

Lithostratigraphy of the Manganese Exploration Sites of the Lebaye Plateau in the Okondja Basin (SE-GABON)

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Abstract

This article examines the lithostratigraphy and typology of manganese mineralization on the Lebaye plateau based on trench observations and approximately one hundred rock samples analyzed by portable X-ray fluorescence. It identifies lamellar manganese ore as the main exploitable facies within a supergene alteration profile derived from manganese-bearing amplites of the Francevillian succession. The manuscript also classifies the ore as medium-grade and raises hydrogeological considerations relevant to the future development of the quarry.

Keywords

Lithostratigraphy, Mineralization, Lamellar, Supergene, Manganese, Hydrogeological

1. Introduction

Gabon is a Central African country covering 266,667 km², located in the Congo Basin. It comprises nine provinces, one of which, Haut-Ogooué Province, is well-known for its mining operations, particularly for uranium (U) and manganese (Mn), which began in the 1960s by companies such as COMUF (a subsidiary of Areva) and COMILOG. Uranium mining ceased several decades ago, while manganese mining has been steadily increasing in recent years, and Gabon aims to become the world's leading producer. To this end, COMILOG has developed programs called "COMILOG 20-20" with ambitious goals, including "8 million tons of Mn

produced”. Following several other companies, such as BHP Billiton and GMFA (GABON MANGANESE & FERRO ALLOYS SA), Nouvelle Gabon Mining (NGM) applied for and obtained exploration permits from the relevant authorities, including the Ministry of Mines. This was based on previous data provided by BHP Billiton, COMILOG, and then GMFA, indicating the high occurrence of manganese (Mn) in certain areas of the Haut-Ogooué region, particularly in Okondja. The objective of this study is to contribute to a better understanding of manganese dynamics and improve knowledge of manganese typology and mineralization on the Lebaye Plateau in the Okondja area. Specifically, it will: (1) describe the different facies, (2) understand manganese dynamics, and (3) determine the appreciable thickness of the mineralized horizon.

2. Geographical and Geological Context

2.1. Geography and Climate

The town of Okondja is the capital of the Sébé-Bricolo department, located north of Franceville, in the Haut-Ogooué province. It is accessible by road from Libreville over a distance of approximately 700 km, as well as from Franceville over a distance of 150 km and from Lastourville over a distance of 130 km.

The population density is low and mainly concentrated in the departmental capital. The rest of the population lives in villages located along the four main roads that 3 connect Okondja to Franceville via Akiéni and Andjoho, on the Okondja-Lastourville road and on the Okondja-Makokou road [1] [2]. **Figure 1** shows the localisation of Okondja area in the Franceville Basin.

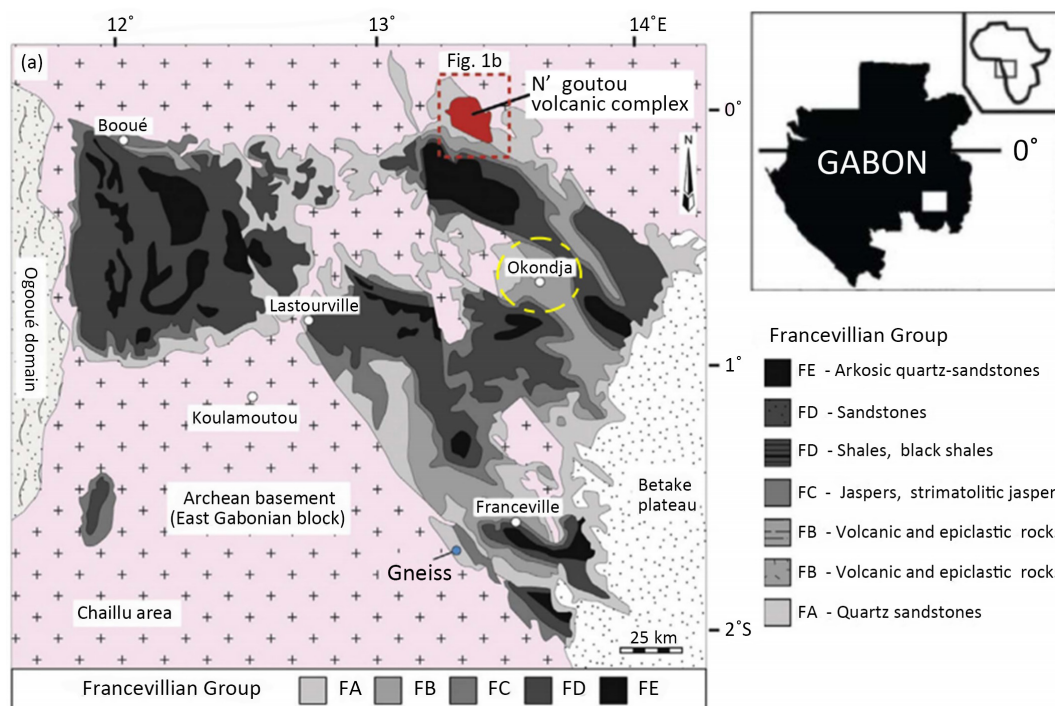


Figure 1. Location of the Okondja area in the Francevillian basin.

In the Okondja region, as in the rest of the Haut-Ogooué province, the climate is equatorial, with two rainy seasons alternating with two dry seasons of similar intensity. Average annual rainfall varies from 1600 to 1800 mm. The average daily temperature is 24.6°C year-round, reaching a maximum of 29°C and a minimum of 21°C [1] [2]. The lowest monthly rainfall is recorded from June to September. The longdry season (June to September) is well-defined and accompanied by relatively low temperatures, averaging 23°C [1] [2]. This is the most favorable time for fieldwork.

2.2. Geology and Geomorphology

In the mining province of Haut-Ogooué, the Franceville Basin is composed of four sub-basins: the Booué Basin, the Lastoursville Basin, the Franceville Basin, and the Okondja Basin [3]. Stratigraphically, the sedimentary thickness of the Booué Basin varies between 200 m and 300 m, while that of the Lastoursville Basin is on the order of 400 m to 600 m. The sedimentary thicknesses of the Franceville Basin vary from 2500 m to 3000 m, and the Okondja Basin has sedimentary thicknesses of nearly 4000m [1] [4]. Lithostratigraphically, the Franceville Basin is composed of five successive units (or groups) [3] [5] [6]:

- 1) Francevillian A is essentially composed of coarse detrital rocks (quartz-arenites, more or less conglomeratic);
- 2) Francevillian B reflects the transition to finer sedimentation, predominantly pelitic to ampelitic, and locally sandstone to conglomeratic and/or dolomitic. This sedimentation is accompanied by volcanism of varying extent and expression depending on the area;
- 3) Francevillian C is characterized by the presence of jasper layers several meters thick, covering a very wide geographical area. Its lithological characteristics and ubiquity make it a key lithostratigraphic marker;
- 4) Francevillian D is quite similar to Francevillian B; essentially pelitic to ampelitic, but with a strong volcanic imprint (tuffs, lavas, volcanosedimentary facies);
- 5) Francevillian E marks a return to predominantly sandstone sedimentation, but with recurrences of fine-grained facies (pelites).

Francevillian B is very well developed in the Franceville and Okondja basins, but is almost absent from less subsiding areas, such as the Lastoursville shoal or the Booué Basin [3].

The FB Formation exhibits two sedimentary evolutions from base to top, leading to its division into two subformations, FB1 and FB2 [3] [5] [7]:

- 1) The FB1 Formation, whose base is primarily composed of fine sediments such as black claystones rich in organic matter and pelites, alternating with brecciated, carbonated sandstone layers.
- 2) The FB2 Formation, approximately 100 m thick, is characterized by beds of fine and massive Poubara sandstone, reaching several tens of meters in thickness, highly silicified, sometimes graded with trough bedding, and the presence of hum-

mocky cross-stratification (HCS).

The exploration permit area consists of steep hills and plateaus dissected by a hydrographic network of streams that drain into the Sébé River, a right-bank tributary of the Ogooué and the main collector of the permit area, along with its tributary, the Lebaye River, which gave its name to one of the six mineralized plateaus within the permit. All the manganese deposits are located in the Sébé basin. The Lebaye, flowing from north to south, crosses the area perpendicularly and divides the plateau that bears its name into two almost equal parts. In terms of relief, the topography shows variations in altitude from 300 to 470 m, with the NW and SW hills being the highest points on the plateau. The Lebaye Plateau, in particular, consists of plateaus and steep hills traversed by small streams [2]. **Figure 2** shows the stratigraphic formations of the Okondja geology.

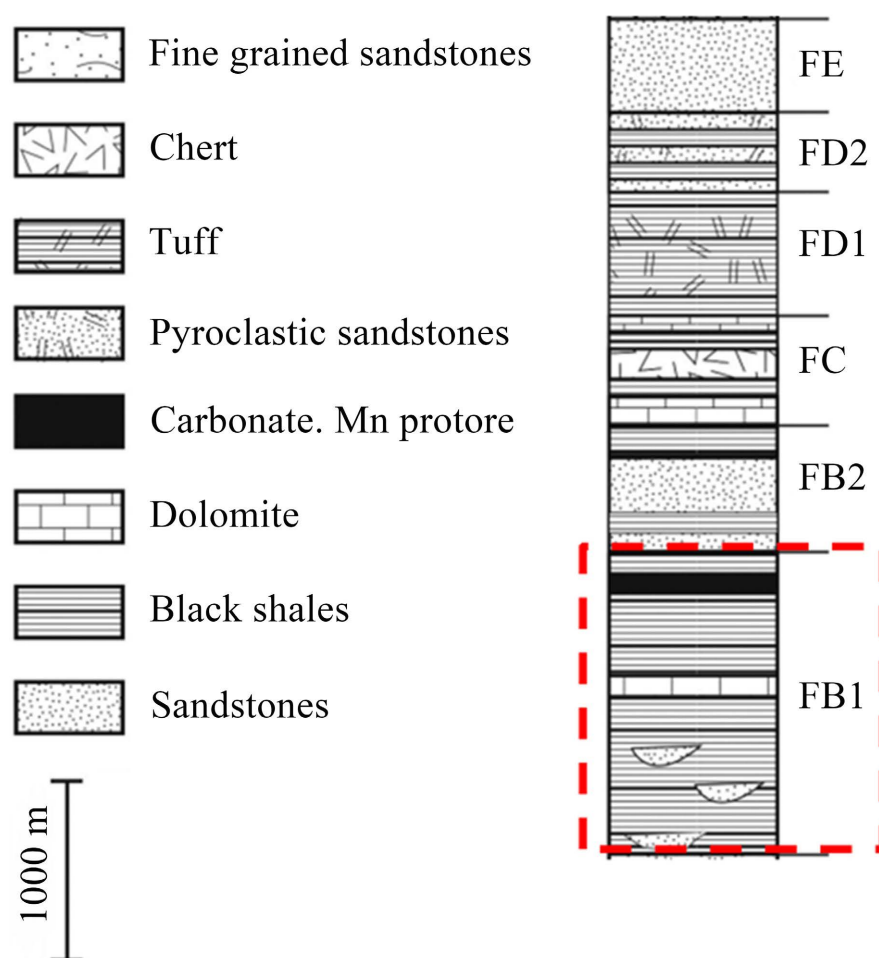


Figure 2. Stratigraphic formations of the Okondja geology.

2.3. Location and Description of the Exploration Permit Area

The area of mining exploration permit No. G2-569, known as “Okondja Manganese”, is delimited in the form of a polygon. This exploration permit covers an area of 747.2km² and contains six plateaus mineralized in Mn (see **Figure 3**).

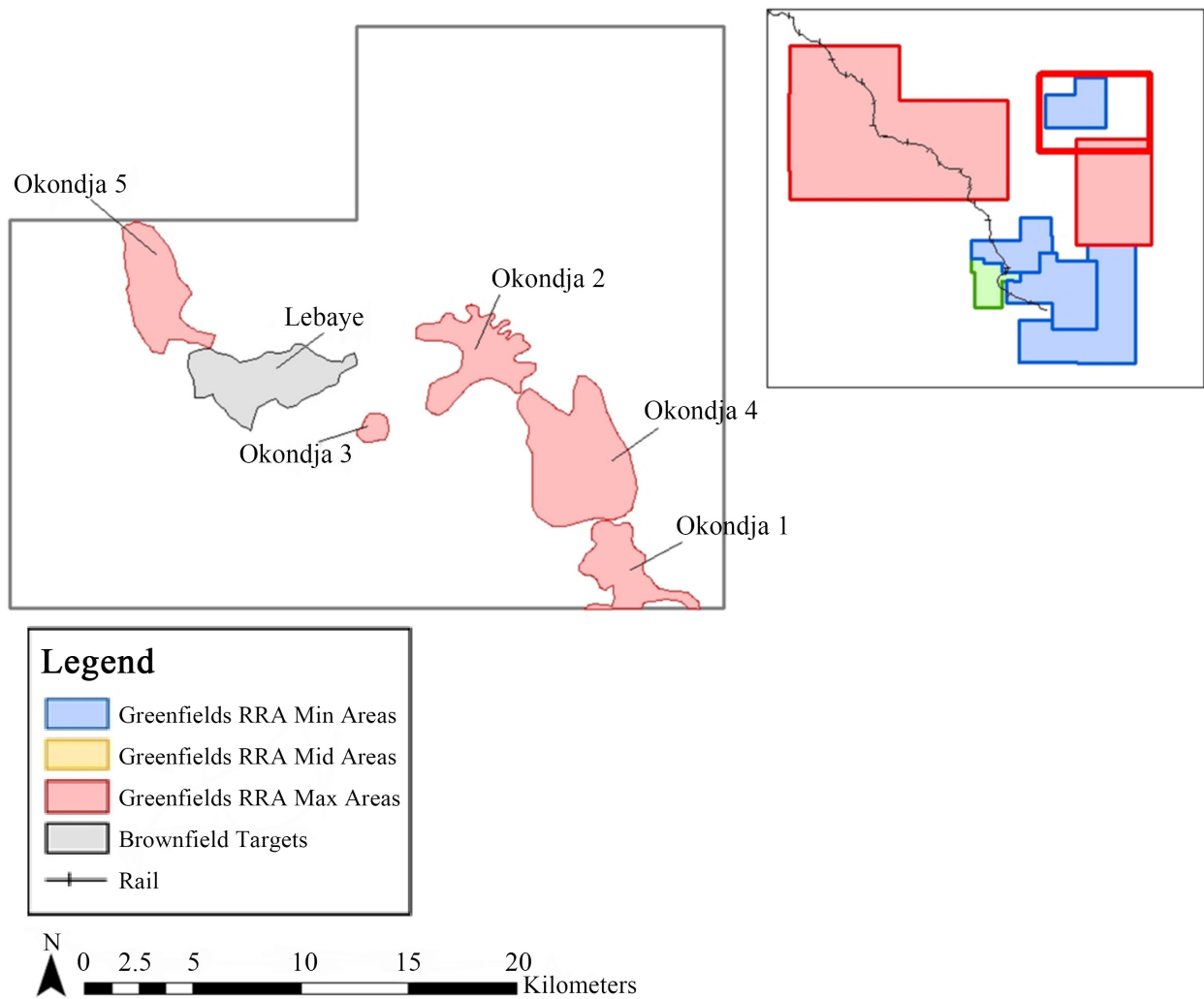


Figure 3. Position of the 6 manganese prospects of the GMF permit including the Lebaye plateau in the center and in blue.

3. Materials & Methods



Figure 4. Photographs of the rehabilitation of the main access road to Lebaye.

A major exploration and evaluation program on the Lebaye plateau has led to several fieldworks, including:

- Preliminary geological survey;
- Exploration using a motorized auger;
- Manual well drilling campaign, mechanized wells and trenches;
- Exploration using boreholes.

In preparation for the start of operations, all internal access roads have been resurfaced to facilitate movement from one point to another using a bulldozer, totaling a cumulative length of over 17 km. **Figure 4** shows the photographs of the rehabilitation of the main access road to Lebaye.

Systematic sampling of the various mineralized lithofacies was carried out in the different profiles of the opened and reopened wells and trenches. These samples were taken from top to bottom, perpendicular to the pit walls, in accordance with applicable standards. A total of 12 trenches were excavated using mechanical diggers, with each trench taking between 4 and 6 hours to excavate. Each trench measured 15 meters in length and 1.5 meters in width. The depth of the pit depended on the completion of the manganese horizon. The maximum depth reached in the pits/trenches was 9.3 meters.

A sampling plan was implemented for the 12 trenches excavated, taking into account the variability of the geological facies:

- 15 m trenches: 10 samples per trench.
- 10 m trenches: 8 samples per trench.
- Control samples (QA/QC): 10 samples (White, Standard, Double).

The number of samples per facies is as follows:

- Mineralized facies (Massive/Platelets): 70 samples.
- Transition facies (Manganiferous Clays): 12 samples.
- Sterile facies (Amplites/Black Shales): 8 samples.
- Quality Control (QA/QC): 10 samples.

However, given the depth of the trenches (7 to 9 m), sampling was carried out vertically, from bottom to top, along the most representative trench walls. The groove method was used over a width of 10 cm and a depth of 5 cm along the different facies. Furthermore, for each meter sampled in the manganese ore, approximately 7 to 8 kg of sample were collected. **Figure 5** shows the photographs of manual work and mechanical trenches opened.

To ensure the validity of the geochemical data before sending it to the laboratory, the Niton XRF analyzer was calibrated using a blank (SiO_2) and a CRM-certified sample (powder sachet). Subsequently, duplicate measurements were taken at different points on the same samples. A minimum startup time of 60 to 90 seconds was required to optimize the detection of the chemical elements (Mn, Fe, and P). Only 10% of the samples were analyzed by XRF, and a correlation curve was established between the XRF values and the laboratory values for manganese (Mn) for validation.

The samples were then sent to the laboratory for geochemical analysis, primarily focusing on the following elements: Mn, Fe, and P. All collected samples were prepared and analyzed using the Niton XRF handheld analyzer.

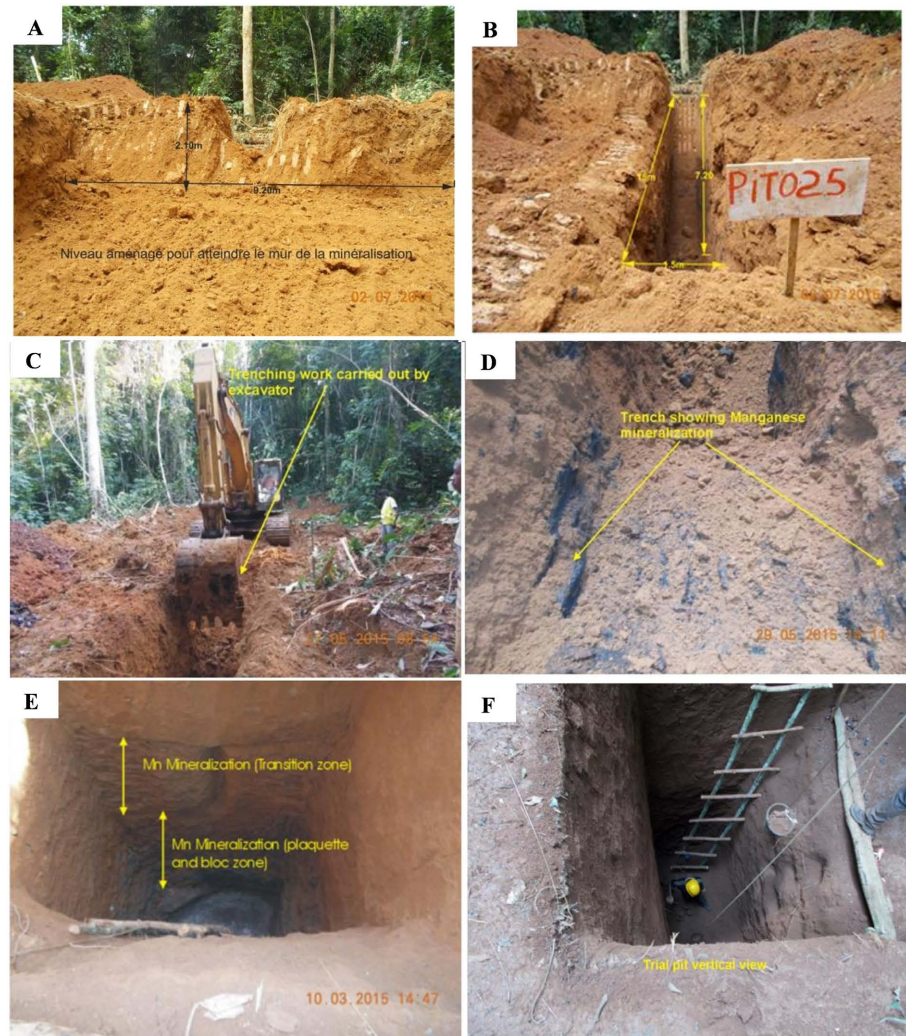


Figure 5. Photographs of manual work and mechanical trenches opened, A: A level designed to reach the mineralization wall, B: dug pit, C: Trenching work carried out by excavator, D: Trench showing manganese mineralization, E: Pit showing two manganese mineralization zones, F: Trial pit vertical view.

A total of 50 samples were analyzed in their raw form, and another 50 samples were washed and analyzed manually. The samples were analyzed according to different particle sizes (> 6.3 mm; 1 mm to 6.3 mm; < 1 mm). **Figure 6** shows the photographs of the packaged samples.



Figure 6. Photographs of the packaged samples (A), transferred (B), stored (C).

GMFA had drilled nearly 550 boreholes to a depth of 20 to 25 meters, resulting in 295 being classified as mineralized ($\text{Mn} > 15\%$) and 255 as waste ($\text{Mn} < 15\%$), using a grid spacing of $200 \text{ m} \times 200 \text{ m}$. The work undertaken by NGM resulted in nearly 600 boreholes to a depth of 25 to 30 meters, of which 348 were classified as mineralized ($\text{Mn} > 15\%$) and 252 as waste ($\text{Mn} < 15\%$), using a smaller grid spacing of $100 \text{ m} \times 100 \text{ m}$. More than 5,000 samples were collected from over 10,000 meters of boreholes drilled during this field campaign on the Lebaye plateau.

4. Results

Manganese mineralization on the Lebaye Plateau is difficult to observe at the surface due to the particularly thick vegetation cover and overburden. The main ore occurs as thin layers of platelets. It is confined to the summit of the plateau, primarily in its eastern half, defined by the Lebaye River, which crosses it perpendicularly and divides it into two almost equal parts.

The manganese mineralization profile comprises several ore facies types occurring in stratiform layers ranging in thickness from 0.2 m to 6.4 m. The mineralized horizon exhibits significant lateral variability, and continuity between excavations is inferred from shallow trench data. Indeed, in the field, it was observed that the ore-bearing layer varies from one location to another. Consequently, small trenches were dug at the surface to verify the continuity of the layers.

The column in **Figure 7** and all its images illustrate the local stratigraphic sequence, from top to bottom, of the manganese deposit as observed in the shafts and exploratory trenches at the Lebaye site:

1) The upper level, constituting the overburden (COV), shows a highly variable thickness from 1.70 m to 6.20 m; it is composed of topsoil ($< 0.50 \text{ m}$) and rests on a considerable layer of waste rock made up of brownish clays.

2) The manganese-bearing Pisolite Zone (PIS) exhibits a variable thickness with frequent gaps from one shaft to another. This layer is composed of manganese pisolites or nodules ranging in size from 0.5 to 1.5 cm in diameter within a clayey and ferruginous matrix. This layer is generally about 0.5 m thick. The COV and PIS levels are considered a barren horizon.

3) The transition zone (ZTR) lies between the overlying pisolitic layer and the underlying platy ore layer. It is composed of a mixture of pisolitic and platy material within a ferruginous clay matrix. Ferruginous concretions are also present. The upper part of the layer is marked by the first appearance of platy ores, and the lower part by the last pisolitic developments. The manganese content is estimated to be higher ($> 20\% \text{ Mn}$) than that of the PIS layer but lower ($< 30\% \text{ Mn}$) than that of the PLA layer. This layer is approximately 1 m thick. This transition zone marks the top of the FB1 formation.

4) The Platy Ore Zone (PLA), or platy ore layer, constitutes the main exploitable lithological layer. The platy ore is hard, coarse, and composed of thin (millimeter-thick) layers of manganese ore. A platy is approximately 3 cm thick. The platys are composed of manganese ores (cryptomelane, pyrolusite, and nsutite)

and clay-iron materials. They typically occur in the coarse fractions (over 19 mm) and represent the main source of block ore. The grades are generally >30% manganese. The thickness of this layer most often varies from 0.5 m to 4 m. More than 70% of the ore is thought to originate from this layer.

5) The Block Ore Zone (BLO) is a block ore layer composed of thicker platys. It develops only sporadically. It is composed of manganese blocks and associated with a brownish/ferruginous clay matrix. Sometimes the manganese blocks are soft and friable. The manganese blocks are most often associated with whitish sericity and concretions of ferruginous minerals. The massive zone (MAS), as its name suggests, comprises massive manganese mineralization. The massive ore consists of tabular blocks or large platelets or placoids of manganese ore with relict layers that are parallel to the parent rock structures. The grades of this type of ore are generally > 35% manganese. This ore is recovered as block material (>19 mm). Less than 10% of the ore originates from this layer, which develops sporadically on the wall of the mineralized body.

6) The clay zone has heterogeneous minor manganese mineralization composed of hard, soft, and friable Mn platelets. The clay zone is composed of clays of various colors. The underlying black schist formations and variegated clays correspond to the saprolite of the manganese horizon.

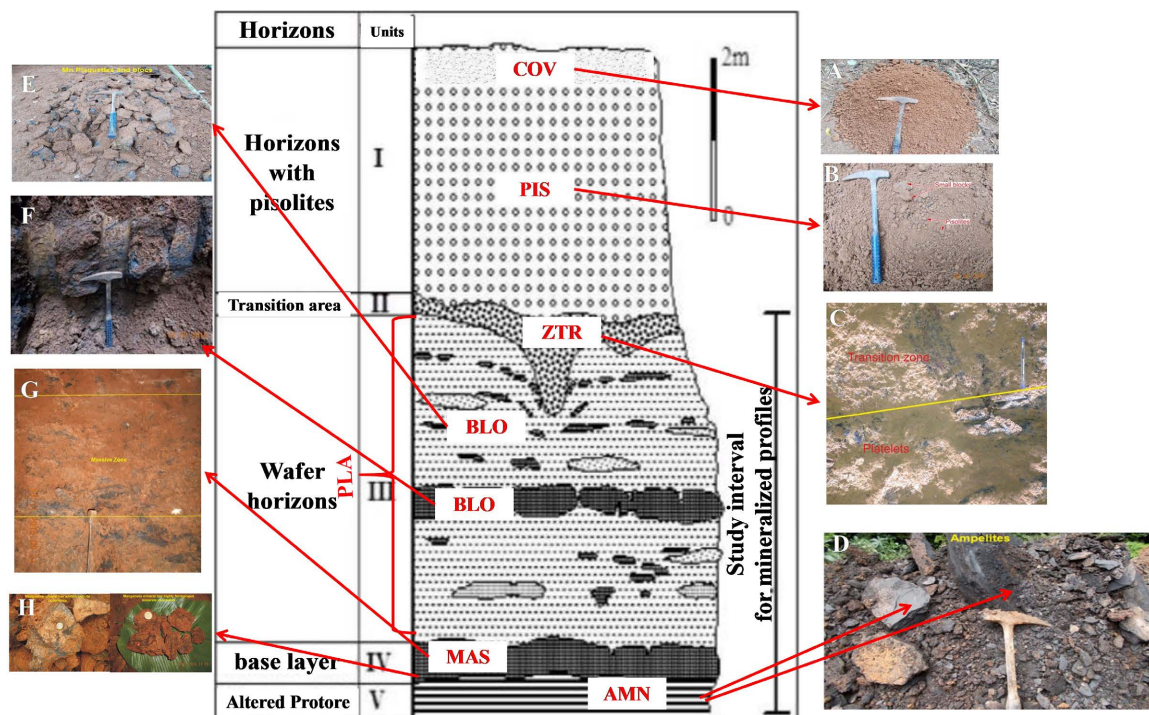


Figure 7. Photograph of the stratigraphic column of the Mn deposits and the different mineralization facies; A: Mixture of pisolites and brownish clays; B: Mixture of pisolites and small blocks; C: Transition zone and plate-like Mn; D: Ampelites; E: Plates and blocks of Mn; F: Massive black blocks rich in Mn; G: Massive reddish blocks rich in Mn; H: Mn with ferruginous and sericitous facies.

Furthermore, examination of the pit and trench profiles revealed that the thick-

ness and lithology (strata) of the Mn-mineralized formations vary from one location to another and frequently exhibit lateral facies variations. In some pits, the Mn mineralization begins directly with a transition zone, followed by a platelet zone, thus explaining the absence of a pisolite zone.

5. Discussion

5.1. Typology of the Lebaye Ore

Observation of the profiles at the Lebaye site, from top to bottom, revealed that: (1) the manganese-bearing pisolite horizon (PIS), covered by altered clay formations (argillites) and vegetation (COV), with a thickness varying between 1 and 7 m, is considered barren; (2) the transition horizon (ZTR), corresponding to a mixture of pisolitic and platy materials with a ferruginous clay matrix, constitutes the top of the FB1 formation; (3) the platy ore (PLA), including the BLO, MAS, and ZTR types, is composed of black pelites, intercalated sandstones, banded pelites, or bedded dolomites, with alternating black shales and black sandstones, and characterized by massive sandstones or Poubara sandstones. All these elements constitute the main phase of the run-of-mine materials of the exploitable mineral resource. (4) The massive zone (MAS) and the clayey zone (AMN), or Mn protore, will constitute the base of the FB1 formation.

These observations suggest marine sedimentation subjected to the action of storm waves typical of the upper offshore [7].

According to [1] and [5], all these facies mentioned above were emplaced as debris flows that passed through canyons feeding submarine fans during the dismantling of the basin margin after periods of base level collapse. After the deposition of these breccias, an alternation appears between light-colored layers corresponding to dolomitic sandstones and dark layers, which are black dolomitic claystones rich in organic matter. This facies is named “banded pelites” in the works of [6] and [8] [9].

On the other hand, and despite the observation of numerous similarities with other deposits of the same Francevillian Supergroup, particularly from a geological point of view (lithology, metallogeny, mineralization typology, etc.), the Lebaye deposit appears as a distinct, complex, and specific deposit in many respects:

- the heterogeneous nature and discontinuity of its Mn mineralization.
- the extreme variability in the quality and thickness of the mineralized horizons.
- to the west of the plateau, on the right bank of the Lebaye River, the Mn mineralization is ferruginous; this is not the case in the eastern half of the plateau.
- the deposit exhibits a very thick overburden layer at its summit, exceeding 6 meters in some places, while this layer is less thick on the slopes.
- The mineralization there is of a soft, friable and relatively hardened nature in the platelet zone and much less consistent in the transition zone.

5.2. The Formation of Manganese Deposits

A distinctive feature of the FB Formation is the sudden appearance of carbonates. These occur primarily as dolomite ($\text{CaMg} [\text{CO}_3]_2$), but are also visible as ankerite ($\text{Ca} [\text{Fe}^{2+}, \text{Mn}^{2+}, \text{Mg}] [\text{CO}_3]_2$), siderite (FeCO_3), and later as the manganese species rhodochrosite (MnCO_3). Volcanic and hydrothermal activity in the Okondja Basin likely contributed to and supplied manganese and iron in the seawater [3].

The manganese content of the seawater was probably very high, which also resulted in a high manganese/iron ratio. Indeed, at the end of the Archean and the beginning of the Proterozoic, numerous iron deposits occurred, but the conditions for manganese precipitation were not met. A model has been proposed by [6] that suggests the precipitation of manganese and iron as oxides on a platform where the dissolved oxygen concentration was high at the surface due to intense biological activity and the rapid burial of organic matter [10].

Periods of transgression favored the transport of Fe^{2+} and Mn^{2+} to the surface via upwelling currents. During regressive periods, these elements precipitated as oxides. Since Mn^{2+} precipitation is inhibited by the presence of Fe^{2+} in the environment [7] [11], the $\text{Fe}^{2+}/\text{Fe}^{3+}$ chemocline was reached before that of $\text{Mn}^{2+}/\text{Mn}^{4+}$, thus favoring the formation of iron-bearing deposits below the manganese layer.

During diagenesis, these elements were incorporated into carbonates, sulfides, and silicates. Mn^{2+} is thought to have reacted with CO_2 or HCO_3^- resulting from the degradation of organic matter below the reducing seawater/sediment interface to form Mn carbonates [6] [10].

5.3. Metallogeny of Okondja Manganese

Observation of samples obtained in the field shows a predominance of brownish clay facies, pisolites, and massive blocks of Mn-rich sandstone, sometimes altered by the presence of iron and ferruginous clay, Mn-rich clay platelets, and variegated ampelites ranging in color from reddish to brown and black, with intercalated Mn layers. All these facies originate primarily from detrital sedimentary rocks, thus suggesting supergene alteration of the FB1 horizon.

The Lebaye deposit was therefore formed by supergene alteration of the black and/or variegated ampelites, initially rich in manganese carbonate (max 13%), to produce ores rich in manganese oxide [2] [4] [5]. The supergene profile of the mineralized bodies is almost identical from one plateau to another. These ores are confined to the upper parts of the plateaus. Lateral continuity and the total extent of the ores are linked to the size and morphology of the plateaus.

The average manganese content in the platelet-bearing manganese lithofacies, which is the main ore, is 35%. The average manganese content in the clayey-sandy horizon with pisolites is 15.5%.

5.4. Manganese Mineralogy of Okondja

From a mineralogical perspective, manganese is found primarily in the form of:

- manganese oxides, with or without silica;

- pyrolusite (MnO_2);
- psilomelane ($\text{mMnO} \cdot \text{MnO}_2 \cdot \text{nH}_2\text{O}$);
- manganese silicates such as braunite ($\text{MnII (MnIII)}_6\text{SiO}_{12}$);
- iron oxides and hydroxides: magnetite-hematite and goethite;
- manganese carbonate: rhodochrosite (MnCO_3) to a lesser extent;
- silica, for its part, is found largely in the form of quartz.

NGM, taking into account the specific geological and geochemical characteristics of its ore, decided to adopt dense medium separation (DMS) technology to improve the efficiency of the recovery process and ensure better control over the final product.

The different types of materials identified as feeds to the dense medium separation circuit exhibit chemical similarities and several types of minerals in common [9]. Particle densities range from 2.43 for pisolites to 3.36 for block goethite.

The ore in flakes has a density of 3.29; the densities of the laterites vary according to their iron and manganese content. Pyrolusite, cryptomelane, and todorokite or lithiophorite (these two phases are indistinguishable by XRD) are identified manganese minerals. kaolinite is the major clay minerals. Iron is found in hematite and goethite. Silica and quartz are also associated with clay minerals. The run-of-mine (ROM) feed to the DMS unit would a priori consist of ores predominantly of pisolite type, secondarily, and especially platelets, blocks, massive ore and mixed transition facies [9].

These materials can be easily separated based on their density to obtain ore concentrates with few or no associated pisolites. Blocky goethite, which is iron-rich and denser than the flake ores, could be found among the concentrates. The implication of the results showing flake ore as the main phase of the run-of-mine materials is that, during ore processing, pisolites could be considered gangue when determining resources and reserves. Consequently, it can be concluded that PLA-type ores, including BLO, MAS, and ZTR types, would constitute the phases forming the exploitable mineral resources.

5.5. Manganese Quality and Detrimental Elements

According to international geological prospecting standards for the elements Fe, Mn, and P, some elements are considered valuable because they can be recovered, even in small quantities, without additional costs during mining; others are considered detrimental when these elements negatively impact the quality of the ore. In the case of manganese, the substance of interest in this study, the potential detrimental element is phosphorus.

A practical classification of manganese and iron ores is established according to their Mn and/or Fe content, and their detrimental elements [9].

Based on their manganese (Mn) and iron (Fe) content, we distinguish:

- Rich ores: more than 50% Mn + Fe (Moanda, Bélinga);
- Medium ores: 30 to 50% Mn + Fe;
- Poor ores: less than 30% Mn + Fe.

Table 1 summarizes the average geochemical results for Mn%, P% and Fe% by zone.

Table 1. Average geochemical results for Mn, P and Fe by zone.

Facies	Mn%	P%	Fe%
Zone bloc	50.25	0.04	2.63
Zone plate	42.28	0.01	3.01
Transition zone	26.29	0.03	8.44
Zone transition/Zone plate	46.54	0.06	5.03
Zone transition/Zone plate/Zone bloc	31.58	0.07	13.69
Zone pisolite/Zone plate	34.99	0.12	11.02
Zone pisolite/Zone transition/Zone bloc	41.08	0.06	5.93

In relation to this classification and based on the analytical data from NGM, the Lebaye manganese ore, with an average content of 47% manganese and iron, undoubtedly falls into the category of medium-grade ores.

Regarding the presence of phosphorus, the analytical data from NGM and its predecessors show that phosphorus levels are relatively low, with an average of 0.071% P with a P/ore ratio of 0.0018 (for an average deposit content of 37% manganese). Large mineralized zones exist where phosphorus is present in almost trace amounts.

From a hydrogeological point of view, it would be wise to carry out an in-depth hydrogeological study in this area of the future quarry in order to estimate the potential interactions between infiltration waters and the hydrogeological environment and to better understand their impact [9].

6. Conclusions

This study, based on data from a major geological and mining exploration campaign conducted by Nouvelle Gabon Mining (NGM) on its G2-569 permit in Okondja, revealed the existence of a significant manganese deposit on the Lebaye Plateau, one of the five manganese-bearing prospects in Okondja.

Manganese mineralization occurs on several plateaus, and the essentially geological profile is consistent from one plateau to the next. The Okondja manganese plateau mineralization occurs in thin layers ranging in thickness from 0.2 m to 6.4 m. The essential ore exhibits a platelet typology.

The manganese deposits are formed by the weathering of the FB1 horizon, composed of black shales, *i.e.*, manganese-bearing calcareous ampelites. The Okondja manganese deposits are therefore shallow or non-outcropping deposits that formed under meteoritic weathering conditions on a source rock pre-enriched in manganese. These are thus supergene deposits. Supergene processes enrich the manganese content from 15% in the black clays to approximately 45% in the ores.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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