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Petrographic and Geochemical Characterization of Mayedo and Kinzoki Ranges (Sumbi Bauxite Region, Kongo Central/DR Congo)

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Abstract

The bauxitic region of Sumbi and its surroundings in Central Kongo (DR Congo) is located in an area corresponding to "bands" of basic rocks made up of microdolerites, basalts and andesites. The problem of this study is linked to the similarity of the phenomena that generated the depositional process of these ferruginous and aluminous formations. The aim of this article is to carry out a chemical and petrographic study of samples of bauxitic materials from the Mayedo and Kinzoki regions, with a view to their possible recovery. To this end, the chemical and petrographic analysis of the weathering formations outcropping in the study area was carried out using X-ray fluorescence and thin section methods. The latter revealed that two lithologies were detected in the healthy rocks: basalts with a mineralogical assemblage of plagioclase crystals, pyroxene microcrystals and oxide opaques; and dolerites represented by plagioclase crystals, pyroxenes and a few quartz crystals. X-ray fluorescence revealed high levels of Al_2O_3 (32.69%) in the Mayedo zone (MHb1). This visibly gibbsite-rich level corresponds to the zone of friable, homogeneous bauxite with a massive, blood-red texture, with an estimated gibbsite percentage of 55.50. The percentage of Fe_2O_3 is high in these zones at 42.77%, hence the dark red colour, reflecting a strong zone of ferruginasation. This horizon contains a high concentration of hematite and goethite minerals. Highly variable SiO_2 contents ranging from 13.48% to 40.82%. These variations are essentially due to the dissolution of silica by leaching and resilification.

Keywords

Bauxite, Ferruginasation, X-Ray Fluorescence, Thin Film, Mayedo, Kinzoki Valorisation

1. Introduction

Any country that wants to base its economic development at least in part on its mineral resource potential must study the geological history of the national territory, inventory its resources and understand them. Mastery of the knowledge of the "geological objects" that make up the soil and subsoil of a country is a necessity for any activity based on sustainable and integrated development affecting various aspects of society (Nehlig, 2019).

The DRC has significant mineral resource potential, including several of its world-class metallogenic provinces and deposits (Putter et al., 2012).

In this DRC's panoply of riches also includes bauxite deposits located mainly in the western part of our country, in the Sumbi bauxite zone in Central Kongo (Monti, 2012). Numerous studies in this humid tropical zone show that the formations are characterized by extensive hydrolysis of primary minerals, with a relatively simple mineralogy dominated mainly by quartz, kaolinite, gibbsite, goethite and hematite (Grosemans, 1959; Keyser, 1959; De Kun, 1965 cited by United States Geological Survey, by Patterson, 1967).

This situation is all the more apparent in the region as other studies undertaken in the region have shown that there is a genetic link from the parent rock horizon (dolerite or basalt) to the ferralite horizon. This study proves that the lateritic bauxite horizons of Central Kongo are original and autochthonous (*in situ*) bauxites formed from geochemical and mineralogical degradation phenomena of the parent rock up to the level of the clay-ferruginous armouries marked by structural changes during ferrallitization. The mineral paragenesis detected is characterised by gibbsite and goethite in significant proportions (Kaseba et al., 1997 cited by Nicolaï, 2009).

These scientific assertions documented in the Sumbi deposit have been attested in a few beaches, four in all at Sumbi, Tsala, Kitsaku and Zimba, but the extrapolation of their conclusions is open to debate, especially as data from the surrounding areas is unavailable. It is therefore necessary to extend the study to these uncovered areas in order to better characterise this deposit and address the issue of the similarity of the phenomena that gave rise to the depositional process of these ferruginous and aluminous formations.

It is against this backdrop that this study was initiated, focusing on the beaches that are most representative of this deposit, in the localities of Mayedo and Kinzoki, for which little data is available.

The main aim of this work is to characterize the petrography and geochemistry of rocks collected from the Mayedo and Kinzoki beaches, with a view to upgrading them and establishing a depositional reconstruction based on the chronology of elemental mobilities in the various profiles drawn up for this purpose.

2. Study Area

2.1. Geographical Context

Our study area is located in the Sumbi sector, in the Seke-Banza territory, Bas-Fleuve district, Kongo-Central province.

Samples were collected from three weathering profiles set up for this purpose. Geographically, the MHa profile near the village of Kinzoki is located at latitude S 5˚2'24", longitude E 13˚22'20" and between altitudes 466 m and 506 m, while the MHb and MHba profiles on the banks of the river Mayedo at Kinzoki, are located respectively at latitudes S 5˚03'09" and S 5˚03'32", longitudes E13˚22'36" and E 13˚23'56" and between altitudes 491 m and 509 m and 510 m and 517 m (**Figure 1**).

2.2. Geological Setting

The bauxitic region of the Central Kongo is located in an area corresponding to "bands" of basic rocks consisting of microdolerites, basalts and andesites (Cahen, 1978). These basic eruptive rocks are interbedded in the lower diamictite of the Kongo Central (Lepersonne, 1950) where the andesites overlying this diamictite form the core of a north-facing anticline, while the basalts outcrop mainly along the anticlinal axis. These rocks are divided into 4 NNW-SSE bands, consistent with the structural direction of the West Congolian chain, and interbedded in the Lower Diamictite Formation and the Sansikwa Subgroup (Lepersonne, 1974 cited by Kaseba et al., 1997).

Surmounted by the Haut-Shiloango group, the lower diamictite and these two groups, together with the Sansikwa, constitute the lower lithostratigraphic terms of the West-Congolian (Tack et al., 2001).

In this region, the lower diamictite is unconformably underlain by the Sansikwa syenites, whose upper bed lithologies consist of more or less coarse quartzites, with phylladic and even schistose layers. On the same lower diamictite formation lies, also by unconformity, the Haut-Shiloango sub-group, also made up of quartzites, phyllades and schists, all resting on a basic conglomerate. The Sansikwa sub-group, for its part, is represented by quartzites and psammites outcropping on the ridge bordering the basic rocks below (Kaseba et al., 1997). Structural measurements of the dips measured in the quartzites of this subgroup show that the basic band forms the core of an anticline with a SSE-NNW axis and little northern flooding.

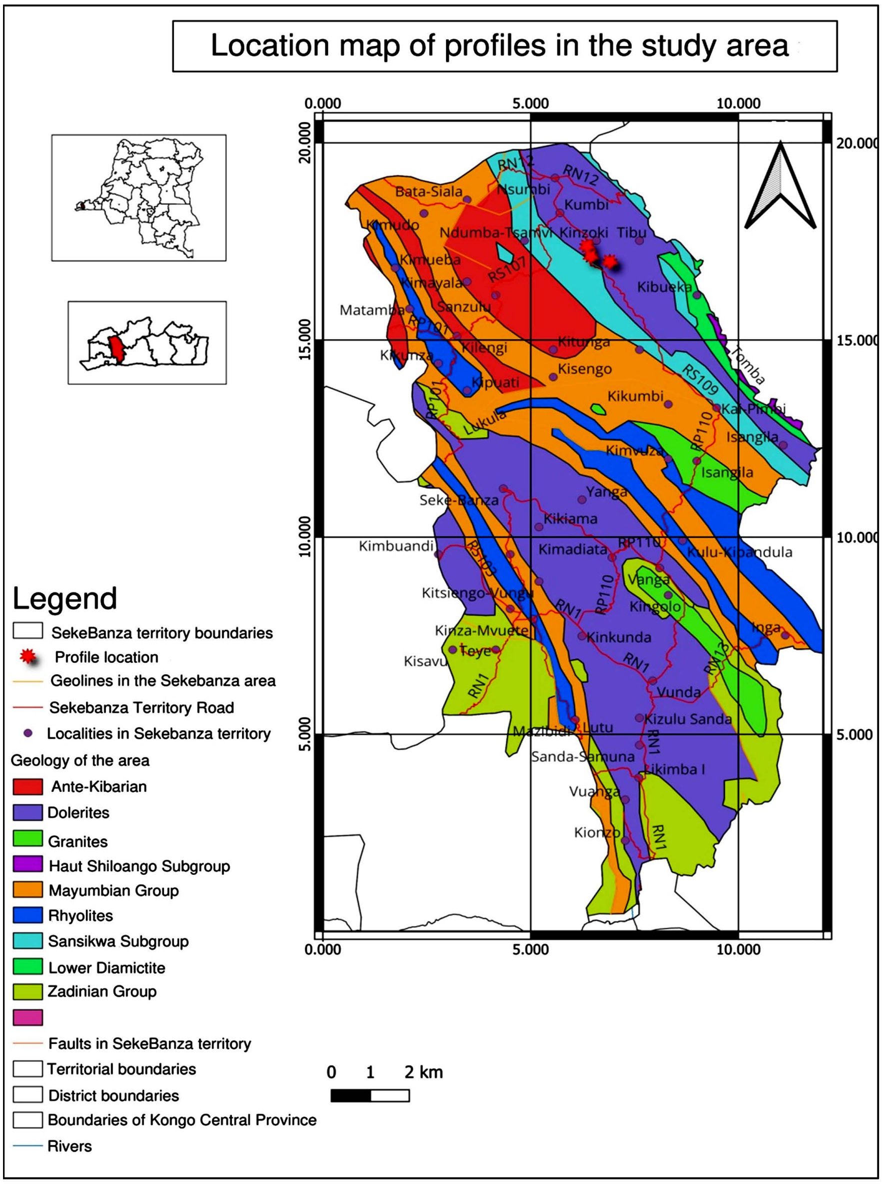


Figure 1. Location of sample points across the three profiles on my geological map of the Seke Banza area.

The 3 to 5 km wide band of basic lava (Figure 2) is symmetrically encased between the two Precambrian sedimentary formations. These layers are upright and include a quartzite layer; these quartzites are erosion-resistant rocks that slow down the erosion of the basic rocks in the Sumbi region. This situation has favoured the preservation of a mid-Tertiary peneplain stretching between 650 and 700 m above sea level. At the end of the Tertiary, the Sumbi plateau was lateralised under a favourable climate, with the formation of a fairly widespread armourstone. In the Pleistocene, the region was covered by 3 to 5 m of clayey silt, before being eroded by the rivers of today, an erosion slowed by the resistant thresholds they have to cross to leave it. These Pleistocene silts consist mainly of kaolin clay and iron hydroxides or oxides, with little or no free quartz.

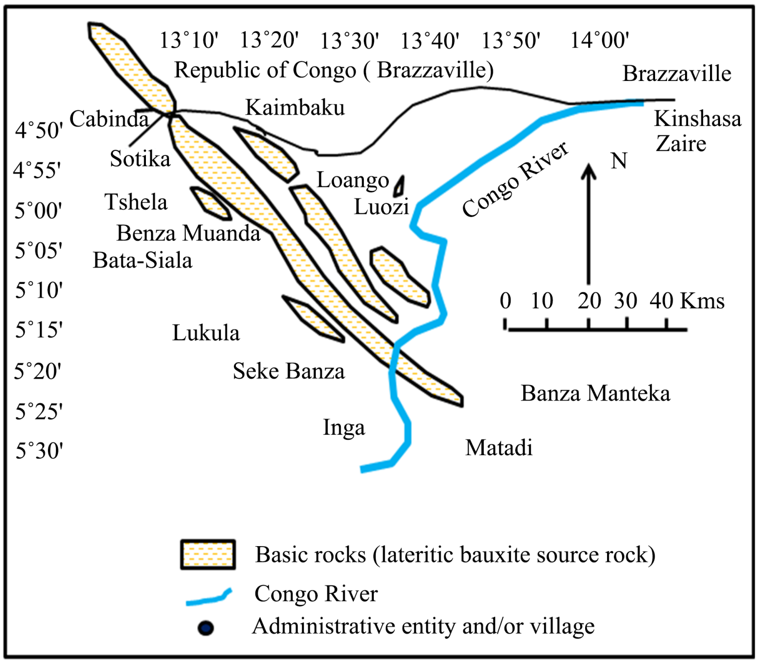


Figure 2. Layout of bands of basic rocks in the bauxite region of Central Kongo (Kaseba et al., 1997).

In the Sumbi region, the lateritic alteration of doleritic and basaltic lavas inter-stratified in the lower diamictite formation and the Sansikwa sub-group is at the origin of the bauxite deposit and this differentiation results from chemical and mineralogical modifications, concomitant with the textural and structural modifications that affected the bedrock (Ongendangenda et al., 1986). The concentrations of major oxides analysed give an average of 42.6% Al_2O_3, 36.9% Fe_2O_3 and 0.5% SiO_2. These laterites consist of gibbsite, kaolinite and goethite. Gibbsite values appear to be highest at depths of between 15 and 30 metres (De Kun, 1965).

3. Methodology

1) Equipment

The rock formations sampled in this study, known as MHa, MHb and MHba, are located near the village of Kinzoki and on the banks of the Mayedo River at Kinzoki, 12 km from the Sumbi sector, in the province of Kongo Central in the west of the Democratic Republic of Congo.

These formations were sampled along profiles drawn up for this purpose. The samples consisted of bedrock and overlying weathering horizons. Chemical parameters were analyzed using a computer-assisted ED-XRF Xepos III spectrometer to determine oxides.

2) Experimental methods

- **Petrography**

Petrographic analysis of thin sections of the source rock assemblages was carried out using a polarising optical microscope in the thin section laboratory of the Geosciences Department of the University of Kinshasa, in order to determine the minerals present, microstructures, hydrothermal alteration minerals, metallic phases and the links or associations between certain minerals. This also enabled the chronology of the system to be determined. First of all, we observed the minerals present on the thin sections, and then defined the alteration minerals such as chlorite and phyllosilicates. Subsequently, the shape, size and relationships between the minerals, such as crystallisation order, texture and remobilisation patterns, were observed.

Also during the observation sessions, photos of thin sections were taken at different magnifications (×5; ×10, ×20). The descriptions of these thin sections enabled us to unravel the mineralogical make-up of the source rock assemblages, their origin or the way they were formed, with a view to considering the mechanisms leading to their evolution in the superficial alteration assemblages.

The petrographic descriptions of the surface alteration assemblages were carried out macroscopically in the field. They consisted of observing the morphological characteristics of the formations contained in each horizon of the profiles studied. The following main features were identified:

- Induration;
- Structure: Typical shapes of large pisolites (after De Graft-Johnson);
- The colour of rocks: colouration and hydration index, assessment of the degree of evolution and the formation environment
- The position of the horizons in relation to the surface (location in the shape);
- Textural changes: assessment and evolution from sound rock to weathering (relationship with parent rock);
- Possibly density.

➢ **Geochemistry**

The chemical parameters of the samples collected were analysed for oxides using a computer-assisted ED-XRF Xepos III spectrometer at the CREN-K geochemical analysis laboratory. Our particular focus is on the concentrations of the major oxides SiO_2, Al_2O_3, Fe_2O_3 + FeO and TiO_2.

To this end, the elements (oxides) were measured with the XEPOS III energy dispersive X-ray fluorescence spectrometer (ED-XRF), using the "FP-Powder" and "TQ-Pellets Fast" methods of the XEPOS III spectrometer. Standards ISE870, ISE 890, ISE919, ISE961 and SOIL-7 containing certain elements of interest were used.

The X-ray fluorescence spectrometer is a multi-element method, using four secondary targets, namely Molybdenum (39.76 KV voltage and 0.88 mA current), Aluminium Oxide (49.15 KV voltage and 0.7 mA current), Cobalt (35.79 KV current and 1 mA current) and finally HOPG Bragg Crystal (17.4 KV voltage and 1.99 mA current) from the palladium anode.

Generally speaking, the samples (3 g of soil in a cuvette/pastille) to be analysed are placed under a beam of X-rays. Under the effect of the X-rays, the samples "resonate" and re-emit their own X-rays—this is fluorescence. By looking at the energy spectrum of the fluorescent X-rays, we see peaks that are characteristic of the elements present, so we know which elements we have, and the height of the peaks can be used to determine the quantity.

The normalized intensities of the spectrometer are proportional to the concentrations, were used to calculate the concentrations of our samples by external calibration, the Peak Kα1 (3.313 KeV) of the K was used for the calculation, the HOPG Bragg Crystal target (17.4 KV voltage and 1.99 mA current) gave the areas that were normalized to the peak coherent and incoherent scattering.

The normalized intensities of the machine are proportional to the concentrations, and were used to calculate the concentrations of our samples by external calibration. The results obtained are shown in the table with the confidence interval according to t-Student at $\alpha = 0.95$.

This analysis made it possible, firstly, to determine the geochemical changes in the different horizons of the profiles in order to define the horizons of aluminous and ferruginous concentrations and their impact on the mineralogical distribution and, secondly, to define the main geochemical transformations occurring in these formations based on the overall chemical analysis of the major elements and some trace elements.

4. Results and Interpretation

4.1. Lithofacies and Correlation of Weathering Profiles

After macroscopic and microscopic analysis of the source rocks (Figure 3) and the overlying superficial weathering formations (Table 1), the rocks in our study area are petrographically characterised by:

4.1.1. For All Source Rocks

Petrographic characteristics show that the rocks studied include dolerites and basalts.

1) Basalts

Macroscopically, the MHa0 sample collected in the field shows a greenish to greyish rock encrusted with millimetre-sized microcrystals of quartz, colourless and with a vitreous lustre visible through their characteristic brilliance. Massive, compact and dense, the rock contains a good proportion of dark minerals that

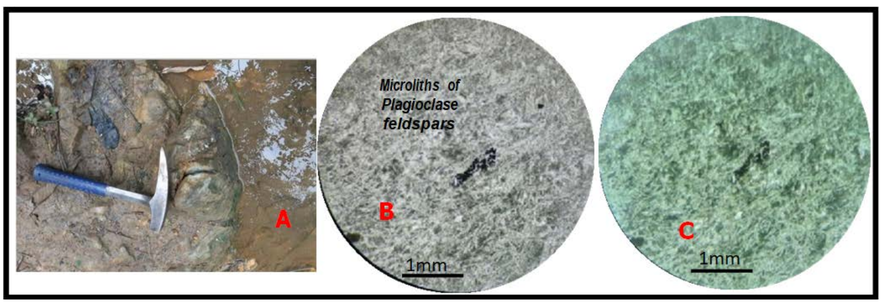


Figure 3. (A) Basalt outcrop; (B) and (C) Thin section microscopic view (LN and LP) of Basalt from the Kinzoki region.

are practically invisible on a mesoscopic scale and are visibly responsible for a large part of the rock's colouring. A few whitish minerals, millimetre to centimetre in size, mostly elongated and dull, are visible and scattered throughout the rock.

On the surface of the rock, the beginnings of weathering can be seen in the presence of a yellowish to reddish indurated clay layer.

Microscopic analysis of this sample shows a mineral assemblage consisting of plagioclases, fine pyroxene crystals and a fairly small proportion of opaque; all in a mesostasis with a microlitic subophitic texture.

In natural light, the crystals (mainly microliths) of plagioclase can be recognised by their colourless nature with appreciable relief and an elongated prismatic shape (laths or rods). Pyroxene microcrystals have a neutral absorption colour, a fairly strong relief and sometimes square cleavages at 87˚ (complementary 93˚).

In polarised light, plagioclases are visible as polysynthetic macles with alternating extinction and low birefringence colour (1st order grey). As for pyroxene crystals, they can be observed by medium birefringence colours (end of 1st to beginning of 2nd order) and oblique extinction.

The opaques visible in the thin layer indicate the presence of iron oxides (magnetite?).

The weight distribution is 80% mesostasis, essentially microlitic, and 20% phenocrysts (pyroxene and plagioclase). The rock is basalt (**Figure 3**).

2) Dolerite

Sampled in MHb0, it generally appears in the field as a greyish to blackish facies. It is massive, compact and dense. There is a high proportion of quartz phenocrysts, some of which are elongated, with a vitreous lustre and characteristic brilliance. The rock also contains a fairly average proportion of whitish, dull minerals of variable shape and millimetre to centimetre size, as well as a large proportion of dark minerals that are not visible to the naked eye and are responsible for the colouring of the rock.

Visibly healthy, a fairly fine contour of alteration can be seen, however, on the shoulders and is very well marked. It consists of a level of indurated yellowish clays.

The microscopic description of this slide shows a typical ophitic or doleritic structure with plagioclase laths larded with ferromagnesian minerals represented by pyroxenes in large sections. The crystalline orientation of the pyroxenes sometimes follows that of the plagioclases.

In LN, plagioclase crystals appear as colourless elongated laths with strong relief; pyroxene has a neutral absorption colour and strong relief.

In LP, plagioclases are visible as polysynthetic macles with alternating extinction and low birefringence colour (1st order grey). Pyroxene crystals can be seen with medium birefringence colours (end of 1st to beginning of 2nd order) and oblique extinction (**Figure 4**).

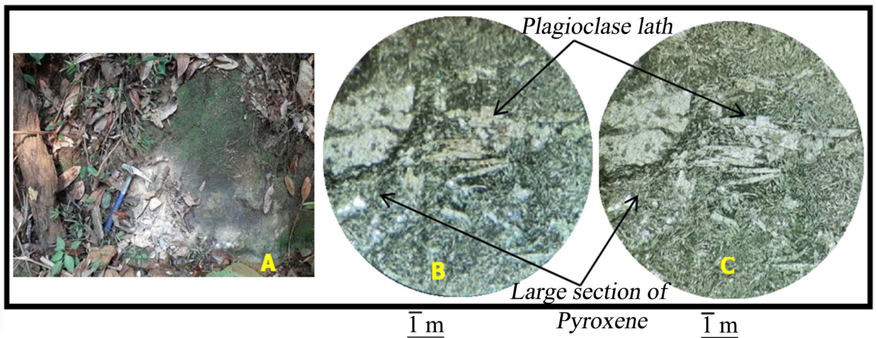


Figure 4. (A) Dolerite sample (Kinzoki regiomn). (B) and (C) Thin section micromscopic view (LN and LP) of dolerites showing plagioclase laths.

4.1.2. Sets of Alterations

The petrographic characteristics distinguish the following horizons from the bottom to the top of the profiles (**Figure 5**).

1) Indurated alterites or aluminous cuirasses with massive, pseudobrechic texture

Represented by samples MHa1 and MHba0, this more or less indurated horizon is made up of large, reddish, decimetric to centimetric-sized, increasingly rounded blocks of alterite, all bathed in a yellowish clay matrix.

After sawing a block (ball), we observe the following:

- A zonation expressed by a succession of alternating reddish bands and yellowish balls;
- The yellow bands are much more abundant than the red ones, which appear only as small lines;
- The cavities observed are occupied by yellowish soil.

2) Unconsolidated ferruginous pisolites in a nodular clay or clay-ferruginous matrix

The samples in the profiles for this horizon are MHa2 and MHb1. Nodular lateritic cuirass of decimetric to metric size, red-grey in the form of clusters, very hard and dense.

The cavities around the curasse are occupied by yellowish clays.

Stripping away the curasse reveals a reddish to dark greenish zone encrusted with fine millimetre-sized quartz crystals.

3) Solid-textured ferruginous and pisolitic bedrock

Sampled only in profile MHa (MHa3). This rock is yellowish in colour with very fine grains and has a smooth, soft and sticky feel. There are virtually no residual alterite inclusions in this rock.

4) Ferruginous stony weathering horizon (pisolitic)

MHa4, MHb2 and MHba2 have been sampled in this category. These are homogeneous clayey soils, more or less compact, with a yellowish to blackish colour due essentially to the influence of organic matter. They become increasingly soft or loose at depth.

5) Surface silty sand cover

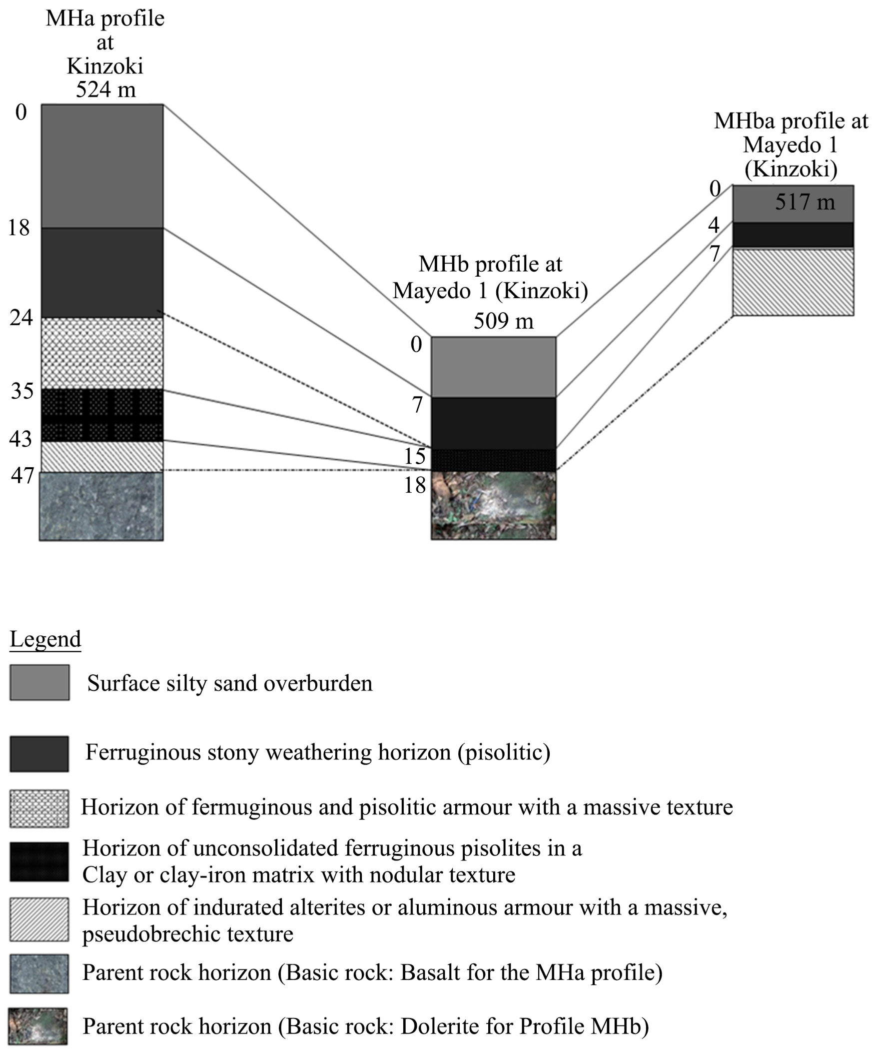


Figure 5. Presentation of the MHa, MHb and MHba weathering profiles and their schematic correlation *in situ* in the study area.

Sampled at MHa5 and MHb3, we observed a brown to yellowish and blackish heterogeneous friable clay soil containing a very small proportion of small balls and/or gravel.

Detailed descriptions of each sample are given in Table 1.

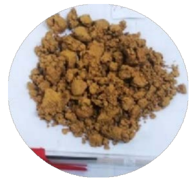
Table 1. Macroscopic description of the weathering assemblages in the various profiles.

Profile	Sample	Description	Photos
MHa	MHa1	The rock is loose, friable and soft, with a yellowish clay-like colour. In this horizon, granules of various shapes (rounded or elongated) of decimetric to centimetric size can be observed, all mixed in a smooth, very fine clay matrix that is a little sticky to the touch. When the granule is broken with a hammer, a red kaolin coloration can be seen inside the granule, which contains fine quartz crystals that can be seen by their characteristic brilliance, and a diffuse stratification in the form of a bank stakes out the interior of the granule.	

Continued

	MHa2	This horizon has a similar facies to the MHa1 horizon, mainly in terms of the clay matrix, which is smooth, very fine and sticky to the touch. However, this level contains fewer granular inclusions. The granules (alterites) observed are centimetric to millimetric in size. Broken up with a hammer, the inside of the granules is greenish in colour, illustrating the degree of weathering of the parent rock. Fine quartz crystals can also be seen inside the granules, with their characteristic brilliance and whitish minerals staining the entire interior of the granule.	
	MHa3	A loose, very fine-grained, yellowish rock with a smooth, soft, sticky feel. There are virtually no residual alterite inclusions in this rock. It may be related to a very fine argillite.	
	MHa4	The facies of this horizon is similar to that of the MHa3 horizon, where the similarities in the matrix are mainly related to the touch and the presence of granular alteritic inclusions. However, in terms of colour, this horizon is influenced by organic inputs from plants; these are reflected by the blackish tendency in this horizon.	
	MHa5	Loose surface rock sampled at the top of the profile, essentially clay, with a yellowish colour that darkens to black as a result of contact with organic matter. Very fine grained, this rock has almost no visible granular inclusions.	
MHb	MHb1	Loose rock with a yellowish clay matrix containing many grains of varying sizes and shapes. Very sticky to the touch, the clay making up the matrix is smooth and soft. The granules show virtually the same colouring inside their bodies.	
	MHb2	Essentially clayey loose rock containing almost no visible grains. The grain size is very fine and has a yellowish colour with a blackish tendency due mainly to the influence of organic matter.	
	MHb3	Rock with the same facies as the MHb2 horizon. However, the dark colouration is much more marked due to the increasing influence of organic matter.	
	MHba0	Horizon with large, decimetric blocks of weathering in a clay matrix. These blocks are heterogeneously coloured, giving a reddish kaolinic and yellowish to blackish colour in places. Hard, more or less compact and relatively less dense, these alterites are rough to the touch. They have many pores as a result of meteoric and organic activity. The alterites contain a number of well-individualised quartz crystals with a characteristic brilliance.	

Continued

MHba1	Loose rock composed of a yellowish to yellowish clay matrix. tends to be blackish, smooth and sticky to the touch. In the matrix, can be some inclusions some granules centimetre-sized alterites. Broken with a hammer, these granules show a reddish kaolin coloration similar to those observed in the MHc0 horizon. Covered and more or less healthy as you move towards the south. At the centre, these granules are easily crumbly.	
MHba2	Loose rock at the top of the essentially clayey profile which is yellowish in colour with a strong tendency black worms showing contact with organic matter. With a very fine grain size, this rock has virtually no structure. no visible granular inclusions.	

The petrographic data shows the following:

For the sound rocks (basic formations), two lithologies were detected: basalts and dolerites. These rocks are considered to be the source rocks that produced the weathering in this region (Abdourahamane et al., 2021).

The basaltic rock studied (MHa0) is formed from a mineralogical assemblage of crystals (mainly microliths) of plagioclases, pyroxene microcrystals and opaques made of oxides, the microscopic characteristics of which have been presented in the body of the work. The dolerite rock is represented by sample MHa0. The mineralogical compilation of this formation consists of plagioclase crystals, pyroxenes and a few quartz crystals.

For the loose rocks that make up the weathering formations, studies carried out by Nahon (1976) on the sequence of ferruginous armour on sandstone from the Cretaceous of N'Dias in Senegal, described the sequence of armour facies in the landscape.

The changes in petrographic facies encountered and described as standard models for the alteration and dismantling of bedrock formations are as follows:

- Bedrock (a);
- The mottled set (b);
- The nodular iron formation (c);
- Massive facies armour (d);
- Mixed facies armour (e);
- The pseudopisolitic armour (here called protopisolitic) (f);
- The ferruginous (pisolitic) pebbly assemblage (g); and
- Surface silty sand (h).

All these facies are found everywhere, with varying degrees of description. In our study area, all the formations described relate to some of the model horizons mentioned above, but other horizons were not sampled.

In the alteration stages encountered in our study area and described in profiles MHa, MHb and MHba, the facies of the mottled assemblages were not observed. However, in this sector the ferruginous assemblages are interpreted as a facies of degradation of the armour from the basaltic rock. In this case, facies (d) would be equivalent to a zone of indurated alterites or aluminous armour with a massive, pseudobrechic texture; armour facies (e), (f) and (g) are to be classified respectively in zones of unconsolidated ferruginous pisolites in a clayey or clay-ferruginous matrix with a nodular texture (e) and that of ferruginous and pisolitic armour with a massive texture (f) and (g); and facies (g) corresponds to the covering horizon of clayey silts.

4.2. Major Oxides

The results of the chemical analysis are shown for each profile in Tables 2-4. These tables show that the formations under study are chemically characterised by:

Table 2. Chemical composition of materials studied in the Kinzoki region.

Oxydes (%)	MHa1	MHa2	MHa3	MHa4	MHa5
SiO_2	23.16	31.26	27.37	27.37	25.64
Al_2O_3	22.69	23.53	22.98	22.98	23.16
KO_2	0.10	0.09	0.07	0.07	0.05
Fe_2O_3	42.77	34.35	38.32	38.32	39.38
NaO_2	0.31	0.26	0.27	0.27	0.25
MgO	0.25	0.46	0.14	0.14	0.13
TiO_2	9.69	9.00	10.06	10.06	10.54
CaO	0.07	0.24	0.03	0.03	0.03
P_2O_5	0.17	0.16	0.16	0.16	0.19
MnO	0.05	0.07	0.05	0.05	0.05
V_2O_5	0.16	0.11	0.11	0.11	0.15
Total	**99.42**	**99.53**	**99.56**	**99.56**	**99.57**

Table 3. Chemical composition of materials studied in the Mayedo region.

Oxides (%)	MHb1	MHb2	MHb3
SiO_2	13.48	27.24	25.13
Al_2O_3	32.69	24.72	23.40
Fe_2O_3	39.81	36.69	39.61
MgO	0.09	0.14	0.13
TiO_2	12.48	10.10	10.59
CaO	0.02	0.02	0.03
NaO_2	0.25	0.27	0.25
KO_2	0.03	0.07	0.08
MnO	0.03	0.05	0.05
P_2O_5	0.25	0.14	0.15

Continued

V_2O_5	0.16	0.11	0.12
Cr_2O_3	0.18	0.13	0.13
Total	**99.47**	**99.68**	**99.67**

Table 4. Chemical composition of materials studied in the Mayedo 2 region.

Oxides (%)	MHba1	MHba2	MHba0
SiO_2	38.69	40.82	22.48
Al_2O_3	25.53	26.15	16.58
Fe_2O_3	30.52	27.77	57.39
MgO	0.21	0.21	0.13
TiO_2	4.00	4.06	2.28
CaO	0.09	0.09	0.05
NaO_2	0.23	0.22	0.30
KO_2	0.09	0.09	0.06
MnO	0.08	0.10	0.09
P_2O_5	0.08	0.09	0.05
V_2O_5	0.12	0.08	0.24
Cr_2O_3	0.11	0.12	0.18
Total	**99.75**	**99.8**	**99.83**

1) For Kinzoki's MHa profile

The results of the chemical analysis are shown in Table 2. This table shows that the weathering materials in the Kinzoki area are chemically characterised by (Figure 6):

✓ Very high SiO_2 contents of the order of 26.96% on average (23.16% - 31.26%). Throughout its evolution in the different horizons of the profiles, the silica evolves in a sawtooth pattern, characterising an alternation of silicification and desilicification processes due essentially to the phenomenon of dissolution. The MHa1 horizon has a low silica content and a fairly high Fe_2O_3 content, indicating significant ferruginous activity to the detriment of silicification.

✓ A fairly high Al_2O_3 content of around 23.07% on average (22.69% - 23.53%); a high percentage of Fe_2O_3 of around 38.63% on average (34.35% - 34.35%). This shows that the horizons analysed are located in the ferruginous and bauxitic zone, indicating high proportions of gibbsite, kaolinite, goethite and haematite;

✓ A TiO_2 content ranging from 9.00% to 10.54%, indicating a very high proportion of anatase or rutile. The alumina content in the alterites studied i s around 23.07% and the Al_2O_3/Fe_2O_3 ratio is in the range 0.53 - 0.69. The rocks in the region are rich in bauxite.

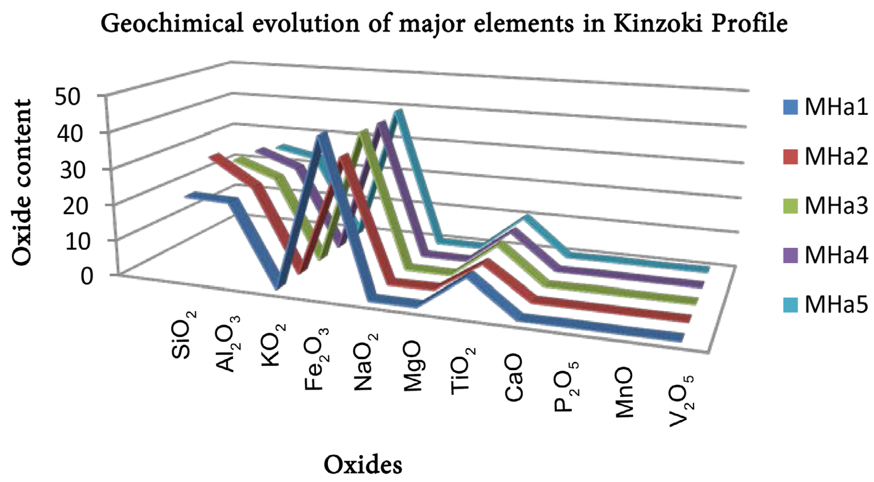


Figure 6. Diagram showing the evolution of the composition of oxides in samples from the MHa Profile at Kinzoki.

2) For the MHb profile in Mayedo 1

The results of the chemical analysis are shown in **Table 3**. This table shows that the materials in the Mayedo zone are chemically characterised by (**Figure 7**):

- ✓ High levels of Al_2O_3 26.94% on average (23.40% - 32.69%). Sample MHb1 has a higher Al_2O_3 content (32.69%), which would indicate that the percentage of gibbsite is higher in this material;
- ✓ A higher percentage of Fe_2O_3 38.70% on average in the horizons analysed, hence the reddish to dark coloration observed (see figure for macroscopic analysis of the sample). These levels are similar in the weathering horizons.
- ✓ A highly variable and low SiO_2 content, averaging around 21.95%. A strong downward trend is observed in the MHb1 horizon, which is visibly rich in aluminous minerals (gibbsite, kaolinite), favourable for the formation of bauxite or bauxitic armour. For the MHb1 and MHb2 horizons, there was a rebound in silica content, followed by a slight drop, essentially due to resilification. This drastic decrease in silica content observed in MHb1 follows the silicic dissolution process. However, in the upper horizons, resilification occurs, causing silica levels to fluctuate around 26%;
- ✓ A TiO_2 content ranging from 10.10% to 12.48%, which would indicate the presence of anatase or rutile. As the alumina content is around 32.69% in the MBh1 horizon of the alterites studied, the Al_2O_3/Fe_2O_3 ratio is less than 2.2. These materials are economically viable.

3) For the MHba Profile at Mayedo 2

The results of the chemical analysis are shown in **Table 4**. It can be seen from this table that the observations made in this profile give fairly high proportions of silica that are chemically similar to the concentrations in the parent rock. We can thus observe that the materials from Mayedo 2 are chemically characterised by (**Figure 8**):

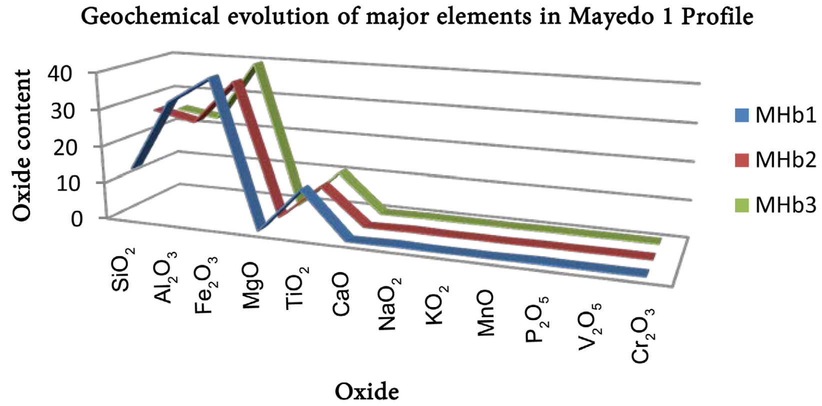


Figure 7. Diagram showing the evolution of the composition of the oxides in the MAYEDO 1 Profile samples.

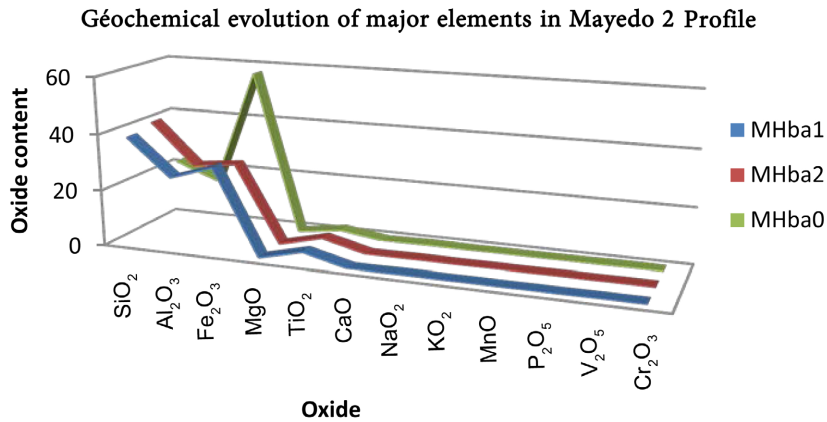


Figure 8. Diagram showing the evolution of the composition of the oxides in Mayedo 2 Profile samples.

- ✓ Relatively average levels of Al_2O_3 (16.58% - 26.15%). This variation in alumina content in the different horizons of the profile is essentially due to the phenomenon of alteration leading to the ferruginasation process and the dissolution of silica by leaching;
- ✓ A very high percentage of Fe_2O_3 for MHc0 (57.39%), hence the dark red colour observed (Figure). This upward trend in Fe_2O_3 content, which decreases from the MHba0 horizon to the superficial horizon, is essentially due to the ferruginasation phenomenon, which is accompanied by a marked increase in iron-bearing minerals (haematite and goethite);
- ✓ Increasing SiO_2 content for MHba0 (22.48%), MHba1 (38.69%) and MHba2 (40.82%). This oxide, inherited from the parent rock, undergoes a drastic downward trend and then stabilises at a certain average threshold in the surface horizons of this profile. This variation trend is the result of the consecutive phenomena of silicic leaching (desilicification) and resilification;
- ✓ A TiO_2 content ranging from 2.28% to 4.06%, which would indicate the relatively low presence of anatase or rutile. The alumina content is around 20% in the rocks studied, and the Al_2O_3/Fe_2O_3 ratio is in the 0 - 1 range.

Chemical analyses show that these materials are characterised by high Al_2O_3 contents (32.69%) in the Mayedo zone (MHb1). This visibly gibbsite-rich level corresponds to the zone of friable, homogeneous bauxite with a massive, blood-red texture described by Kaseba et al. (1997), whose estimated gibbsite percentage is 55.50.

The percentage of Fe_2O_3 is high at Kinzoki (Kinzoki beach) with 42.77%, hence the dark red colour; thus reflecting a strong ferruginasation zone (Njoya et al., 2017). This horizon contains a high concentration of hematite and goethite minerals. The SiO_2 content is highly variable, ranging from 13.48% to 40.82%. These variations are essentially due to the dissolution of silica by leaching and resilification.

At Kinzoki and Mayedo, the amount of TiO_2 varies greatly from 2.28% to 12.48%, hence the presence of anatase. However, at Mayedo, the TiO_2 values are relatively low, indicating the very low proportion of anatase or rutile in this region (Bernard, 1973; Sinisi, 2018).

The mobilisation of iron oxides in significant proportions in the horizons immediately above the parent rock follows the armouring process. The individualisation of iron, which is very advanced in these soils, allows it to be set in motion and concentrated in this lower horizon. Initially, more or less hardened concretions are formed, followed by the formation of true armour as a result of the cementing of the whole (Maignien, 1954).

Based on the above chemical analysis, we can conclude that the alteration typology is that of armourstone on basic rocks (doleritic basalt), the contents of which show compositions of elements (oxides) rich in iron, richer in kaolinite, richer in haematite and relatively poor in quartz (Alain et al., 1976). The mobility of these elements between different horizons is essentially due to infiltration water and the water table, which has been defined as a main factor controlling the laterisation process (Bonte, 1958; Nahon, 1976).

5. Conclusion and Perspectives

The study of the surface weathering formations in our study area enabled us to characterise, petrographically and geochemically, the evolution of the weathering profiles of the formations outcropping in and around Kinzoki. We also determined the mechanisms involved in the transformations that took place during the formation, evolution and degradation of the various geological formations studied.

In the Kinzoki and Mayedo Beaches, the alteration of the dolerites and basalts led to the individualisation of five sets of autochthonous horizons, which differ from one another in their respective petrographic and geochemical characteristics.

- ✓ The level of indurated alterites or aluminous cuirasses with a massive, pseudobrechic texture, with a zonation expressed by a succession of alternating reddish bands and yellowish balls;
- ✓ The horizon of unconsolidated ferruginous pisolites in a clayey or clay-ferru-

ginous matrix with a nodular texture. The hard, dense, decimetre to metre-sized cuirasses are coloured red-grey to dark reddish or greenish and encrusted with fine quartz crystals;

- ✓ The horizon of ferruginous and pisolitic Cuirasse with a massive texture, yellowish in colour, whose very fine grains are smooth, soft and sticky to the touch;
- ✓ The horizon of ferruginous pebbly alterites (pisolitic) containing more or less compact homogeneous clay soils of a yellowish to blackish colour under the influence of organic matter;
- ✓ The covering horizon of silty sand with a crumbly, heterogeneous surface, brown to yellowish and blackish in colour, with a small proportion of gravel.

Chemical analysis by XRF revealed high levels of Al_2O_3 (32.69%) in the Mayedo area (MHb1), indicating a high concentration of gibbsite in the unconsolidated ferruginous pisolite horizon described above.

The high Fe_2O_3 contents observed at Mayedo 2 and Kinzoki (57.39% and 42.77% respectively) are essentially due to the ferruginisation phenomenon, which is accompanied by the individualisation and marked increase in iron-bearing minerals (haematite and goethite). As for silica, its evolution in all the profiles is almost similar. Highly concentrated in the source rocks, it shows a downward trend in the intermediate horizons and an upward trend in the surface formations. These variations are attributed to the process of silica dissolution by leaching and resilification.

The titanium content observed in the ranges studied varies from 2.28% to 12.48%, indicative of the presence of anatase and rutile.

A quantification of the mineralogical balance based on diffractogram analyses of the samples from this area will enable us to better identify the horizons with high bauxite potential, and will provide a precise zonation of these ores for possible exploitation.

Conflicts of Interest

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

References

Abdourahamane, D. B., Mamady, C., Mupenge, M. P., & Mallam, M. H. (2021). Mineralogical and Geochemical Characteristics of the Sangarédi Bauxite Deposit, Boké Region, Republic of Guinea. *Environmental and Earth Sciences Research Journal, 8,* 11-22. https://doi.org/10.18280/eesrj.080102

Alain, B., Jean-Claude, L., & Pion, J. C. (1976). Originalite de l'alteration et du cuirassement de dykes basiques dans le massif de granite de Saraya (Senegal oriental). *Bulletin de la Société Géologique de France, S7-XVIII,* 45-49. https://doi.org/10.2113/gssgfbull.S7-XVIII.1.45

Bernard, H. (1973). Mineralogical and Geochemical Study of Bauxite Formations in Western Cameroon. *Publications of the Office for Overseas Scientific and Technical Research, Geology Series, 5,* 97-112.

Bonte, A. (1958). Reflections on the Origin of Bauxites and the Superficial Alteration of

Limestones. In *Proceedings of the 83rd Congress of Learned Societies of Paris* (pp. 147-165).

Cahen, L. (1978). Stratigraphy and Tectonics of the West-Congolian Supergroup in the Middle and Outer Zones of the West-Congolian (Pan-African) Orogen in Bas-Zaire and Neighbouring Regions. In *Annals of the Royal Museum of Tervuren* (p. 83). https://lib.ugent.be/catalog/rug01:002157883

De Keyser, W. L. (1959). A Note on the Composition and Processing of Bauxites from the Lower Congo. *Bulletin of the Royal Academy of Overseas Sciences, 4,* 975-991.

De Kun, N. (1965). *The Mineral Resources of Africa* (740 p.). Elsevier.

De Putter, T., & Decree, S. (2012). *The Mining Potential of the Democratic Republic of Congo (DRC), Myths and Components of a Mining Dynamic, Congolese conjunctures (2012)* (pp. 47-61). Éditions L'Harmattan.

Grosemans, P. (1959). Bauxite in the Bas-Congo. *Bulletins de l'Académie Royale des Sciences, 2,* 457-469.

Kaseba, M. K., Paepe, R., Boski, T., Herbosch, A., & Naud, J. (1997). Genesis and Evolution of Lateritic Bauxitic Profiles on Post-Eocene Levelling Surfaces in Bas-Zaire (Zaire). In J.-M. Charlet (Ed.), *Cornet International Colloquium: Stratiform Copper Deposits and Associated Mineralisation* (pp. 409-442). Mons Polytechnic Faculty, Royal Academy for Overseas Sciences.

Lepersonne, J. (1950). New Elements Concerning the Stratigraphy of Ancient Sites in Bas-Congo Provin. In *Bruxelles, 3e Congrès national des Sciences* (p. 22).

Lepersonne, J. (1974). *Geological map of Zaire at 1:2,000,000 and Explanatory Note.* Dépt. Mines, Dir. Géol. Republic of Zaire, 66 p. Summary and samenvatting Mus. roy. Central Africa, Tervuren (Belgium), Geol. Dept. Min, Rapp. Ann. 1975, (pp. 146-150).

Maignien, R. (1954). *Different Cuirassment Processes in A. O. F. O. F. Extract from the Proceedings of the 2nd Inter-African Soil Conference, Léopoldville* (pp. 1469-1486). Document No. 116.

Monti, L. M. (2012). *The Congolese Mineral Industry—Volume 1, Figures and Challenges* (322 p.). Editions le Harmattan.

Nahon, D. (1976). *Ferruginous Cuirasses and Calcareous Crusts of Western Senegal and Mauritania. Evolutionary Systems: Geochemistry, Structures, Relays and Coexistence* (232 p.). *Science, Strasbourg, Mémoire Sciences Géologiques 44,* 232 p.

Nehlig, P. (2019). *Improving Geological Knowledge of the Subsoil, a Challenge for France, Géosciences, la Revue su BRGM pour une Terre Durable* (p. 16).

Nicolaï, H. (2009). Progrès de la connaissance du Congo, du Rwanda et du Burundi de 1993 à 2008. *Belgeo, 3-4,* 247-404. https://doi.org/10.4000/belgeo.7306

Njoya, D., Njoya, A., Kamlo Ngueteu, A., Tchuindjang, Y. D., & Nkoumbou, C. (2017). Caractérisation chimique et minéralogique de quelques indices de bauxite de Foumban (Ouest-Cameroun). *International Journal of Biological and Chemical Sciences, 11,* 444-452. https://doi.org/10.4314/ijbcs.v11i1.35

Ongendangenda, T., Mpiana, K., & Kampunzu A. B. (1986). *Characterisation of West Congolian Volcanism Using Clinopyroxenes: The Case of the Basic Rocks of Sumbi in Bas-Congo* (pp. 153-162). UNESCO, Geology for Economic Development.

Patterson, S. H. (1967). *Bauxite Reserves and Potential Aluminium Resources of the World* (pp. 78-79). Geological Survey Bulletin 1228. United States Government Printing Office.

Sinisi, R. (2018). Mineralogical and Geochemical Features of Cretaceous Bauxite from San Giovanni Rotondo (Apulia, Southern Italy): A Provenance Tool. *Minerals, 8,* Article No. 567. https://doi.org/10.3390/min8120567

Tack, L., Wingate, M. T. D., Liegeois, J.-P., Fernandez-Alonso, M., & Deblond, A. (2001). Early Neoproterozoic Magmatism (1000-910 Ma) of the Zadinian and Mayumbian Groups (Bas-Congo): Onset of Rodinia Rifting at the Western Edge of the Congo Craton. *Precambrian Research, 110,* 277-306. https://doi.org/10.1016/S0301-9268(01)00192-9