



HAL
open science

Phosphate deposits of the Senegal-Mauritania-Guinea Basin (West Africa): A review

Jean-Pierre Prian

► **To cite this version:**

Jean-Pierre Prian. Phosphate deposits of the Senegal-Mauritania-Guinea Basin (West Africa): A review. SYMPHOS 2013, 2nd International Symposium on Innovation and Technology in the Phosphate Industry, Compagnie Sénégalaise des Phosphates de Taïba, May 2013, Agadir, Morocco. pp.27 - 36, 10.1016/j.proeng.2014.09.008 . hal-01132025

HAL Id: hal-01132025

<https://brgm.hal.science/hal-01132025>

Submitted on 16 Mar 2015

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



“SYMPHOS 2013”, 2nd International Symposium on Innovation and Technology in the Phosphate Industry

Phosphate deposits of the Senegal-Mauritania-Guinea Basin (West Africa): A review

Jean-Pierre Prian^{a*}

BRGM, the French Geological Survey, BP 36009, F-45060-ORLEANS CEDEX 2, France

Abstract

Among the four areas of calcium phosphate mineralization in the Senegal-Mauritania-Guinea Basin, only the Taïba deposit in Senegal has been in production since 1960 by the Compagnie Sénégalaise des Phosphates de Taïba (CSPT). The N’Diendouri-Ouali Diala (Matam) deposit has been producing some phosphate as well since 2008. The other two areas, Bofal-Loubboïra in Mauritania and Saliquinhé-Farim in Guinea-Bissau, were discovered and explored three decades ago, but never put into production because of their distant location or unfavourable geological conditions. Recently, however, mining companies have become interested in their potential.

The two eastern (Bofal-Loubboïra and N’Diendouri-Ouali Diala) and western (Taïba-Tobène and Saliquinhé-Farim) deposit areas are identified by specific characteristics concerning their lithostratigraphy, initial marine environment, paleogeography, types of phosphate grains in the ore, structure of the mineralization traps of phosphate grains, processes of syn-sedimentary reworking and winnowing of the grains, chemical composition of the ores, etc. The western deposits stand out because of a complex evolution of the mineralization in an environment that changed from marine to continental, and by their pedogenetic paleo-weathering in the site of their final concentration. This weathering caused a complete leaching of all calcite and enrichment in phosphate (natural pre-enrichment of the ore), and occurred during the Late Eocene to earliest Oligocene. We discuss the characteristics of these four West African phosphate deposit areas, stressing the similarities between the Taïba and Saliquinhé deposits, as well as the succession of complex geological processes, first marine and then continental, that led to their formation.

© 2014 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Peer-review under responsibility of the Scientific Committee of SYMPHOS 2013

Keywords: Deposits, phosphates, sedimentary.

1. Presentation

The huge sedimentary Senegal-Mauritania-Guinea Basin, mainly filled with Cretaceous and Tertiary deposits, is the westernmost coastal basin of West Africa and among the largest of Atlantic basins, with a surface area of about 340,000 km². From north to south, it covers four countries: Mauritania, Senegal, the Gambia and Guinea Bissau. Along the coast, its length is about 1,500 km and its east-west width is nearly 560 km at the latitude of Dakar.

The basin hosts **four calcium-phosphate deposit areas of Eocene age (Fig. 1)**. Their tonnage is small compared to the giant deposits of North Africa and the southern Mediterranean area, their individual resources being around 50 to 150 Mt of phosphate, but the ores in three of the areas have high P₂O₅ grades (≥30%). All four areas clearly show the sedimentary settings and terms of marine phosphatogenesis during the Eocene in West African coastal basins, as well as the paleogeographic and hydrodynamic

* Corresponding author. Tel.: +33 2 38 64 34 34.
E-mail address: jp.prian@brgm.fr

factors that allowed the concentration of phosphate in grains, followed by pedogenetic paleo-weathering that led to natural enrichment of the deposits and their intrinsic commercial value.

The four deposit areas lie in eastern and western phosphate-mineralization domains that are about 400 km apart in the Eocene sedimentary basin. The two eastern deposit areas are **Bofal-Loubboïra** and **N'Diendouri-Ouali Diala**—the latter better known as **Matam**—about 140 km distant. The two western deposit areas, **Taïba-Tobène** and **Farim-Saliquinhé**, lie about 340 km apart. The two domains have specific characteristics that clearly differentiate between them.

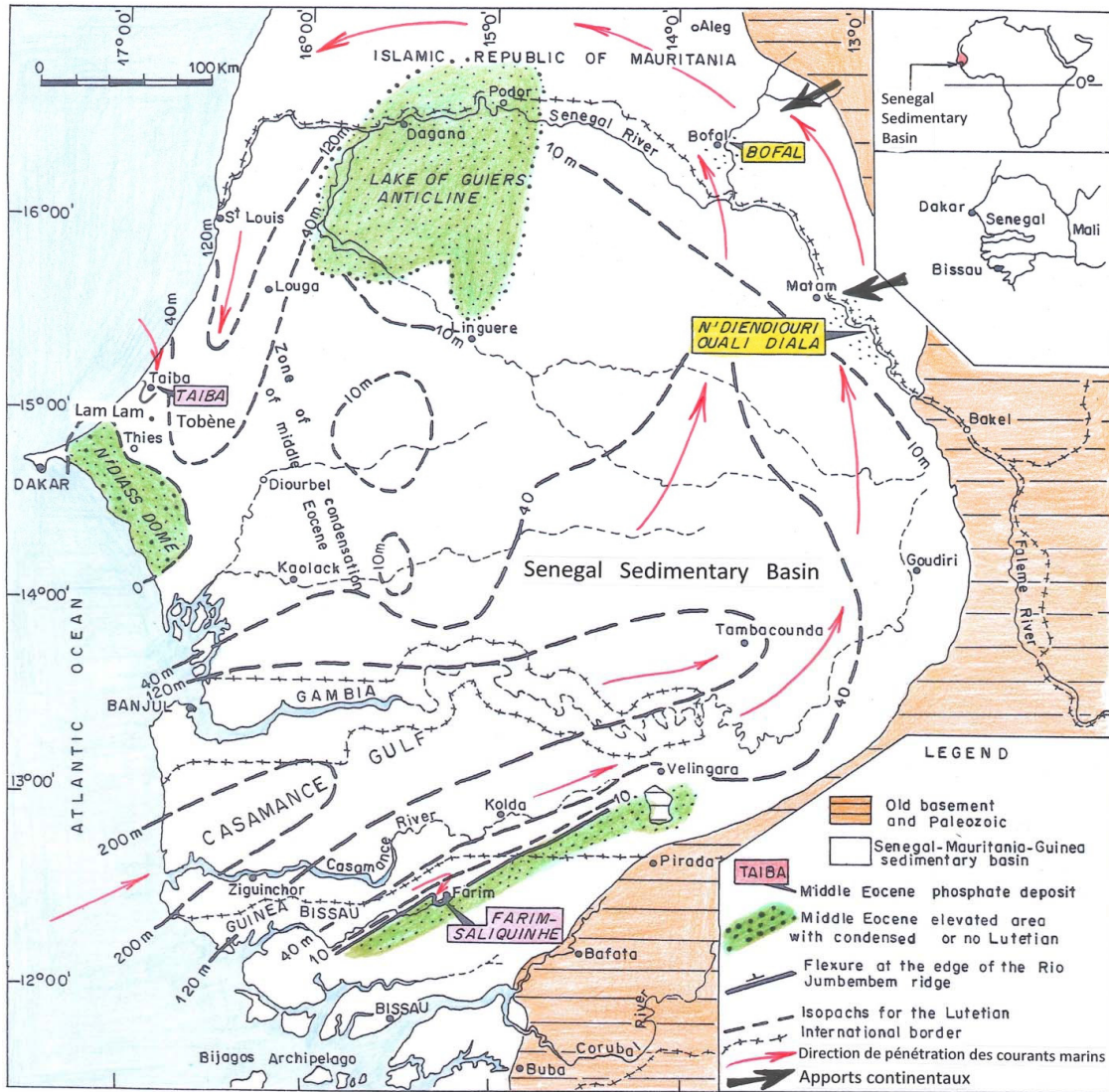


Fig. 1 – Location of the four calcium-phosphate deposit areas of the sedimentary Senegal-Mauritania-Guinea Basin, plotted on a paleogeographic map of the basin during the Middle Eocene (after Prian, 1989).

2. The eastern deposits

The deposits of Bofal-Loubboïra (SW Mauritania) and N'Diendouri-Ouali Diala (a.k.a. Matam) in eastern Senegal, on the right and left banks of the Senegal River, respectively, are located in an internal marine shelf environment, on the eastern edge of the Senegal Basin, near the Mauritanides basement.

3. Size of the deposits

The Bofal and Loubboïra deposits (about 68 km²), adjacent and separated by the Oued Guellouar river, are being explored in detail by Bofal Indo Mining Company SA (BIMC). In the 1980s, their geological resources were estimated by means of 114 pits over a 1 km grid at 93 Mt (Boujo and Ould Jiddou, BRGM, 1982). **Bofal** contained 69.7 Mt at 20.05% P₂O₅ in a phosphate layer 1.73 m thick on average and with a high average stripping ratio of 7.4; **Loubboïra** had 23.7 Mt at 19.05% P₂O₅ in a layer 2.03 m thick on average (locally sub-exposed) and with an average stripping ratio of 4.6. In view of the widely spaced exploration grid and the major vertical and lateral variations of the phosphate layer, these resources are inferred and remain to be certified. Reprocessing of the BRGM data by SNC Lavalin showed inferred resources of 115 to 118 Mt, of which only 41.63 Mt at 19.08% P₂O₅ would be exploitable (BIMC data, 2012).

The adjacent N'Diendouri and Ouali Diala (Matam) deposits, covering about 9 km², host reserves of 28 Mt at 29.1% P₂O₅ and 12 Mt at 27.6% P₂O₅, respectively, for a total of 40 Mt. They were initially evaluated between 1980 and 1984 by means of 162 pits over a grid of 250 by 350 m (Pascal, BRGM, 1985, 1987). These reserves were increased through the recent work by the "Société d'Etudes and de Réalisation des Phosphates de Matam" (SERPM). The average thickness of the phosphate is 2.85 m under 5 to 16 m of sandy clayey overburden. A particularly rich part of the N'Diendouri deposit, with very little overburden, has been mined in open cast as a small operation by SERPM since 2008. The raw phosphate is packed as granules, without chemical processing, for direct agricultural use in the region, as part of satisfying the objectives of the GOANA (Grande Offensive Agricole pour la Nourriture and l'Abondance; Great Agricultural Offensive for Food and Abundance) project.

4. Lithostratigraphy, characteristics and depositional environment of the phosphatic mineralization

The two eastern deposit areas (Bofal-Loubboïra and N'Diendouri-Ouali Diala) are part of an area of basin-edge and internal-shelf deposits. The phosphatic succession overlies or, going east (Loubboïra), laterally passes into a fine detrital succession called Gorgol Sandstone (Elouard, 1975) or Gorgol Formation (Barusseau et al., 2009), whose age is Late Paleocene (Thanetian) to Early Eocene (Ypresian), based on the Selacian teeth identified at N'Diendouri-Ouali Diala (Cappetta, 1984). This near-shore detrital formation discordantly overlies the Cambro-Ordovician metamorphic basement of the Mauritanides, 30 km east of Kaédi, in Mauritania.

5. Bofal-Loubboïra deposit

The phosphatic succession (from less than 1 m to 12 m thick) has a varying lithology, ranging from only phosphate (monolayer) to alternating phosphate-dolomite-claystone marked by rapid lateral and vertical variations of facies and thickness (Boujo and Ould Jiddou, 1983; Lô, 1987). The mineralization occurs in one to five thin phosphate layers of less than 0.50 m to 3.25 m thick (average 1.73 m at Bofal and 2 m at Loubboïra; Boujo and Ould Jiddou, 1983). The phosphatic succession is eroded in the Oued Guellouar valley that separates the two deposit areas. According to macrofaunal elements, the age of the phosphatic succession is early Middle Eocene (early Lutetian). The Selacian teeth indicate a (slightly older) Early Eocene age (Cappetta, in Boujo and Ould Jiddou, 1983).

The phosphatic levels are fine- (<1 mm) to coarse- (<5 mm) grained, and generally consist of phosphareno-rudite with various phosphatic elements. These include abundant whole or broken coprolites, phosphatic lithoclasts with rare matrix, phosphatized internal moulds (microgastropods, lamellibranchs, dentalia, bryozoans, sea-urchin radiola), pellets including radiolarian or diatom fustules, and bone debris. Such phosphatic elements are associated with a major fine-quartz fraction. The gangue is clayey with abundant detrital quartz, of fluvial-deltaic origin. Sandstone containing reworked phosphate grains is rare.

The P₂O₅ grades of the phosphareno-rudite are variable, commonly low (10-15%), but locally high (28-30%) in levels rich in phosphate grains and poor in detrital quartz. The average grade is 20.05% P₂O₅ for the Bofal deposit and 19% for Loubboïra. The grainsize fractions over 400 µm and up to 4 mm contain the highest P₂O₅ grades (35 to 36%), whereas those below 400 µm are low in P₂O₅ (10 to 17%). SiO₂ content is high (40 to 56%), related to the high detrital quartz content. The CaO/P₂O₅ ratio of 1.43 indicates a low substitution rate of PO₄³⁻ by CO₃²⁻. Al₂O₃ and Fe₂O₃ contents are lower at Bofal than at Loubboïra, respectively 2.36% and 1.70%, against 5.20% and 2.66%. The sub-exposed part of the Loubboïra deposit, in the east, has higher Al₂O₃ (7.65%) and Fe₂O₃ (4.09%) contents due to soil weathering. Such surface alteration disappears below 8-m depth in the exploration pits.

Phosphatic sedimentation took place in a marine near-shore environment, as is suggested by the presence of pelecypods and gastropods. The very poor fauna indicates a confined environment. Access to the open sea is only shown by internal moulds of pteropods (pelagic molluscs). The slight reworking of phosphate grains took place under a strong littoral or continental influence, the origin of the major detrital-quartz fraction. This terrigenous fraction is more abundant to the east (Loubboïra), on the edge of the basin toward the continent, than to the west (Bofal) where phosphate reconcentration was more important. To the west, the

phosphate deposits pass into a littoral to neritic domain with dominant organic-detrital and chemical sedimentation. The low concentration of phosphate grains is probably due to the absence of well-defined trapping structures and the action of long-shore currents that spread and disseminated such grains in other sediments.

6. N'Diendouri-Ouali Diala (Matam) deposit

The clayey and limy phosphatic member, 6 to 10 m thick, lies in the middle of an Early Eocene succession (based on Selacian teeth), about 15 m thick, and comprising montmorillonite and attapulgite levels, limestone, dolomite and chert. It commonly contains two mineralized levels with an average thickness of 2.85 m, separated by a metre-thick layer of (dolomitic) clay. The upper phosphatic level generally dominates, but locally the two levels can coalesce where the intermediate barren layer is absent; in addition, strong vertical and lateral variations exist in the phosphate layer.

The phosphatic rock (phospharenite to phospharenorudite) is friable to slightly consolidated. It consists of diverse and unsorted phosphatic grains, including fine pellets (50 to 250 μm) without structure and variably enriched in organic matter; elongate coprolites of a few millimetres to some centimetres; aggregates of pellets and coprolites; small phosphatized bioclasts (lamellibranchs, gastropods, foraminifera, etc.); large bone debris and fish teeth. The minor gangue is mostly clayey and shows local diagenetic phenomena, such dolomitization, de-dolomitization and calcitization.

The average weighted P_2O_5 grade of over 300 phosphate samples is 28% for the Ouali Diala deposit and 28.9% for that of N'Diendouri (Pascal, 1988). The $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ contents are low, near 3%, except on the edges of the mineralized domain because of weathering and secondary ferruginization. SiO_2 contents are below 10%. The average $\text{CaO}/\text{P}_2\text{O}_5$ ratio is around 1.55. Only 1.5% of the determined CaO exists outside apatite (IFDC, 1984).

Irregular and sporadic hydrodynamics led to secondary reconcentration of phosphate elements with grain sorting. This is coarse in the south (Ouali Diala) where the grains are large coprolites and phosphatic lithoclasts, and gradually finer to the north (N'Diendouri) with extremely small phosphate pellets, as 80% of the phosphate passes the 180- μm mesh and no grains of a few millimetres are found. This very intense hydrodynamic winnowing was accompanied by a natural enrichment of the reconcentrated phosphates, with grades of 30 to 33% P_2O_5 , whereas the average grade of the N'Diendouri deposit is 28.9% P_2O_5 (Pascal, 1987). In the south-west part of the N'Diendouri area, such very fine phosphate forms a submarine accumulation dune, about 1 km long, 300 to 400 m wide and up to 7 m thick, representing a mass of about 5 Mt phosphate (Pascal, 1987). This is the high-grade zone that has been mined since 2008. The main phosphate bodies thus are accumulation masses and slopes rather than paleo-depressions and -channels that were infilled.

7. The western deposit areas

The two western deposits (Taïba-Tobène and Farim-Saliquinhé), close to the Atlantic domain and connected to it, are part of a paleogeographic system of sandbanks and channels that created small paleomorphological traps for concentrating reworked phosphate grains of an originally calcitic-phosphatic sediment. Such deposits are slightly younger than the eastern ones, as the marine phosphatogenesis was dated late Lutetian, instead of basal Middle Eocene (early Lutetian) for the eastern deposits.

8. Size of the deposits

The Tobène deposit (26 km^2) in the Taïba area has been mined since 2003 by the Compagnie Sénégalaise des Phosphates de Taïba (CSPT), after the N'Domor Diop and Keur Mor Fall deposits were exhausted. It hosts mineable reserves of 50 Mt of phosphate at 27.34% P_2O_5 and low $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ contents (2.78%), in a single layer of 5.20 m useful thickness, below 38 m of sandy-clayey overburden (Béchon and Lebas, 1976). From 2003 to 2009, the Tobène quarry has mined—from an area of slightly over 2 km^2 —5.9 Mt of ore at 26% P_2O_5 and 3.55% $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$, from a phosphate layer of 6.52 m below 38 m of overburden (Gueye, 2009).

The adjacent **N'Domor Diop** and **Keur Mor Fall deposits**, today exhausted and immediately north-west of Tobène, hosted about 80 Mt of phosphate at 30% P_2O_5 in a phospharenite layer of 7 m thickness on average (varying from 5 to 12 m).

We should also mention the potential **Pire Goureye deposit**, held by the CSPT, located immediately east of the Tobène area, and discovered and explored in the 1950s. It hosts 25 Mt of phosphate at 22.8% P_2O_5 (grade after cleaning an ore of 34.3% P_2O_5), in a layer 6.15 m thick below 25 m of overburden (CSPT, 1983; Sustrac, 1984; Sustrac et al., 1990). This deposit is the result of reworking—during the Neogene—of primary Middle Eocene phosphate mineralization (phosphate of the "Guéoul" type of Tessier, 1952).

The **Saliquinhé-Farim deposit** (about 25 km^2 for the rich phosphate layer called FPA) holds inferred resources of 112 Mt at 30% P_2O_5 ; it was explored from 1981 to 1983 by 69 cored boreholes over a grid of 500 m to 1 km (Prian and Gama, 1983). Champion Resources Inc. in 1997 confirmed and increased these resources to 166 Mt (measured and indicated reserves) by new drilling to the north-west of the deposit. The sandy phosphate layer of 6.20 m maximum thickness (3.30 m thick on average) lies

under sandy-clayey overburden of at least 26 m. The present development project by GB Minerals is based on ore reserves of at least 50 Mt.

9. Lithostratigraphy (Fig. 2)

The Taïba, Tobène and Lam Lam deposits. The footwall of the calcium phosphate layer consists of Lam Lam marl and attapulgite clay of early Middle Eocene age (early Lutetian, Brancart and Flicoteaux, 1971). The overlying late Lutetian phospharenite layer is 5 to 12 m thick at Taïba (average of 7 m), but can be as much as 22 m thick in the centre of the "gutter" that acted as a trap for the granular phosphate (CSPT, 1983; Sustrac, 1984). At Tobène, the phosphate is about 6 m thick.

The type section of the Taïba deposit (Slansky et al., 1965; Atger, 1970) comprises two layers: a lower heterogeneous part of beige to brown sandy phospharenite, 'polluted' by chert sub-parallel to the bedding, and a more homogeneous upper part of lighter coloured phospharenite, almost without chert. Chert nodules in the lower layer can be as much as 2 m long and certain "nougat" facies correspond to local diagenetic silicification of phosphate zones.

The section of the **Tobène deposit** is similar, but lacks the large chert nodules (Samb, 2002). To the north-east, the phospharenite mass abruptly passes into phosphatic and sedimentary limestone, in particular the early Lutetian nummulitic limestone (Tessier, 1952). The relation between the two formations is seen as a lateral passage (Atger, 1970; Sustrac, 1984).

The Farim-Saliquinhé deposit. Here, the footwall of the phosphatic layer consists of limestone with small benthic foraminifera (Uvigerinidae). This formation is dated by planktonic foraminifera as latest Early Eocene to earliest Middle Eocene (early Lutetian). An uneven and silicified hard-ground is commonly seen in drill cores at the top of this limestone.

The overlying phosphate layer comprises two parts: a lower bioclastic calcareous-phosphate member (called FPB), depleted in P_2O_5 (less than 10% to 15%), that can be as much as 14.5 m thick in the Farim area; and an upper phosphate member without any carbonate (called FPA), up to 6.20 m thick and rich in P_2O_5 (30% and more), consisting of weathered sandy to slightly indurated phospharenite, with a clayey (smectite and kaolinite) matrix. The phospharenite locally contains small amounts of small detrital quartz grains in the matrix. The contact between the two layers generally is clear, but locally slivers of white micritic limestone occur at the base of the phospharenite layer (weathering front?). Above the deposit, the FPA member is capped by a thin (10 cm) sandy-ferruginous crust with pyrite, marcasite and siderite that marks an emersion and erosion surface, as well as a sedimentary lacuna on top of the FPA. In fact, several drill holes along the eastern margin of the deposit show that the FPA member wedges out to less than 50 cm thickness, and is replaced by an intercalated siliceous level, by means of a furrowed surface between the top of the calcareous-phosphatic FPB member and the footwall of a calcareous-dolomitic formation that is missing above the FPA deposit, as it has been eroded around the deposit (Fig. 2).

Stratigraphically speaking, a rich planktonic foraminifera fauna (Monciardini, 1982) and about thirty species of Selacian teeth (Capetta, 1983) dated the calcareous-phosphatic FPB formation as middle to late Lutetian. Bourdillon and Roger (1984) noted a reworked Paleocene and Early Eocene microfauna. The phosphatic FPA member was dated late Lutetian to earliest Late Eocene on the basis of Selacian teeth. The top of the FPA member marks a lithostratigraphic discontinuity. At the eastern border of the deposit, the FPB member and its top level of 10- to 50-cm-thick silicified phospharenite, is covered by a calcareous-dolomitic formation that can be as much as 50 m thick. This unit wedges out to the west and does not exist over the FPA deposit. This "upper" calcareous-dolomitic formation has a Middle to Late Eocene age, and locally its uppermost part is Early Oligocene. It is covered by foliated green clay (1 m to less than 5 m)—locally containing thin aluminous phosphate levels—that unconformably overlies all older formations, especially the FPA phospharenite layer, and is probably of Early Oligocene age. It is itself overlain by a thin conglomerate, and then by a black lignitic clay unit (Lignite Group of the oilmen), dated as Oligocene to Early/Middle Miocene on the basis of pollen (Fauconnier, 1983).

The top of the phospharenite layer in the Taïba and Saliquinhé deposits is thus marked by a hiatus in sedimentation, covering the Late Eocene to Early Oligocene interval in the Taïba-Lam-Lam deposits (Brancart and Flicoteaux, 1971), which is also noted above the Saliquinhé deposit (Monciardini, 1982; Prian, 1983). During this period, therefore, the carbonate source rock of the FPA ore was exposed, becoming weathered and enriched in phosphate. However, to the east and north of Saliquinhé a new sedimentary sequence was deposited during the Late Eocene to Early Oligocene, with the formation of upper dolomitic limestone that wedges out and is absent over the deposit itself.

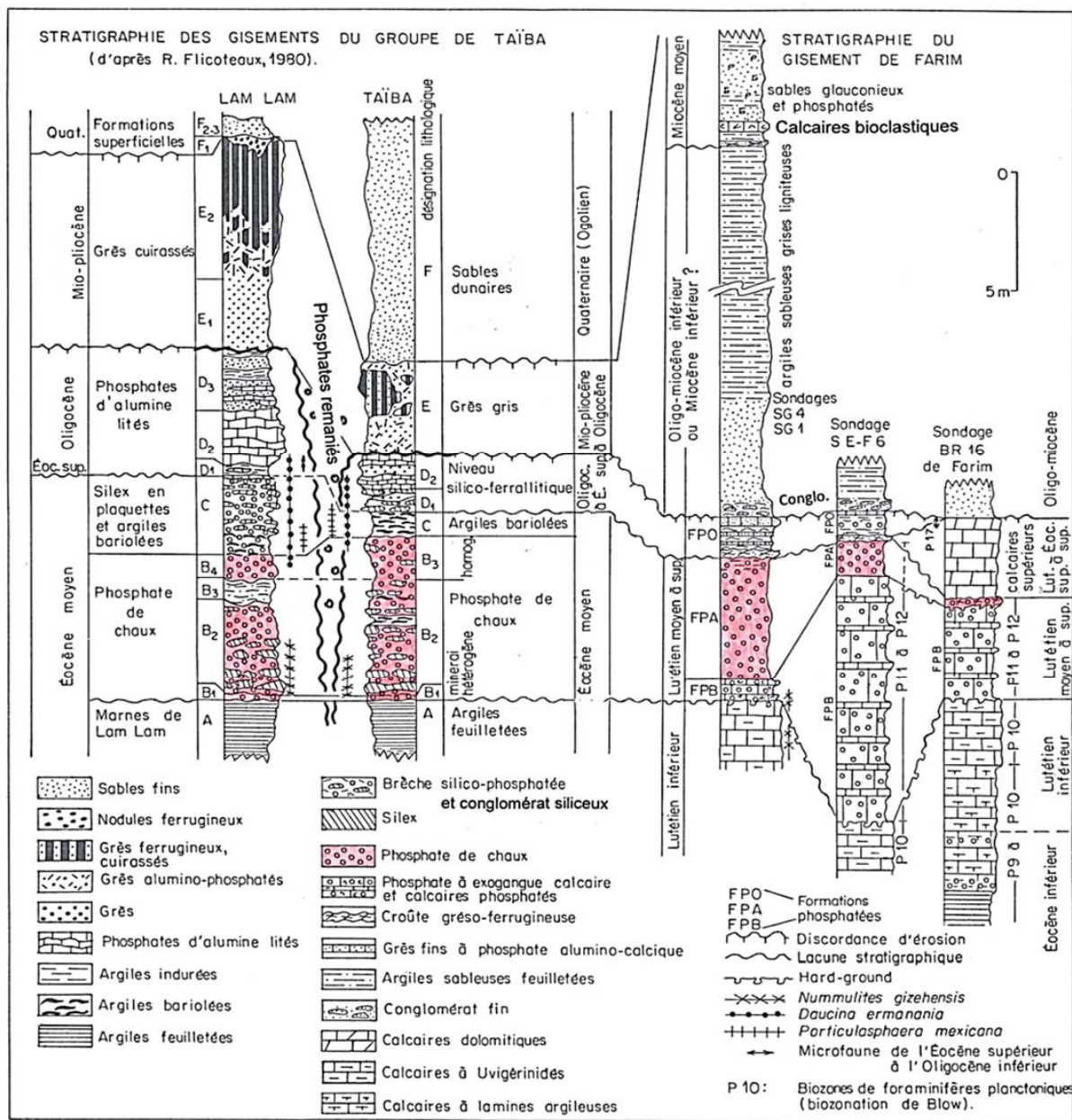


Fig. 2 - Lithostratigraphy of the deposits of the Taïba group (Senegal) and the Saliquinhé-Farim deposit (Guinea Bissau). From Prian and Gama, 1987, modified.

10. Paleogeographic controls and morphological traps

At basin scale, the deposits were formed in an external marine-shelf domain open to the sea. They were controlled by general and local paleo-oceanographic and paleogeographic conditions in areas where, during the Middle Eocene, a thin and condensed succession was deposited.

The deposits of the Taïba area lie at the end of what was a great SSW-NNE gulf during the Middle Eocene, which was open to the north and, in the west, had an area of shallows that connected the emerged areas of Ndiass and Lake Guiers (Fig.1).

The Farim-Saliquinhé deposit is located on the south edge of the Senegal Basin and the great (Tertiary) Casamance Gulf, with an east-west axis at the level of the high Farim-Dabo-Vélingara area.

At a local scale, the Taïba-Tobène and Saliquinhé deposits were controlled by a shallows-and-trough configuration during the Middle Eocene, which acted as a trap for slightly reworked phosphate concentrations. The phosphate mineralization then became weathered and enriched into phosphate ore in its locations of final deposition.

At Taïba, the structural map of the phosphate footwall (or hanging wall of the Lam Lam marl formation) shows a trough with a SW-NE axis, about 2 km wide and 10 km long, slightly dipping to the north-east (Atger, 1970).

At Saliquinhé, the structural map of the footwall of the calcareous-phosphatic FPB formation shows a synform structure with a SW-NE axis at the rear of the gulf, open to the north-east and about 4.5 km wide by 6 km long. The structural map of the footwall of the phosphate-rich FPA looks like a vast closed basin within the calcareous-phosphatic FPB formation to the east, and within limestone of the of the FPB footwall on the west side. The north-east to south-west thinning of the FPB limestone, from 14 m to 0 m over 2 km of horizontal distance, is due not only to sedimentary wedging-out over a shallows area, but also to limestone dissolution related to weathering of the FPA, thus creating a small morphological trap for the concentration of granular phosphate.

11. Petrochemistry of the ores

The rich phosphatic layer of both deposit areas mostly consists of very fine-grained and very rich phosphate (phospharenite), leaving little intergranular space for a clayey matrix or phosphatic cement. Such friable to slightly indurated phospharenite can be assimilated to phosphatic grainstone. This richness in phosphate grains goes hand-in-hand with high P_2O_5 grades (30% and over).

In the Taïba deposit, the phospharenite of the ore has a high P_2O_5 grade (30 to 33%), with little silica (7.30% SiO_2) and penalized by high Al_2O_3 (3.2%) and Fe_2O_3 (3.6%) grades. In the Tobène deposit, the run-of-mine ore is less rich in P_2O_5 (Table 1), but its characteristics are satisfactory for obtaining a good-quality commercial concentrate (Samb, 2002; Gueye, 2009). Decarbonation of the ore is confirmed by low values of the CaO/P_2O_5 ratio (1.35 to 1.37).

In the Saliquinhé deposit, the phospharenite consists of sandy to slightly indurated sediment, in which all elements are phosphatized. The grainsize is fine, 98% of the grains passing a sieve mesh of 0.8 mm and 100% the 20 mm sieve size. The +50 μm to -800 μm grainsize fraction is the largest in weight (68%), in contained P_2O_5 (72%), and in P_2O_5 grade (33%) (C.S.P.T., 1983b, in Prian and Gama, 1983). The fine fraction (<50 μm) also contains high P_2O_5 grades (29%), representing 24% of the contained P_2O_5 in the ore (26% in weight). The coarse fraction, over 800 μm , is depleted in P_2O_5 (20%) and negligible as far as contained P_2O_5 (3.5%) and weight (5.5%) are concerned. The average grade of the ore is 30% P_2O_5 ; it contains little silica (8.90% SiO_2), but is rich in Al_2O_3 and Fe_2O_3 because of its clayey matrix and ferriiferous minerals that are locally present in the cement (Table 1). As at Taïba-Tobène, the low CaO/P_2O_5 ration of 1.40 confirms the decarbonation of the ore.

Table 1 – Selected chemical data for the ores from Taïba, Tobène and Saliquinhé

	Taïba (from Slansky, 1980)	Tobène (from Gueye, 2009)	Saliquinhé (from Prian and Gama, 1987)
$P_2O_5\%$	33.30	26.00	30.90
$SiO_2\%$	7.30		8.90
$Al_2O_3\%$	3.20	3.55	2.73
$Fe_2O_3\%$	3.60		4.10
CaO%	45.10	35.62	43.40
$CO_2\%$	1.40		3.10
F%	3.75		3.0
CaO/P_2O_5	1.35	1.37	1.40

12. Phosphatic biomass and paleoenvironments

In the phospharenite of both deposit areas, the grains with biogenic support are the most important fraction with the coprolites. At Taïba-Tobène, the microfauna in the phospharenite layer is rich in species but poor in general, represented by pelagic and benthic forms, thus witnessing of a microfauna mixed by oceanic currents coming from the open sea. This microfauna is identical in the phospharenite layer and in the reef limestone that laterally grades into phosphate. Most phosphate elements are internal

moulds of microfossils (globigerinids, nummulites, daucines, operculinids, miliolids, algae, etc.), whose calcareous tests were dissolved and replaced by phosphate, or are locally silicified (Brancart and Flicoteaux, 1971; Lucas et al., 1979), as well as egg-shaped phosphatic grains with a cortex (pseudo-oolites). The rare microfaunal elements and the limited number of genera suggest restrictive ecological conditions. The benthic species (Nummulites, Rhodophyceae) indicate warm and shallow water, less than 100 m deep.

At Saliquinhé, the biophase supporting infra-millimetric phosphate grains is again very abundant in the phosphatic FPB limestone and in the FPA phospharenite. It consists of benthic and planktonic foraminifera, bryozoans, and debris from echinoderms, crustacean, micro-gastropods, radiolarian and, more rarely, bivalves and ostracods. In the FPA ore, among the phosphatized micro-organisms (conserved as internal phosphatic moulds) and in the grain matrix, we find abundant pteropods (pelagic micro-gastropods), eponinids and uvigerinids (benthic foraminifera). Small teeth and bone debris are common as well. Some levels are also very rich in unbroken oblong fish- or crustacean coprolites, often rounded, indicating that this fragile material did not suffer major hydrodynamic reworking within the basin. Such phosphatized biogenic concentrations suggest a thanatocoenosis of marine organisms, and especially micro-organisms, in a confined environment rich in organic matter.

The small size of the phosphate grains in the FPA ore indicates strong winnowing by currents in their place of final concentration. The grains lie very close together and are imbricated, leading to a much reduced intergranular space, probably caused by water escaping during emersion of the phospharenite body. The proportion of matrix/cement is thus very low compared to that of phosphate grains. The matrix is clayey and the cement locally is phosphatic, consisting of collophanite (cryptocrystalline phosphate) or recrystallized apatite. This, irregularly distributed, phosphatic cement locally explains the high P_2O_5 grades (up to 38%) in certain dark-grey phosphate levels—around one metre thick—of the Saliquinhé layer. No trace of carbonate (calcite or dolomite) is seen in the cement or in the phosphatized biophase. The ore is completely decarbonated.

The underlying calcareous-phosphatic FPB member, of late Lutetian age, contains two foraminifera associations, one rich in uvigerinids, the other with Nonion, Planulina and boliviniids, locally associated with nummulites, indicating an environment of distal to proximal infralittoral deposition (Bourdillon et al., 1984).

Above the phosphatic FPB and FPA members, the upper calcareous-dolomitic formation encloses an impoverished and little diversified biophase, indicating a near-shore proximal to middle-shelf depositional environment, more internal than the previous environments.

13. Relation between phosphatic and phospharenite limestones. Genesis of the ores

At Taïba, the phosphate layer to the north-east grades into nummulites-bearing phosphatic and reef limestones (Atger, 1970; Brancart and Flicoteaux, 1971). This rather abrupt lateral passage forms the limit of the deposit. Within the phospharenite layer, a few limestones are found as well, in particular in the Tobène deposit. The hostrock of the decalcified Taïba ore is a micritic limestone with lime phosphate and some phosphatized microfauna (Flicoteaux, 1980). Once in its place of final deposition, the physico-chemical composition of the phospharenite was further modified by leaching due to percolating rainwater, a diagenetic process described by Lucas et al. (1979). These authors state that the leaching of the calcite was complete, notwithstanding the abundant limestones around the deposits. This completely decarbonated the phospharenite of the deposit, shown by the replacement of calcareous tests of the foraminifera by cryptocrystalline phosphate (collophanite) and by the transformation of apatite that acquired small amounts of CO_2 of 1.20 to 1.40 (measured contents) and 1.85 to 2.29 (calculated contents), according to Lucas et al., 1979). The Taïba deposit thus was the result of the evolution of a primary deposit through weathering and leaching by rainwater that further concentrated the P_2O_5 grade of the ore. Flicoteaux (1980) stated that the weathering was poly-phased, reflecting a long evolution of tropical climatic conditions. The initial leaching and the start of forming a ferruginous and phosphatic duricrust at Lam Lam (aluminous phosphates) probably took place either from the Oligocene to the Messinian (over 15 to 20 Ma), or from the Middle Miocene to the Messinian (over 4 to 5 Ma).

At Saliquinhé, similar conclusions can be put forward, but more precise data are available for the relations between phosphatic limestone and the phospharenite of the deposit, and for the period during which decarbonation and weathering occurred. The phospharenite of the FPA layer (maximum thickness of 6.20 m) is not the result of weathering of the slightly phosphatic bioclastic FPB limestone (maximum thickness of 15 m to east of the deposit), or of limestone dissolution, extraction of disseminated grains and reconcentration. It rather derives from a distinct phospharenite level, very rich in biogenic phosphate grains, and intercalated between the top of FPB (above a ravined hard-ground) and the overlying dolomitic limestone. The remains of this level, 10 to 50 cm thick, with a siliceous or calcitic cement, were intersected by several boreholes to the east of the deposit.

As at Taïba, the FPA phospharenite is entirely decarbonated. The limy tests of the numerous foraminifera serving as support of the phosphate grains were completely replaced by phosphate (collophanite), whereas such replacement is absent or partial in the FPB microfauna. Moreover, collophanite locally occurs as cement, indicating the existence of late-stage phosphatization by slight reworking within the sedimentary environment, after the final mechanical reconcentration of grains that already contained phosphate. In the cement, local pyrite, marcasite and siderite crystals are further indicators for pedogenetic alteration having affected the FPA ore during emersion of the deposit. The CaO/P_2O_5 is higher than at Taïba (1.40 rather than 1.35 to 1.37), as are the CO_2 contents (3.10% against 1.40%).

This emersion, having caused decarbonation and enrichment of the ore in phosphate, took place between the start of the Late Eocene and the start of the Oligocene, corresponding to the non-deposition of the upper dolomitic limestone over the deposit, or

over a period of about 10 Ma. The FPA layer was little affected by the more thorough alteration of calcium phosphate into aluminous phosphate. Nevertheless, the uppermost part of FPA can locally show such alteration over 10 to 50 cm thickness (a whitish, sandy phosphate with a spongy aspect). Locally, thin (10 to 50 cm) layers of aluminous phosphate are also found in thinly bedded green clay overlying the FPA, itself underlying black and locally bituminous lignitic clay, the Lignite Group of oilmen, of Oligocene to Early Miocene age. Such alteration of the phosphatic and clayey succession into aluminous phosphate is not as important as in the Thiès-Lam Lam region, south of Taïba, where the aluminous phosphate crust can be 10 to 12 m thick. In the Farim-Salioukhé region, the tropical weathering that accompanied the Late Eocene emersion was interrupted by deposition of the black clays of the Lignite Group, whereas in the Lam Lam-Thiès region this weathering continued as the area was not covered by these deposits and remained above baselevel.

14. Conclusions

The individual mineable reserves of the four calcium-phosphate deposits of the Senegal-Mauritania-Guinea Basin are low (around 50 to 70 Mt), and three of them are penalized by their distant location and geological characteristics. Nevertheless, they constitute important natural resources for all three countries.

The two eastern deposit areas, formed at the end of the Early Eocene or during the earliest Middle Eocene, are quite different from the two western deposits. This difference lies in their distinct sedimentary and paleogeographic settings that conditioned the ore quality. At Bofal and Louboïra, on the eastern rim of the Senegal-Mauritania Basin in an internal marine-shelf domain, the ore has a low P_2O_5 grade as currents spread the phosphate grains over large areas, without structural traps for concentrating them. Moreover, this ore is 'polluted' by detrital quartz deriving from the continent. At N'Diendouri-Ouali Diala, the irregular bottom currents, scouring the internal marine shelf with hydrodynamic winnowing of the phosphate grains, caused secondary reconcentration of the minerals and built sub-marine dunes of phospharenite rich in P_2O_5 , as at N'Diendouri.

The two western deposit areas were created during the Middle Eocene (late Lutetian) in a distal to proximal external-marine shelf environment with many shallows and channels communicating with the open sea, and well supplied with phyto- and zooplankton by upwelling currents coming from the Atlantic. After a general transgression, the sea progressively withdrew, creating great lagoons in which a biotope developed with few species but many individuals, indicating biological confinement of the environment that led to mass mortality. The wealth of organic matter and favourable chemical conditions in the basal water layer triggered phosphate formation. The phosphate grains in this environment were reworked and winnowed through hydrodynamic action, before re-deposition in nearby morphological traps. Such phosphate concentrations then progressively emerged, leading to strong alteration and leaching by rainwater that caused the complete dissolution of calcite and its replacement by phosphate (specifically the epigenesis of fossil calcite tests by phosphate). Any phosphate remobilized during leaching could precipitate as cement of the phosphate grains. With continuing emersion, the pedogenetic alteration further developed with local precipitation of ferruginous products in the cement. This paleo-weathering occurred from Late Eocene until Early Oligocene times. At Salioukhé it was stopped by renewed sedimentation, but south of Taïba (in the Lam-Lam and Thiès deposits) it continued in the areas above baselevel by further evolution of the weathering profile and the partial or total transformation of lime phosphate into a thick aluminous phosphate below the laterite crust.

The genesis of the calcium phosphate ores in the deposits of the Taïba region and in the Salioukhé deposit—and their present economic interest—thus are the result of a conjunction of favourable marine phenomena (phosphatogenesis, calcareous-phosphatic source rock) and complex processes of continental paleo-weathering, during the interval between Eocene and Oligocene.

References

- [1] Atger M. (1970) – Données sur la géologie du gisement de phosphate de Taïba et les gisements d'origine sédimentaire marine. Rap. Int. Inédit 70-AT-06, Comp. Sénéq. Phosph. Taïba, Serv. Géol. – Prospect., 14 p.
- [2] Barusseau J.P., Roger J., Serrano O., Duvail C. (2009) – Notice explicative de la carte géologique du Sénégal à 1/200 000, feuilles de Saint-Louis – Dagana, Podor – Saldé, Matam – Semmé. Ministère des Mines, de l'Industrie et des PME, Direction des Mines et de la Géologie, Dakar, 55 p.
- [3] Boujo A. and Ould Jiddou E.H. (1982) – Les gisements de phosphate de la vallée de l'Oued Guellouar : Bofal et Louboïra (Mauritanie). Synthèse des connaissances. Campagne de recherche 1981-82. Rap. BRGM 82 RDM 025 AF.
- [4] Boujo A. and Ould Jiddou E.H. (1983) – Une découverte récente de phosphate : les gisements de Bofal et de Louboïra (Mauritanie méridionale, région du fleuve Sénégal). Chronique de la Recherche Minière n° 472, septembre 1983, p. 37-52.
- [5] Boujo A., Giot D., Monciardini C., Robelin C., Roger J., Vinchon C. (1983) – Caractères sédimentologiques et diagénétiques de la série phosphatée de Bofal-Louboïra (Mauritanie méridionale, région du Fleuve Sénégal). Inventaire et étude des composants phosphatés. Rap. BRGM 83 SGN 850 GEO.
- [6] Boujo A., Capetta H., Ould Jiddou E.H., Monciardini C., Robelin C., Roger J. et Vinchon C. (1984) – Etude d'un gisement phosphaté de type plate-forme interne : les gisements de phosphate de Bofal et de Louboïra (Mauritanie). Note. Interne BRGM, Service Sédimentologie, 84 GEO ES 019.
- [7] Boujo A. and Ould Jiddou E.H. (1989) – The Eocene phosphate deposits of Bofal and Louboïra, Mauritania. In: Phosphate Deposits of the World, vol. 2: Phosphate rock resources, p. 207-213; edited by Notholt et al., Cambridge University Press, first published.
- [8] Bourdillon C., Roger J., Andreieff P., Monciardini C. (1984) – Etude sédimentologique et micropaléontologique de séries phosphatées du Paléocène et de l'Eocène de la région de Farim (Guinée Bissau). Rap. BRGM 84 SGN 187 GEO.
- [9] Brancart R. and Flicoteaux R. (1971) – Age des formations phosphatées de Lam-Lam et Taïba (Sénégal Occidentale). Données micropaléontologiques, conséquences stratigraphiques et paléogéographiques. Bull. Soc. Géol. Fr., (7), 13, 3-4, p. 399-408.
- [10] Cappetta (1983) – Détermination des dents de poissons des phosphates de Farim. Etude inédite, Laboratoire de Paléontologie, Université de Montpellier.

- [11] Cappetta (1984) – Rapport sur les faunes de Sélaciens de Matam (NE Sénégal). Recherche de phosphates au Sénégal. Rap. BRGM 85 RDM 009.
- [12] C.S.P.T. (1983a) – Monographie de la Compagnie Sénégalaise des Phosphates de Taïba. Revue de l'Industrie Minérale, Paris, mars 1983, pp. 117-140.
- [13] C.S.P.T. (1983b) – Etude minéralurgique préliminaire du minerai FPA des phosphates de Farim (Guinée Bissau). Etude C.S.P.T. n° 83/03/SAN/AMB du 30 mai 1983, S.A. Niang et L. Dieng, 40 p.
- [14] Elouard P. (1975) – Formations sédimentaires de Mauritanie atlantique. In : Notice explicative de la carte géologique à 1/1 000 000 de la Mauritanie. Edit. BRGM, pp. 171-213.
- [15] Fauconnier D. (1983) – Etude palynologique de 59 échantillons de la mission phosphate Farim (Guinée Bissau). Etude BRGM 83 GEO EM 166.
- [16] Flicoteaux R., Nahon D., Paquet H. (1977) – Genèse des phosphates alumineux à partir des sédiments argilo-phosphatés du Tertiaire de Lam-Lam (Sénégal). Suite minéralogique. Permanences et changements de structures. Sci. Géol. Bull., 30, 3, pp. 153-174, Strasbourg.
- [17] Flicoteaux R. (1980) – Genèse des phosphates alumineux du Sénégal occidental. Etapes et guides de l'altération. Th. Sci., Univ. Marseille St-Jérôme, 1980 et Mém. Sci. Géol. Univ. Strastbourg, 1982, n° 67.
- [18] Gueye A.S. (2009) – Analyse comparative de données de sondages prévisionnels et de résultats d'exploitation du panneau de Tobène entre 2003 et 2009. Cartographie des anomalies de couche. Mémoire de Master II, Université de Dakar, UCA/FST/Département de Géologie.
- [19] International Fertilizer Development Center (IFDC) (1984) – Characterization of phosphate rock from Matam (Sénégal). Rap. inédit IFDC, Alabama, USA.
- [20] Lucas J., Menor E. d. A., Prévôt L. (1979) – Le gisement de phosphate de chaux de Taïba (Sénégal). Un exemple d'enrichissement par altération. Sci. Géol. Bull., 32, p. 39-57, Strasbourg.
- [21] Lô Khalidou (1987) – Etude géologique des gisements de phosphates de Bofal et de Louboïra (Mauritanie méridionale). Thèse Lab. Géol. Univ. Nice, 199 p.
- [22] Monciardini C. (1982) – Phosphates de Guinée Bissau. Microbiostratigraphie et paléoenvironnement. Bilan résumé de la première phase de l'étude. Etude BRGM SGN/GEO 82 GEO EM 11.
- [23] Pascal M. (1985) – Recherche de phosphates au Sénégal. Campagne 1980-1984. Rapport final. Etude géologique et minière des nouveaux gisements de phosphates du Département de Matam (secteur N'Diendouri et Ouali Diala). Rap. BRGM, Dir. Min. Géol. Sénégal, DMG/BRGM/85 – RDM 009.
- [24] Pascal M. (1987) – Nouvelles découvertes de minéralisations phosphates au Sénégal : les gisements de N'Diendouri – Ouali Diala (département de Matam, région du fleuve). Chronique de la Recherche Minière, n° 486, pp. 3-24, BRGM Orléans, France.
- [25] Pascal M. and Faye C. (1989) – The Matam phosphate deposits, Senegal. In: Phosphate deposits of the world, vol. 2, Phosphate rock resources, p. 295-300, edited by A.J.G. Notholt, R.P. Sheldon and D.F. Davidson, Cambridge University Press.
- [26] Prian J.P. (1983) – Contrôle tectonique et morphologique de la sédimentation phosphatée sur la bordure méridionale du bassin sénégal-mauritanien : exemple du gisement de phosphate de chaux éocène de Farim (Guinée Bissau). Rés. Communication séance spécialisée Soc. Géol. Fr., « Bassins sédimentaires en Afrique », Marseille, Trav. Lab. Sci. Terre, Fac. Sci. Marseille St-Jérôme, sér. A, n°15, p. 61-62.
- [27] Prian J.P. and Gama P. (1983) – Géologie, genèse et évaluation des ressources du gisement de phosphate de Farim (Guinée Bissau). Rap. BRGM 83 DAK 004, 2 vol. (unpubl. rep.), BRGM France.
- [28] Prian J.P. (1986) – Géologie de la bordure méridionale du golfe tertiaire de Casamance (Sénégal et Guinée Bissau). In : Documents n° 101 du BRGM, p. 5-32.
- [29] Prian J.P. and Gama P. (1987) – Le gisement de phosphate éocène de Farim-Salioukhé (République de Guinée Bissau). Chronique de la Recherche Minière, n° 486, pp. 25-54, BRGM Orléans, France.
- [30] Prian J.P. (1989) – The Farim-Salioukhé Eocene phosphate deposit (Guinea Bissau, West Africa). In: Phosphate deposits of the world, vol. 2, Phosphate rock resources, p. 277-283, edited by A.J.G. Notholt, R.P. Sheldon and D.F. Davidson, Cambridge University Press.
- [31] Samb M. (2002) – Evolution géochimique des phosphates sédimentaires du gisement de Tobène (Sénégal). Implications pour l'exploitation industrielle. J. Sci., vol. 2, N°2 (2002), pp. 68-74.
- [32] Slansky M. (1980) – Géologie des phosphates sédimentaires. Mémoire du BRGM n° 114, 92 p.
- [33] Slansky M., Lallemand A., Millot G. (1965) – La sédimentation et l'altération latéritique des formations phosphates du gisement de Taïba (République du Sénégal). Bull. Serv. Géol. Als.-Lorraine, t. 17, fasc. 4, pp. 311-324.
- [34] Sustrac G. (1984) – Plan Minéral de la République du Sénégal. BRGM pour DMG Sénégal, 3 volumes. Phosphate vol. 1, p. 64-101.
- [35] Sustrac G., Boujo A., Giot D., Maurin G., Pascal M., Prian J.P. (1988) – General presentation of exploration for sedimentary phosphate conducted by BRGM in Africa. Chronique Recherche Minière, Special issue, august 1988, BRGM France.
- [36] Sustrac G., Flicoteaux R., Lappartient J.R., Prian J.P. (1990) – Phosphates in West and Central Africa. The problem of Neogene and Recent Formations. In: Phosphate Deposits of the world, vol. 3, Neogene to Modern phosphorites, pp. 127-142, edited by W.C. Burnett and S.R. Riggs, Cambridge University Press.
- [37] Tessier (1952) – Contribution à la stratigraphie et à la paléontologie de la partie ouest du Sénégal (Crétacé et Tertiaire). Thèse Sci. Univ. Marseille, 1950 et Bull. Dir. Mines A.O.F. ; 14, tomes I et II, Grande Imprimerie Africaine, Dakar.