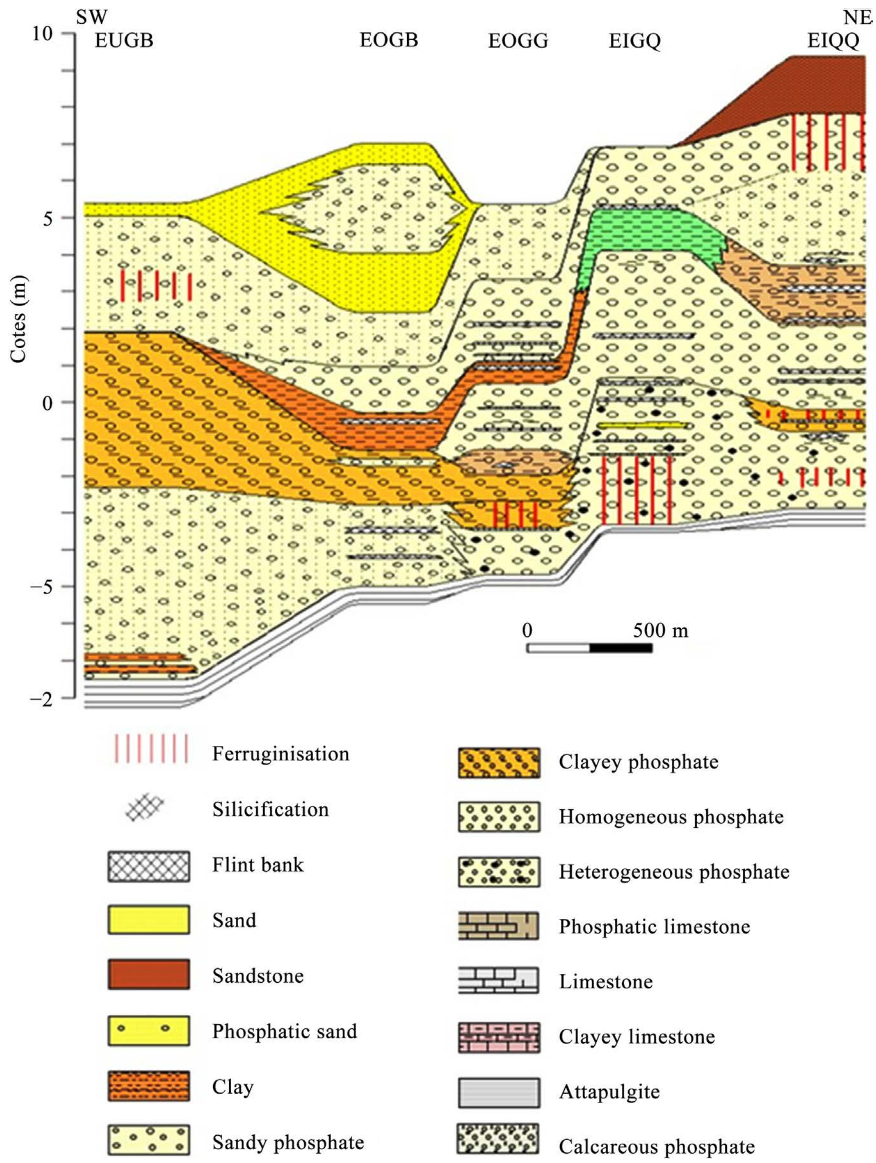

Figure 5. Lithological section of boreholes in the western sector [9].

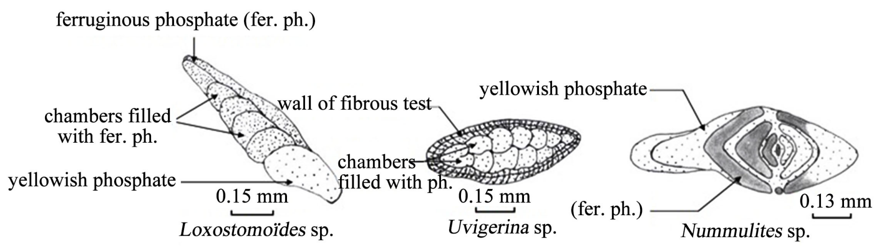

Figure 6. Foraminifera with epigenized test.

filled with gibbsite (Figure 7(a)). These transformations are common over the extent of Tobene, although the bioclasts of the central sector seem to have somewhat more conserved their original calcitic mineralogy. However, the micritization is very pronounced there. We also note that the oxidation is more frequently observed on biogenic debris in the eastern sector.

4.2.2. The Lithogenic Particles

1) The phosphatic grains

In Tobène deposit, the phosphatic grains, with variable sizes and forms, are quite numerous. They form in the marine environment. There are composed of:

a) Phosphatic grains without endgangue

These phosphatic grains, more or less blunted and observed on the whole of the deposit, are generally rich in organic matter. They are sometimes cracked or surrounded by a thin film of ferruginized phosphate (**Figure 8(a)**).

b) Phosphatic grains with endogangue

i) Grains with quartzose endogangue

There are phosphatic grains with inclusions of quartz debris, sometimes angular or blunted. These quartzes can also have, in some cases, an altered surface. In addition to these quartzose inclusions, we have organic matter dispersed more or less regularly inside these grains (**Figure 8(b)**). They are present in all sectors of Tobène deposit (YUJN, OIQL, EIQQ, …).

ii) Grains with calcitic endogangue

They are found mainly in the western sector of Tobène (UYND) and characterized by inclusions of micritic calcite crystals, which recrystallize, by places, into quite fine sparite (**Figure 9(a)**). They show an angular to subrounded form.

iii) Grains with aluminous endogangue

The gibbsite is detected in some phosphatic grains in the South-West of Tobène (AASS) and then characterizes the alteration of the deposit.

iv) Grains with bioclastic endogangue

They include grains with phosphatized bioclastic endogangue and coated phosphatic grains (**Figure 9(b)** and **Figure 9(c)**).

The phosphatized bioclastic endogangue, noted at West Tobène (YASJ) and East Tobène (EUGB), consists of foraminifera totally epigenized in phosphate with the disappearance of the test and the conservation of the internal mould. These grains are filled with calcium phosphate combined with black organic matter often in the form of granules.

As for the coated phosphatic grains, they are knowing in all sectors of Tobène deposit. They can be rich in organic matter or surrounded by a film of ferruginous phosphate.

2) Oolites

They are ovoid grains consisting of a nucleus, of variable nature, constituting the endogangue, and a cortex of concentric layers (**Figure 10**). These inorganic grains, already listed in Taïba, characterize agitated, shallow marine environments and hot climates.

In addition to these generally alpha oolites, there are superficial oolites or oolites with a thin cortex, also known as protolites. With variable forms and sizes, they are few in number and present in all the sectors. Their cortex and nucleus are often affected by phenomena of epigeneis of the carbonate in phosphate.

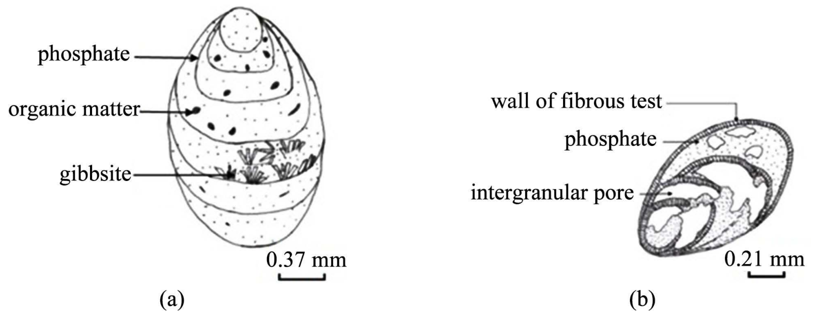

Figure 7. *Daucina ermaniana obtusa*: (a) Chambers filled with gibbsite; (b) Pores.

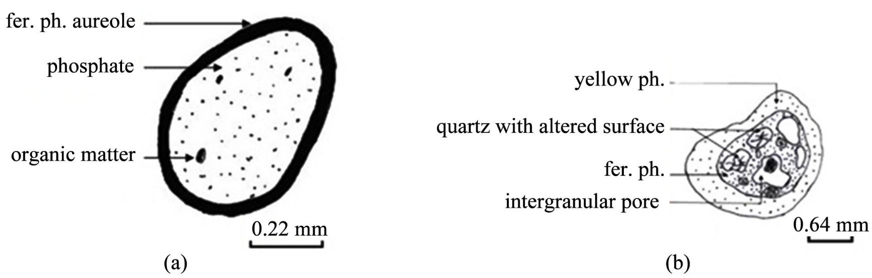

Figure 8. Phosphate grain (a) without endogangue; (b) with quartzose endogangue.

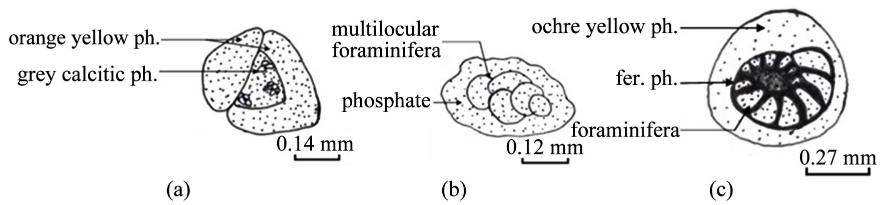

Figure 9. Phosphatic grain (a) with calcitic endogangue; (b) and (c) with bioclastic endogangue.

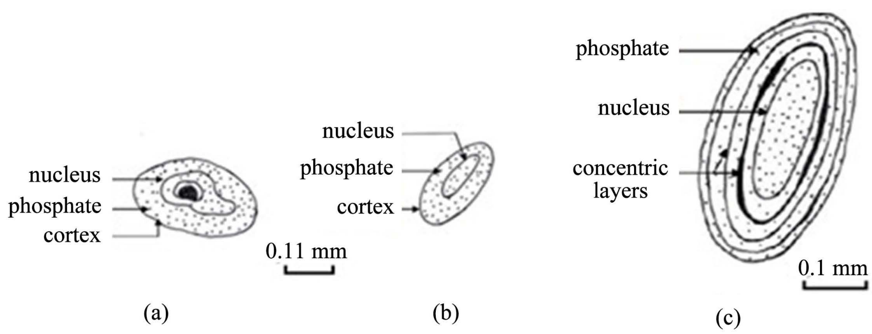

Figure 10. Epigenized oolites.

Thus, they are formed oolites with phosphatic core with a cortex in concentric laminations also phosphatic. These grains would have undergone diagenetic cycles marked by the crackings and oxidations.

Note that these oolites are often accompanied by coprolites (Figure 11), especially in the central sector of Tobène (OIBD and YILJ surveys). These coprolites are of two types: some without mineral endogangue and others with mineral endogangue, which can be quartzose or calcitic.

3) Peloids

They are micritic grains consisting of carbonated mud, rounded, elliptic or ovoid and of fecal origin (**Figure 12**). Very abundant in the phosphatic facies, they are generally formed in marine environment. They have generally a smooth external structure and unlike coprolites, devoid of internal structure [15] [16] [17].

In the western sector, the peloids are characterized, in places, by the presence of endogangue, phosphatic exogangue sometimes ferruginized, but also of intragranular porosity.

Absent in the East, micritized peloides are often associated, at the center of the panel, with other phosphated, also showing irregularly distributed organic matter. The phosphatic peloids formed from the filling of foraminiferal chambers are quite common in some deposits, as that of Taïba. These are, in many cases, old foraminiferal chambers with dissolved calcitic test (Globigerinidae), phosphatized [18] [19] [20].

4) lithoclasts

The petrographic observations revealed three groups of lithoclasts, often rich in organic matter and sometimes affected by intragranular porosity (**Figure 13**). They show an association of quartzose, bioclastic, aluminous (gibbsite), oolithic or carbonate endogangue.

According to the sectors of the deposit, the nature of these lithoclasts can vary. Thus, we distinguish:

- a group of lithoclasts with phosphatic tendency, noted in the West and in the center of the deposit;
- a group of lithoclasts with sandstone tendency, noted particularly in the West;
- a group of lithoclasts with ferruginized phosphatic tendency, mainly located in the East.

The petrographic examination of the phosphate series of Tobène allowed noting that this one underwent important modifications such as the phenomena of dissolution. This latter, affecting both the cement and the visible grains, is highlighted by intra or intergranular porosities.

The intragranular porosity is most often related to the dissolution of the visible grains (**Figure 7(b)** and **Figure 8(b)**). It is essentially a vacuolar porosity.

The intergranular porosity results either from an original arrangement of the deposits or from a dissolution of the cement or particles. These dissolved elements can recrystallize thus filling some porosities. A fracture porosity affects sometimes the cement, indicating a compaction after the cementing (**Figure 14**).

The phenomena of epigenesist are also observed in all the sectors of the Tobène deposit. They affect generally the originally calcitic tests and foraminiferal chambers, the cortex and nucleus of oolites, the nucleus of composite grains and the lithoclasts.

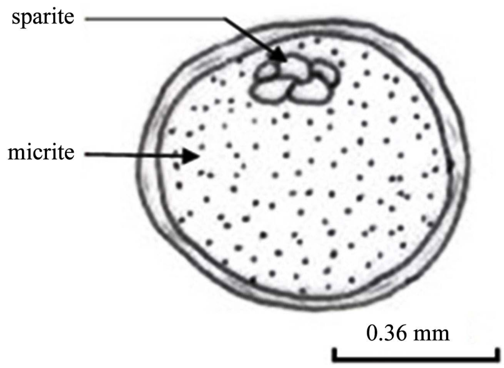

Figure11. Coprolite in transverse section.

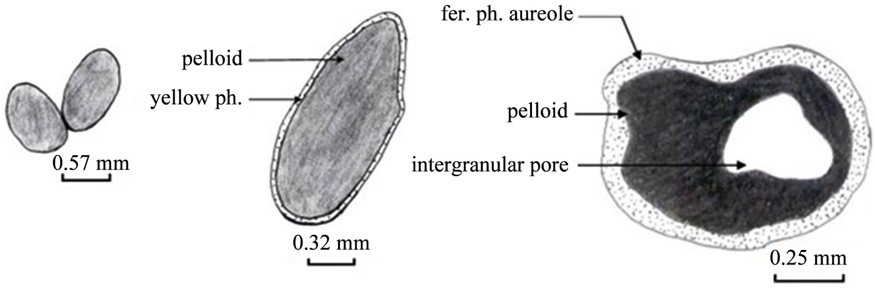

Figure 12. Peloids with variable forms and sizes.

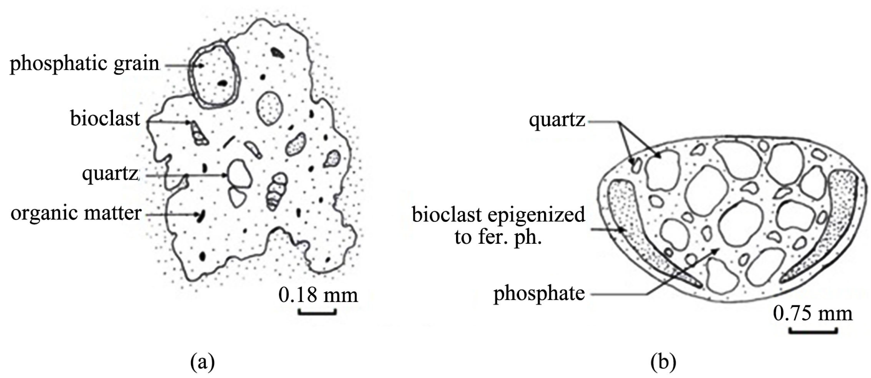

Figure 13. Phosphatic lithoclast.

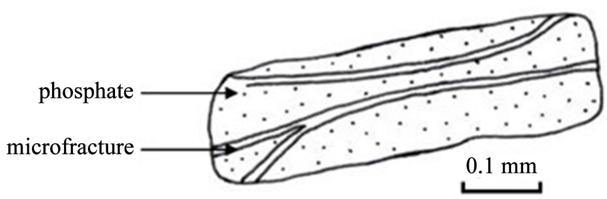

Figure 14. Phosphatic grain in longitudinal section.

Thus, the visible grains of the facies of Tobène deposit are essentially phosphatized elements, some of which have retained their original calcitic character.

However, the presence among others of goethite and gibbsite, both in cement and visible grains, reflects a ferruginization. This latter indicates alteration and of post-diagenetic transformations that underwent the phosphate ore. In the various sectors of Tobène deposit, this alteration affects all the constituents of the rock.

Whatever the sector, the frequent ferruginous indurations towards the Northeast seem to reflect the existence of a southwest/northeast alteration gradient parallel to the fault trough.

4.3. Mineralogy

The mineralogical examination by X-ray diffraction concerned samples taken from the different lithological units of the phosphate series.

All the data collected show that fluorapatite, which is more concentrated in the phosphate layer than in the rest of the phosphate series, is the characteristic mineral of the calcium phosphate of Tobène. It is very often associated with apatite, which is in much smaller quantity. The quantity of these minerals decreasing from bottom to top of the phosphate series, they can completely disappear in the silico-ferralitic unit in favour of millisite, crandallite, wavellite, analcime, ..., as it is shown in the **Figure 15** [10].

Contrary to the work of [12] revealing only the calcite, the carbonates are represented in Tobène by the calcite and the dolomite. The calcite is very present in the West in the heterogeneous phosphate consisted of clayey limestone (AASS sounding) or phosphatic limestone (UYND sounding) and becoming less frequent towards the eastern sector in favour of the dolomite. This latter was detected for the first time in the central sector, exactly in the heterogeneous phosphate (OIBD and YILJ), and became more abundant in the East in the homogeneous phosphate (EUGB).

The silica is essentially represented by the quartz, which is present everywhere in the deposit. Its proportions vary irregularly along the phosphate series, but they are still more important in the silico-ferralitic unit, the clays and the layer sands.

As for the clays, they consist of smectite, illite, kaolinite and palygorskite. Their nature is diverse and their distribution related to the lithology.

Thus, the palygorskite characterizes exclusively the clayey wall of the series, that is to say the attapulgites (**Figure 15**). From a lateral distribution point of view, this mineral is almost present throughout the deposit and relayed by places by the calcite, precisely in the calcareous zones (UYND, AASS and YILJ).

In the rest of the phosphate series, it is relayed by the kaolinite, which is the most abundant clay in the phosphate facies. It can associate with the smectite.

The smectite, although present in the phosphate layer, abounds more in the roof clays. The illite, the least frequent clay, was detected only in the phosphatic layer and the roof clays. This latter mineral, present sporadically throughout the deposit, is always associated with gibbsite, kaolinite and/or smectite.

Contrary to the calcium phosphate, the phosphate facies of the silico-ferraliticunit are essentially marked by alumino-calcic minerals (crandallite and millisite) and

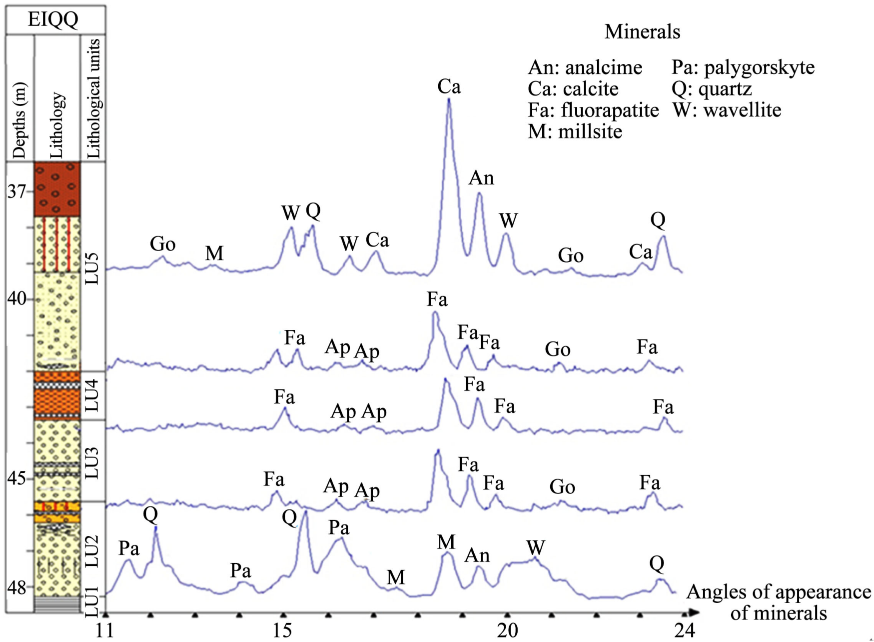

Figure 15. Lithology of the EIQQ borehole and the diffractograms of the analysed phosphate samples [10].

aluminous minerals (wavellite). These minerals are very often associated with gibbsite and analcime. In the phosphate layer, these minerals of alteration abound also in contact with clayey beds and layer sand.

The ferruginous minerals are mainly represented by the goethite. This mineral is very often associated, in the silico-ferralitic unit, with minerals of alteration (crandallite, millisite, wavellite, analcime, ...); whereas in the phosphate layer its presence is accompanied by that of the clays (smectite, kaolinite).

5. Discussion and Conclusions

The phosphatic group of Taïba (KeurMor Fall, NdomorDiop and Tobène) was formed around a NE-SW synclinal ridge [5], in a very calm tectonic basin, favourable to chemical sedimentation with formations dipping to the West [11].

The Tobène phosphate deposit in question comprises three formations: the formation of foliated attapulgite clay, on which lies the formation calcium phosphate, including the heterogeneous and homogeneous members, which is surmounted by the formation with alteration alumina phosphate with platy flint rich in Daucina, alternating with clay and phosphate sand [1].

The formation of calcium phosphate is distinguished by the presence, in its lower part, of calcareous facies. This latter, marked by the presence of calcite, is more widespread in the West, where it may represent, by places, the heterogeneous phosphatic member. This member shows, from west to east, a lateral variation of thickness and especially of facies.

So, even if Tobène deposit presents the same lithological units that the other panels of NdomorDiop and KeurMor Fall, it is characterized, among others, by lateral variations. These concern mainly the marl clayey wall, the heterogeneous phosphate and the variegated clay of the roof, which pass respectively to limestones, clayey or phosphatic limestones and phosphatic clays (**Figure 5**). These lateral variations of facies are the result of a variation of the physico-chemical conditions of the sedimentary environment. Moreover, this association of limestone with phosphate indicates that the calcite precipitation conditions are very similar to those of phosphate, even if the limestone is deposited at a greater distance from the shore and thus develops towards the deepening zones of the basin where are located KeurMor Fall panel and a part of that of NdomorDiop [5]. We also note at Tobène the phosphate formation has two facies with distinct petrographic characters (heterogeneous phosphate, homogeneous phosphate) and is naturally shallower, given the deepening towards the NE of the axis of the fault trough. Thus, the thickening of the limestone at the same time as the deepening of the basin indicates that the structure of the basin strongly influenced the phosphate sedimentation.

These facies, both limestone and phosphate, present a large diversity of visible grains. Therefore, the frequency of typically marine bioclasts, oolites, coprolites and peloids, as well as angular quartz grains reflecting a reworking of the phosphate deposit, and coated grains, indicate that the phosphate genesis of Tobène occurred in a high-energy marine environment.

From a lateral evolution point of view, the notable decrease from west to east of biogenic elements is due to the reduction of the upwelling regime favourable to the proliferation of fish and many marine organisms essentially planktonic [21]. This fact is concomitant with an increase of detrital supply from the continent. Thus, we can say that the sea has transgressed, in this zone of Tobène, towards the East during the Middle Eocene, moment of deposit of the calcium phosphate [11] [14], for then regressing in the Upper Eocene. In addition, the phosphate deposition and its conservation would be favoured by the synclinal ridge, which served as a structural trap [5]. Vertically, this transgression-regression suite is corroborated by the fact that the various visible grains, both biogenic and lithogenic, relatively abundant in the calcium phosphate, become less abundant and less diversified in alumina phosphate.

Moreover, the various petrographic data, coupled with mineralogical and structural data, seem to confirm that the phosphate of Tobène deposit has undergone two successive phases of transformations.

- The first diagenetic phase occurred in a tectonically very calm environment marked by a stop of the subsidence, which was active in the Cretaceous [11]. This phase is characterized, among other, by the dissolution affecting the cement as well as the visible grains. This physicochemical phenomenon has produced a loss of carbonates of the original phosphate and led to the transformation of apatite into fluorapatite, under the action of interstitial acid waters. Similarly, the crystallization of the dolomite in the deeper sectors (central and eastern) is attributed to the dissolution of the calcite of the upper level (western Tobène).

Also, during the burial, the increase in temperature and pressure favoured the recrystallization of dissolved minerals under new conditions. It is the case of the sparite ranges noted in the micritic mass (**Figure 11**). However, the microcrystalline character of the sparite, by places, proves that the process of "sparitisation" is incomplete.

This dissolution-recrystallization is accompanied by a phosphatic epigenesis, notably of carbonate tests, related to a supply of mineral substance.

Finally, the compaction, one of the rare irreversible diagenetic phenomena, is marked by the presence of fractures (**Figure 14**) indicating an early settlement under the effect of the overlying sediment weight. This fracturing informs also about the high intensity of the compaction.

- The second phase of the transformation is post-diagenetic. It is a lateritic alteration, following the Upper Eocene regression and the emergence of the phosphate deposit, coinciding with the accentuation of the Cretaceous fracturing [22]. These phenomena have so led, under humid tropical climate, to the transformation of calcium phosphate (fluorapatite) into alumino-calcic phosphate (crandallite and Millisite) and/or aluminous phosphate (wavellite). Very often, these altered facies show a strong accumulation of clayey neoformed minerals (among others, the kaolinite resulting from the alteration of palygorskite and the illite of the clay beds) and siliceous minerals (analcime resulting from the crystallization of aluminosilicate material of clays [23]. Depending on the intensity of alteration, these facies present a more or less intense ferruginization, marked by the formation of the goethite resulting from the Fe released on place during the alteration of clays. From a petrographic point of view, the observation of gibbsite ranges in cement and bioclasts (**Figure 7(a)**), as well as the presence of ferruginized phosphatic grains (**Figure 8(a)** and **Figure 9(b)**), prove that the alteration affected all the components of the phosphate ore of Tobène.

The intensity of post-diagenetic phenomena seems to be increasing towards the Northeast of Tobène parallel to the deepening of the fault trough and indicates a more intense alteration of this part of the deposit.

Finally, all these diagenetic phenomena (compaction, dissolution-recrystallization and epigenesis) and post-diagenetic phenomena (alteration, neoformation) have resulted in the modification of the internal structure of the phosphate rock of Tobène and determined a mineralogical suite witness of the sedimentological history of this rock. However, these modifications do not detract from the quality of the ore.

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